Trade, CO_2, and the Environment

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Abstract

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Abstract. This paper puts trade's benefits and environmental costs on the same theoretical and empirical footing in order to provide a more complete measure of trade's welfare effects. The paper describes a model of trade and the environment, compiles new data on the CO_2 emissions from shipping, and estimates key parameters using instrumental variables. Results show that international trade's benefits exceed international trade's environmental costs by two orders of magnitude. While proposed regional or global carbon taxes on the CO_2 emissions from transporting goods would increase global welfare and increase the implementing region's GDP, they would also harm poor countries.

1 Introduction

Economists have long argued that trade liberalization improves social welfare by increasing real income levels. This paper starts from the idea that trade may also generate a negative externality by contributing to climate change. Trade can generate this externality by requiring long-distance shipping of goods and by relocating production to regions which emit large amounts of CO_2 to produce a given good.

This paper builds a unified theoretical and empirical framework which can compare international trade's benefits against its environmental costs. The paper describes a model of trade and the environment, compiles new data on CO_2 emissions from international and intranational shipping, and estimates the model's key parameters via instrumental variables. The model and data are used to examine two types of counterfactuals.

The first counterfactual asks: how would welfare change if all international trade ceased? Autarky for all countries is (hopefully) not a realistic policy, but it provides a benchmark for studying real policies. I find that international trade increases CO_2 emissions by 5 percent. Several influential papers ask whether international trade is good for the environment (Antweiler, Copeland and Taylor 2001, Copeland and Taylor 2003, Frankel and Rose 2005), and this conclusion provides a clear answer—no. However, the global gains from international trade, equal to $5.8 trillion annually, exceed the environmental costs of international trade by a factor of 180.[1]

Second, the paper assesses the welfare consequences of several proposed climate change regulations. I focus on the EU's current effort to regulate the CO_2 emissions from domestic and international airplane flights, which the *New York Times* has repeatedly described as "one of the most contested environmental initiatives ever undertaken" (Kanter 2011, Kanter 2012). I also analyze US regulations of the CO_2 emissions from all forms of shipping, which were part of the Waxman-Markey Bill of 2009 that passed the US House but not the Senate.

[1] The "environment" in this paper refers exclusively to climate change. Although this paper's framework could be applied to any pollutant, due to data limitations I do not measure the effects of "local" pollutants like sulfur dioxide (SO_2) or nitrogen oxides (NO_x).

Finally, I analyze a global tax on the CO_2 emissions from air and sea shipping, which the 1997 Kyoto Protocol required but which has not been implemented. These counterfactuals all represent incomplete regulation, so their environmental and welfare effects have theoretically ambiguous signs. I focus on these policies because almost all existing climate change research analyzes the regulation of production and not transportation; because the growth of CO_2 emissions from international transportation exceeds CO_2 emissions growth from any other sector (IEA 2011); and because transportation's central role in international trade means this analysis can help answer the important question of how trade affects the environment.

I find that these policies all increase global welfare but have two surprising properties. First, these policies are regressive and decrease welfare in poor countries. This is surprising because poor countries suffer the largest proportional damages from climate change. However, poor countries specialize in goods with high weight-to-value ratios, which require relatively large amounts of shipping fuels. Second, unlike almost any other environmental regulation, the regional policies increase GDP in implementing region at the expense of other regions. This is because these policies resemble small unilateral tariffs, and such tariffs can benefit a large country by decreasing the relative prices of imported goods (Bickerdike 1907).[2]

This paper uses assumptions on the structure of preferences, production, trade costs, pollution emissions, and equilibrium. For expositional purposes, I describe a simple Armington (1969) trade model, in which each country produces one variety per sector and varieties are differentiated by country of origin. Analogous assumptions, however, would provide similar welfare calculations under other important trade theories (Arkolakis, Costinot and Rodríguez-Clare 2012).[3] These models depend on variables which are difficult to measure, but an approach from Dekle, Eaton and Kortum (2008) makes most of these variables unnecessary.

To estimate this model's key parameters, the paper uses instrumental variable regressions to estimate trade elasticities separately for 13 sectors. These parameters are arguably the most important parameters in trade. They can guide trade negotiations, enable the quantitative evaluation of past policies like NAFTA, measure the gains from trade, and explain why international trade is growing faster than global production (Baier and Bergstrand 2001, Yi 2003, Caliendo and Parro 2011). These parameters represent the bilateral elasticity of trade in dollars with respect to bilateral trade costs.[4] Like Hummels (2001),

[2] The standard terms-of-trade argument assumes that a tariff is applied to international and not intranational trade. The logic of the standard argument still applies in this paper's setting because international shipping is more fuel-intensive than domestic shipping.

[3] Eaton and Kortum (2002), Bernard, Eaton, Jensen and Kortum (2003), and this paper's Armington (1969) model provide numerically equivalent welfare measures. Because this paper analyzes multiple sectors, intermediate goods, and tariff revenues, Krugman (1980) and Chaney's (2008) application of Melitz (2003) would produce different measures. An emerging literature provides quantitative welfare comparisons between these models (Balistreri, Hillberry and Rutherford 2011, Costinot and Rodríguez-Clare Forthcoming).

[4] In Armington (1969) models, the trade elasticity represents the elasticity of substitution across national

I use reported shipping costs. I also use panel data and obtain two measures of shipping costs for each observation. Using one of these measures as an instrumental variable for the other increases estimates of the trade elasticity in absolute value, which is consistent with the presence of attenuation bias due to classical measurement error. Using this instrumental variables regression, I obtain a trade elasticity of -7.91 for the global economy overall, -7.33 for manufacturing, and a range of -0.77 to -18.55 for thirteen sectors.

To apply the model, I combine data from national commerce offices and public records to obtain what I believe is the most comprehensive set of files ever compiled on international and intranational shipping costs, transportation mode choice, pollution emissions, and trade flows. For 13 sectors of production, five modes of transportation, and 128 countries, these data measure how economic activity affects climate change, representing nearly one million carbon emission estimates. Together, these provide a complete accounting of carbon emissions from the global economy.

I test each set of results against independent estimates to assess their accuracy. I obtain encouraging evidence. When aggregated to broad categories that are comparable, my aggregate CO_2 emissions resemble those of international organizations. For my regression estimates of trade elasticities, estimated bilateral demand is more elastic for more homogenous goods (Rauch 1999). For my analysis of carbon taxes, a simpler approach – Harberger (1964) triangles – obtains comparable global welfare measures.

This paper builds on four literatures. First, this paper builds on research in trade and the environment (Antweiler et al. 2001, Copeland and Taylor 2003, Frankel and Rose 2005) by analyzing real-world policies using data from many countries, using a structural "gravity" model of trade, and focusing on transportation. Most of the trade and the environment literature uses Heckscher-Ohlin or reduced-form models, analyzes pollutants like SO_2 which primarily affect the region where they are emitted, and focuses on production. Unlike much of this literature, I do not describe environmental regulations as endogenous to income, in part because most benefits of abating CO_2 emissions accrue to other countries, so the effects of income or price shocks on CO_2 regulations is likely to be limited (Cole and Elliott 2003).

The second body of research studies regulation and generally uses structural models, or computable general equilibrium (CGE) models, or reduced-form regressions (Bovenberg and Goulder 1996, Greenstone 2002, Nordhaus 2008, Elliott, Foster, Kortum, Munson, Cervantes and Weisbach 2010, Balistreri and Rutherford 2012). This paper uses a hybrid that combines the strength of each approach: reduced-form regressions estimate the key parameters of a structural general equilibrium model, and the model is then applied to recover the full welfare

varieties. In Ricardian models with Fréchet-distributed technology (Eaton and Kortum 2002), it represents the inverse dispersion of productivity. In models of monopolistic competition with heterogeneous firms and Pareto-distributed technology (Melitz 2003, Chaney 2008), it represents the shape parameter of the Pareto distribution. In welfare analyses, this parameter plays similar roles in all of these models (Arkolakis et al. 2012).

consequences of untested policies.[5] My joint analysis of transportation and production also contrasts with that literature's focus on production.[6]

Third, the paper builds on a literature which develops robust approaches to measuring the gains from trade (Eaton and Kortum 2002, Alvarez and Lucas 2007, Dekle et al. 2008) Researchers have applied this approach to many empirical trade questions (Donaldson Forthcoming, Ossa 2011, Harrigan 2010, Caliendo and Parro 2011). The broad differences between this more recent trade literature and long-standing CGE papers are an emphasis on using few assumptions; close ties between theory, econometrics, and data; and richer and more plausible microfoundations. I build on this literature by accounting for the environmental costs of trade and by calculating confidence regions for welfare estimates.[7]

Finally, my estimates of trade elasticities and measurement of fuel costs also build on existing work. Some research uses reports of shipping costs (Hummels 2001), while others infer trade costs from trade flows (Anderson and van Wincoop 2004, Head and Ries 2001). One study estimates carbon emissions for international trade flows (Cristea, Hummels, Puzzello and Avetisyan Forthcoming). Sections 4 and 5 compare this paper's methodology and results with these literatures. My finding that measurement error biases conventional estimates of the trade elasticity towards zero may have broader applicability, and it suggests that the gains from trade are smaller than conventional estimates would imply.

The paper proceeds as follows. Section 2 outlines the theory. Section 3 describes the paper's data sources. Section 4 describes new measures of the CO_2 emissions from shipping. Section 5 reports new estimates of the trade elasticities. Section 6 measures the full welfare effects of international trade. Section 7 applies the model to evaluate regional and global carbon taxes. Section 8 describes sensitivity analyses, and Section 9 concludes.

2 Model of Trade and the Environment

The model describes a world of N countries, each with a fixed labor force L and a representative consumer. Production requires only one factor ("labor"). In this Armington (1969) model, each country produces one variety per sector, and varieties are differentiated by country of origin. The rationale for this simple model is expositional: Ricardian models with more realistic microfoundations (Eaton and Kortum 2002, Bernard et al. 2003) would generate numerically equivalent welfare calculations.

[5] Baldwin and Venables (1995) compare CGE models and regressions.

[6] Several studies assess how the EU ETS would affect ticket prices and potential airline profits (Faber and Brinke 2011). Keen, Perry and Strand (2012) measure potential revenue and deadweight loss from taxes on international air and sea shipping.

[7] Lai and Trefler (2002) and Hertel, Hummels, Ivanic and Keeney (2007), which use different frameworks from most of this literature, are the only trade papers I know which report a confidence region for the gains from trade.

2.1 Primitive Assumptions

A1. Preferences. Consumers have constant elasticity of substitution (CES) preferences over varieties within a sector, Cobb-Douglas preferences across sectors, and experience quadratic damage from climate change:

$$\begin{aligned} U_d &= \left[\prod_{j=1}^{J}\left(Q_d^j\right)^{\alpha_d^j}\right]\left[\frac{1}{1+\left(\mu_d^{-1}\sum_{o=1}^{N}E_o\right)^2}\right] \\ Q_d^j &= \left(\sum_{o=1}^{N}\left(Q_{od}^j\right)^{\frac{\sigma^j-1}{\sigma^j}}\right)^{\frac{\sigma^j}{\sigma^j-1}} \end{aligned} \tag{1}$$

The first bracketed term in (1) represents the utility from consuming goods, and the second bracketed term in (1) represents the disutility from climate change. The term Q_d^j is a CES aggregate of the varieties Q_{od}^j, each representing trade from origin country o to destination country d of sector j goods. The elasticity of substitution between sector j varieties is $\sigma^j > 1$. Due to the Cobb-Douglas preferences across sectors, country d spends the share α_d^j of its expenditure on sector j. Total CO_2 emissions due to country o are E_o, and the parameter μ_d dictates the social cost of CO_2 emissions. CO_2 emissions are an externality that the representative agent takes as given when making consumption decisions. This model has no feedback loop from the environment to trade—the negative environmental externality of trade decreases utility, but climate change does not affect trade directly.

These preferences imply the following consumer price index for sector j in country d:

$$p_d^j = \left[\sum_{o=1}^{N}(p_{od}^j)^{1-\sigma^j}\right]^{\frac{1}{1-\sigma^j}}$$

Here p_{od}^j is the price for sector j varieties produced in country o and sold in country d. The expenditure required for one unit of utility is then $P_d \equiv \Pi_{j=1}^{J}(p_d^j)^{\alpha_d^j}$.

The functional form for climate damages is common in environmental economics (Nordhaus 2008, Weitzman 2012), with two exceptions. First, many papers describe damages as a function of climate and use atmospheric science to determine how CO_2 emissions affect climate. Assumption (1) approximates those models by using a quadratic damage function to summarize both how CO_2 emissions affect climate and how climate affects utility. For this paper's counterfactuals, this specification provides a marginal social cost of carbon emissions which is nearly constant. Second, many papers describe climate as affecting output rather than utility. Because sector- and region-specific estimates of climate impacts are not well known, I use the

reduced-form approximation of describing climate damage as affecting utility directly.[8]

The parameter μ_d quantifies the magnitude of climate damages such as diminished human health. I rely on the large climate change literature to measure μ_d; it is the only parameter in this paper that cannot be determined within the model. The climate change literature assumes utility functions which are similar but not identical to equation (1). For example, the DICE model (Nordhaus 2008) assumes a utility function with constant relative risk aversion preferences where output is multiplied by a climate damage function which is quadratic in temperature. Assumption (1) allows expenditure shares α_d^j and climate damages μ_d to vary across countries. This assumption, however, does not allow elasticities of substitution σ^j to vary by country. I make this restriction to increase tractability: models with heterogeneous trade elasticities do not in general lead to the simple gravity equation which has an appealing empirical and theoretical basis (Fieler 2011).

A2. Production Technology and Market Structure. Firms have Cobb-Douglas production technology and trade costs take the "iceberg form," where $\tau_{od}^j \geq 1$ units must be shipped for one to arrive:

$$c_o^j = (w_o)^{\beta_o^j} (p_o^j)^{1-\beta_o^j} \tag{2a}$$

$$p_{od}^j = c_o^j \tau_{od}^j \tag{2b}$$

Labor has price w_o and share β_o^j. Intermediate goods have price p_o^j and share $1-\beta_o^j$. Firms engage in perfect competition and arbitrage price gaps over space, so the product price at destination d equals the production cost c_o^j multiplied by a trade cost τ_{od}^j. This cost function arises if output in each sector is combined into an intermediate good specific to that sector. Production uses the same CES price aggregator as consumption, so p_o^j represents both the consumer price index and the price of intermediate goods shown in (2a).

A3. Transportation Technology. Trade costs can be decomposed as follows:

$$\tau_{od}^j = (1+t_{od}^j)(1+f_{od}^j)\exp(\delta_{od}^j) \tag{3a}$$

$$t_{od}^j = \sum_{m=1}^{M} D_{odm}\kappa_{odm}^j W_{odm}^j \xi_m \gamma_1 (t_{odm}^{j,X} + t_{odm}^{j,M}) \tag{3b}$$

$$f_{od}^j = \sum_{m=1}^{M} D_{odm}\kappa_{odm}^j W_{odm}^j \xi_m \gamma_2 P^{oil} \tag{3c}$$

Here t_{od}^j represents the carbon tax per dollar of expenditure, f_{od}^j represents the fuel cost per dollar of expenditure, and δ_{od}^j represents all other bilateral trade frictions. Equation

[8] Sector- and region-specific damages have been estimated for agriculture. The RICE data used to calibrate climate damages reflect estimates of how climate change will affect agriculture in each country, so the climate damages used here incorporate those estimates.

(3a) summarizes two types of trade costs: an "iceberg" component $(1 + f^j_{od})\exp(\delta^j_{od})$; and a carbon tax t^j_{od} which is rebated lump-sum to consumers. The costs δ^j_{od} are difficult to observe—they summarize tariffs, border effects, language differences, informational barriers, and other barriers to trade (Anderson and van Wincoop 2004).

Equations (3b) and (3c) relate carbon taxes and fuel consumption to observable data. The variable D_{odm} represents the distance between countries o and d via transportation mode m. Distances differ by transportation mode because ships cannot travel overland. The variable κ_{odm} represents the share of o-d trade in dollars transported by mode m. The variable W_{odm} represents the weight-to-value ratio for goods traded between countries o and d by mode m. The variable ξ_m represents the fuel efficiency of transportation mode m, defined in grams of CO_2 emitted per ton-km transported. This functional form builds on Cristea et al. (Forthcoming). The variable P^{oil} represents the global oil price in dollars per barrel of crude. The variable $t^{j,X}_{odm}$ represents the carbon tax rate for exports, measured in dollars of tax per ton of CO_2, and $t^{j,M}_{odm}$ represents the carbon tax rate for imports. The constants γ_1 and γ_2 convert units of measurement.[9] I treat the global oil supply as perfectly elastic, so shifts in oil demand due to counterfactuals do not affect pre-tax oil prices. These equations embody two important restrictions: they assume perfect competition in the transport sector and imply that the counterfactual analyses will treat D_{odm}, κ_{odm}, W_{odm}, and ξ_{odm} as fixed.

A4. Environment. Trade and production generate CO_2 emissions as follows:

$$E_d = \sum_{o,j} (\gamma_3 f^j_{od} + \chi^j_o) \frac{X^j_{od}}{p^j_{od}} \tag{4}$$

Equation (4) shows how trade contributes to climate change by affecting CO_2 emissions from both production and transportation. Here χ^j_o represents the CO_2 emissions per unit of output for sector j in country o, and the constant γ_3 represents tons of CO_2 emitted per dollar of fuel. The ratio X^j_{od}/p^j_{od} represents the units of goods produced in country o and consumed in country d. Trade generates an environmental externality through shipping (f^j_{od}) and through relocating production to countries with differing CO_2 emissions rates from production (χ^j_o). Because domestic trade plus international trade accounts for all of a country's gross output, and because domestic shipping fuel plus international shipping fuel equals total shipping fuel consumption, equation (4) accounts for CO_2 emissions from all economic activity, and not merely from international trade.

[9] Specifically, $\gamma_1 = \frac{ton^2}{kg*g} = 10^{-9}$ and $\gamma_2 = \frac{ton*barrel}{kg*g} = 0.43^{-1} * 10^{-9}$, using the USEPA's standard value of 0.43 tons of CO_2 per barrel of crude oil. All tons in this paper are metric.

2.2 Competitive Equilibrium

A5. Market Clearing. Consumers maximize utility, firms maximize profits, and markets clear.

Demand has two stages. In the first stage, Cobb-Douglas preferences across sectors mean that each country spends the share α_d^j on sector j. In the second stage, countries allocate this expenditure across varieties within a sector according to the following "gravity" demand:

$$\lambda_{od}^j = \left(\frac{c_o^j \tau_{od}^j}{p_d^j} \right)^{\theta^j} \tag{5a}$$

Here λ_{od}^j represents the share of country d's expenditure on sector j which is devoted to goods from producing country o.[10] I use the notation $\theta^j \equiv 1 - \sigma^j$ to highlight that the elasticity in equation (5a) does not merely represent a preference parameter, but represents the key trade elasticity of a large family of gravity models.

Profit maximization and utility maximization imply the following expenditure:

$$X_d^j = (1 - \beta_d^j) I_d^j + \alpha_d^j I_d$$

Here total expenditure on goods from a sector, $X_d^j \equiv \sum_{o=1}^N X_{od}^j$, sums expenditure on intermediate and final goods. Income from sector j, $I_d^j = F_d^j X_d^j - T_d^j - \phi_d^j$, sums pre-tax imports and net exports. Here $F_d^j \equiv \sum_{o=1}^N \lambda_{od}^j / (1 + t_{od}^j)$ is a weighted measure of carbon taxes. Full income $I_d = w_d L_d + R_d + T_d$ sums labor earnings $w_d L_d$, carbon tax revenue R_d, and net imports T_d. Formally, $R_d = \Sigma_{o,j} [t_{do}^{j,X} X_{do}^j / (1 + t_{do}^{j,X}) + t_{od}^{j,M} X_{od}^j / (1 + t_{od}^{j,M})]$, where $t_{do}^{j,X}$ represents the carbon tax per dollar of d's exports and $t_{od}^{j,M}$ the carbon tax per dollar of d's imports.

Market clearing implies that imports equal exports for each country:

$$\sum_{o,j} \frac{X_{od}^j}{1 + t_{od}^j} = \sum_{o,j} \frac{X_{do}^j}{1 + t_{do}^j} + T_d + \phi_d \tag{5b}$$

For each country, trade is imbalanced sector-by-sector. A country's total net imports across sectors equals T_d, which is positive for a country with a trade deficit. Here net imports T_d represent a transfer from the rest of the world to country d which is fixed in counterfactuals.[11] The parameter ϕ_d measures international financial flows due to carbon taxes on exports.

[10] The "gravity" description comes from analogy to physics, where gravitational attraction between objects rises with their mass (analogously, GDP) and declines with their distance (trade cost). Most trade theories generate a gravity relationship. Dozens of authors who test this assumption in cross-sectional data obtain similar parameter estimates and an R-squared between 0.75 and 0.95 (Anderson 2011). Leamer and Levinsohn (1995, p. 1384) describe these estimates as "some of the clearest and most robust empirical findings in economics."

[11] In a dynamic model, these transfers would represent intertemporal borrowing from the rest of the world.

Formally, $\phi_d = \Sigma_{o,j} X_{do}^j t_{do}^{j,X}/(1+t_{do}^{j,X}) - \Sigma_{o,j} X_{od}^j t_{od}^{j,M}/(1+t_{od}^{j,M})$, where $t_{do}^{j,X}$ represents the carbon tax per dollar of d's exports, and $t_{od}^{j,M}$ the carbon tax per dollar of d's imports.

2.3 Counterfactual Calculations

Using this model to measure the welfare effects of a new policy involves simple calculations. Algebra shows that the indirect utility function for this model is

$$V_d = \left[\frac{I_d}{P_d}\right]\left[\frac{1}{1+\left(\mu_d^{-1}\sum_{o=1}^N E_o\right)^2}\right]$$

Here social welfare equals the product of real income and environmental damage.

Because credible measures of prices, wages, and trade costs for all countries are difficult to obtain, I reformulate the model in terms of proportional changes (Dekle et al. 2008). Let x' denote the value of variable x after a policy is imposed and $\hat{x} \equiv x'/x$ represent the proportional change in x due to the policy. In this model, the equivalent variation is

$$\hat{V}_d = \left[\frac{\hat{I}_d}{\hat{P}_d}\right]\left[\frac{1+\left(\mu_d^{-1}\sum_{o=1}^N E_o\right)^2}{1+\left(\mu_d^{-1}\sum_{o=1}^N E_o'\right)^2}\right] \tag{6}$$

Equation (6) represents the amount a country would pay before introducing a policy in order to end up with the same utility level that the policy would provide. I evaluate counterfactuals by constructing empirical analogues to equation (6).

2.4 From Theory to the Data

In applying this model to counterfactuals, three objects play key roles: the effect of carbon regulations on trade costs ($\hat{\tau}_{od}^j$); trade elasticities (θ^j); and bilateral expenditure shares (λ_{od}^j).

The data $\hat{\tau}_{od}^j$ measure how a specific regulation changes trade costs for each sector and country pair. Section 4 describes data which measure $\hat{\tau}_{od}^j$ as a function of fuel costs per dollar of trade (f_{od}), using assumption (3a).

The elasticities θ^j represent the causal effect of log bilateral trade costs on log bilateral trade flows for sector j, holding wages and prices in each country fixed. These estimates, shown in Section 5, help analyze the effects of the counterfactuals I study because each counterfactual is equivalent to a change in trade costs. Although I estimate θ^j with data from specific countries and years, under assumption (1), θ^j describes the effects of trade costs for any country and years.

The data λ_{od}^j describe bilateral trade between all countries in a baseline year. I obtain these data from public sources.

The key equations from the model used in counterfactuals are the structure of trade costs (3a), the gravity equation (5a), trade balance (5b), and social welfare (6). The trade cost assumption shows how carbon taxes affect trade costs. The gravity equation reveals how wages and prices affect trade flows and provides the regression equation to estimate θ^j. Trade balance defines market equilibrium, which pins down the effect of a policy on wages. The measure of welfare is used to evaluate counterfactuals.

3 Data

I apply this model using data on bilateral trade for the year 2007 between 128 countries for 13 tradable sectors and one non-tradable sector.

3.1 CO_2 Emissions from Trade

Measuring CO_2 emissions as described in (3c) and (4) requires data on distances, transport mode shares, weight-to-value ratios, fuel efficiency, and production emission rates.

Distance. The Center for International Prospective Studies (CEPII) provides data on intranational and international distances (D_{odm}) for air, rail, and road trade (Mayer and Zignago 2005). These data account for population-weighted international distances, and intranational distances are defined as $0.67\sqrt{area/\pi}$ (Head and Mayer 2010).

Measuring transportation fuel costs requires estimates of distances for maritime trade. Geographic information system (GIS) files from ESRI describe the locations of all major global ports and land masses. Each non-landlocked country has at least one port, and in each country, I assume that all maritime trade flows through the port city with the greatest population. For the US, I assume that 80 percent of trade travels through New York and 20 percent through Los Angeles. To measure distances by sea, I create a one-degree grid spanning the globe. For each grid cell, I permit a ship to travel to any cell within three degrees of longitude or latitude, so long as that travel does not cross land. I apply the Floyd (1963)-Warshall (1962) algorithm to find the shortest path between every city pair, which measures the sea distance between their respective countries.[12]

Transportation Mode Shares. Data on the share of goods transported by each mode (κ^j_{odm}) are the most difficult to obtain since most public datasets do not identify transport modes. To compile these data, I obtained several files which together cover 83 percent of global trade by value and 74 percent of global trade by weight (see the Appendix). I obtain data from US Imports and Exports of Merchandise (US air and sea); North American Freight (US truck and train); Trade Statistics of Japan (Japan); the Global Trade Atlas compiled by Global Trade Information Services (China); EU Secretariat (external trade is

[12] Feyrer (2009b) constructs a similar measure.

publicly available and internal trade I obtained by request); and the Latin America Integration Association (ALADI, for Argentina, Bolivia, Brazil, Chile, Columbia, Ecuador, Paraguay, Peru, Uruguay, and Venezuela). All data represent the year 2007 except EU internal trade, which is from the most recent year available (2000). I group unknown, post, pipeline, and self-propulsion transportation modes into one "other" category.

I impute transportation mode shares for the 17-26 percent of international trade flows where data do not report them (see the Appendix). Mode shares have two important statistical properties: each share lies in $[0, 1]$, and shares for each trade flow must sum across transportation modes to one. I use a fractional multinomial logit (Papke and Wooldridge 1996) to impute mode shares for trade flows where mode data are unavailable. I believe is the only statistical model that fits the requirements of the data.[13]

Weight-to-Value Ratios. The data sources recording mode of transportation also record weight-to-value ratios (W). These data report the total value and quantity of each trade flow, but not all quantities represent weights. I aggregate over the transportation mode datasets to obtain weight-to-values used to fill in missing data (see the Appendix).

Fuel Efficiency. Fuel efficiency (ξ_{odm}, measured in gCO_2/ton-km) for air and sea shipping is measured from published data as follows. For airborne trade, data on global ton-km and global fuel consumption imply a fuel economy for air freight of 985.97 gCO_2/ton-km (IATA 2009).[14] For maritime trade, the CO_2 emissions due to international transportation (IEA 2011) and the international ton-km reported by the shipping industry imply fuel efficiency for sea freight of 9.53 gCO_2/ton-km.[15] This approach is not possible for rail and road shipping because I know of no data on total global fuel consumption for these transport modes. Instead, I compare across estimates in the transportation literature, each representing a specific region. This approach leads to fuel economy estimates of 23.0 gCO_2/ton-km for rail and 119.0 gCO_2/ton-km for road (Appendix Table 1). I impose a fuel consumption rate (ξ) of zero for the "other" transportation mode.

CO_2 from Production. I use estimates of the CO_2 emissions from production compiled by the Global Trade and Analysis Project (GTAP). GTAP uses the Tier 1 method of the

[13] OLS and Tobit fitted values for each mode need not lie in the $[0, 1]$ interval, even when adding-up constraints impose that shares sum to one. Beta and Dirichlet distributions exclude the extremal values 0 and 1. I use this imputation for all domestic mode shares since no data report them.

[14] Because airplanes form atmospheric contrails which warm the climate, many scientists estimate that airplanes contribute 1.5 to 3.0 times more to climate change than their CO_2 emissions would imply. For simplicity, I follow most policymakers in measuring airplanes' climate change impact according to their CO_2 emissions.

[15] For air, IATA reports a global air fuel economy of 39.0 liters/ton-km. I convert this to gCO_2 using the US Energy Information Agency's reference rate of 9.57 kg CO_2 per gallon of jet fuel. For sea, IEA (2011) reports that international marine transportation emitted 624.5 $MtCO_2$. Freight accounts for 90 percent of civilian ship CO_2 emissions (IMO 2009, p. 160) and the IEA international maritime data generally exclude military ship emissions (Reece 2004). Dividing CO_2 emissions of 562.05 $MtCO_2$ by the 50.6 trillion ton-km of international freight reported to be traded by ship gives the 11.11 rate.

Intergovernmental Panel on Climate Change (IPCC 1997) to compile these data. For each sector and country in the year 2007, these data report the tons of CO_2 emitted by producing the good. I use the GTAP data because it provides extensive country and sector detail. The Tier 1 method has the lowest data requirements and simplest methodology—it generally multiplies physical quantities of fuel consumption by mean emissions coefficients. GTAP obtains these data from input-output matrices and national accounts data for each country.

3.2 Shipping Costs for Estimating Trade Elasticities

I use quarterly reports of transportation costs and trade values for all US and Australian imports over the period 1991-2010.[16] The US data come from the US Imports of Merchandise dataset. I had the Australian Bureau of Statistics compile the Australian data. The US data report trade at the 10-digit Harmonized Commodity Description and Coding System (HS) level, while the Australian data report trade at the 6-digit HS level. The Appendix explains how I translate these data into the 13 sectors I analyze.

3.3 Counterfactuals: Welfare Effects of International Trade and EU, US, and Global Carbon Taxes

I use data on bilateral trade, gross output, and CO_2 emissions from production for the year 2007 from GTAP. These data report values for 128 countries and 57 sectors.[17] Their data are based on the UN's Comtrade data for goods. I aggregate these data to 14 sectors, including one non-tradable sector, which are comparable across all the datasets used in this paper.

The only parameter which this paper cannot estimate is μ_d, which is isomorphic to the social marginal cost of CO_2 emissions, i.e., the present discounted value of the change in current and future welfare due to emitting one additional ton of CO_2. The paper does not estimate this parameter because μ_d aggregates information that is beyond the scope of this paper: the damages of climate change (e.g., diminished human health), the atmospheric processes translating CO_2 emissions into climate change, and the trends and discounting of these values over future centuries to obtain their present value. Almost all economic models of climate change rely to some extent on other studies' estimates of climate damages. This paper takes a simple approach: every aspect of trade, emissions, and consumption is estimated within the paper, and then the question of how carbon emissions affect welfare is left to the large literature focused on this question.

[16] Only these countries could provide panel data on transport costs for many sectors and years. 1991-2010 is the period for which I obtained quarterly data covering both countries.

[17] The data include all world production, but small countries are combined due to data limitations. I combine the "Rest of the World" and "Other Oceania" countries. Gross output equals value added (GDP) plus the value of intermediate goods. Total domestic purchases (X_{oo}) are calculated as gross output minus international exports.

I choose the values of μ_d so that a one ton increase in CO_2 emissions decreases global GDP by \$19.96. This reflects the estimate of the marginal social cost of CO_2 emissions by an interagency panel of the US government (Greenstone, Kopits and Wolverton Forthcoming), which bases its analysis on three integrated assessment models (FUND, DICE, and PAGE). The calculation assumes a 3 percent social discount rate. The value \$19.96 for the year 2007 linearly extrapolates the Interagency estimates of \$21.40 for the year 2010 and \$23.80 for the year 2015. For each counterfactual, I set the carbon tax rate equal to this social cost of carbon.[18] I also show results for each of the paper's counterfactuals under alternative values for the social cost of carbon or \$4.10 and \$1170. The low value of \$4.10/tonCO_2 reflects a 5% discount rate from the Interagency panel. The high value of \$1170 reflects the most extreme value estimated in a version of the DICE model with risk-averse policymakers and large and uncertain potential impacts of climate change (Cai, Judd and Lontzek 2012).

To assign this global cost of climate change to individual countries, I choose μ_d so that the global impact of marginal increases in CO_2 emissions is \$19.96/ton, but the country-by-country impact is proportional to GDP in the quantities documented in the RICE model (Nordhaus and Boyer 2000, p. 4-44).[19]. For 13 distinct regions of the globe, Nordhaus and Boyer report the damage due to a 2.5C warming, with all impacts monetized.

4 CO_2 Emissions from Trade

This paper compiles data on the CO_2 emissions from shipping because these data are necessary to apply the mode. This section describes salient facts from these data because they provide novel evidence on how shipping contributes to climate change.

4.1 Results: CO_2 Emissions from Trade

Total Emissions. The CO_2 emissions due to production of traded goods and due to international transportation have similar orders of magnitude. International shipping emitted 1.5 gigatons of CO_2 in the year 2007, domestic shipping emitted 1.9 gigatons, the production of traded goods emitted 1.2 gigatons, and the production of nontraded goods emitted 25.3

[18] I use this value for the US and EU counterfactuals because the US government has chosen this global rate as its official measure of the social cost of carbon, and because this value is similar to forecasts of EU carbon allowance prices over the next decade (Point Carbon 2012).

[19] The functional form in assumption (1) does not allow for benefits from climate change, whereas in the Nordhaus and Boyer data, eight country-regions are projected to benefit from climate change: Australia, Canada, Hong Kong, Israel, New Zealand, Singapore, Russia, and the Rest of Europe. In the year 2007, these countries accounted for 3.6 percent of global population and 7.7 percent of global GDP. The Rest of Europe is an aggregated country which combines Andorra, Bosnia and Herzegovina, Faroe Islands, Gibraltar, Guernsey, Vatican City, Isle of Man, Jersey, Macedonia, Monaco, Montenegro, San Marino, and Serbia. For consistency with the standard quadratic damage function, I assume that each of these country-regions has zero damage from climate change.

gigatons (Table 1). In total, I calculate global CO_2 emissions in 2007 of 29.9 gigatons.[20]

In aggregate, production emits far more CO_2 than transportation. Goods production is responsible for almost 90 percent of global CO_2 emissions. Although this measure of production includes direct household consumption (e.g., residential heating), even with a more detailed breakdown, the vast majority of CO_2 emissions come from production rather than transportation.

By Country. Differences in CO_2 emissions from shipping across countries presage this paper's finding that poor countries lose the most from rising prices of shipping fuels. Shipping fuel emissions depend on the weight-to-value ratio of goods, the distance goods are shipped, and the mode used for transportation, which all vary across the globe (Appendix Figure 1). Wealthy countries like the US and Europe disproportionately trade technological goods with low weight-to-value ratios. Poorer regions like Africa and the Middle East generally trade in heavy mining and agricultural goods like crude oil, grain, and iron ore. Distances to trading partners are greatest for Africa and lower for the US and EU. Wealthy countries are most likely to trade by airplane, while countries in Asia, Africa, and Latin America use more overland and maritime trade. Panel D of Appendix Figure 1 reports the fuel costs per dollar of trade (f_{od}) separately by country. This map makes clear that poor regions of the world, especially sub-Saharan Africa, are likely to experience the largest relative effects of rising shipping costs.

By Transport Mode. Differences across transport modes provide one reason why ex ante one might expect rich countries to pay the highest relative costs of regulations which increase the price of shipping fuels (Table 1 and Appendix Table 1). Airplanes emit nearly 100 times as much CO_2 as ships do to move one ton-km. Rail shipment is nearly as efficient as sea shipment, and truck shipment has intermediate efficiency. Maritime trade accounted for nearly half of international shipping emissions, airborne trade for about a fourth, rail trade for about a fifth, and road trade for a small share. In part because air shipment is so costly, road trade accounts for most freight—trucks account for 69 percent of all CO_2 emissions due to shipping. Sea transportation is important for international trade and accounts for 44 percent of international shipping CO_2 emissions, but is relatively unimportant for domestic trade.

4.2 How Reasonable Are These CO_2 Estimates?

Comparison to International Organizations. This section has described detailed measures of CO_2 emissions from shipping for nearly a million specific trade flows. It is useful to evaluate these estimates by comparing them against independent sources which provide coarser measures of CO_2 emissions but which can therefore use simpler data and methods.

[20] Other sources report similar global estimates (Boden, Marland and Andres 2010, IEA 2011).

The totals implied by my data are close to totals of these published sources (see the Appendix). For example, the EU collected data from every airline landing or departing in the EU about their fuel consumption in order to plan for the inclusion of airplane CO_2 emissions in the EU cap-and-trade system. I estimate total air freight CO_2 emissions involving the EU of 75.3 $MtCO_2$, while the European Commission (2011) implies a value of 78.9. To provide another comparison, I measure total sea freight of 7,900 tons, whereas UNCTAD (2009) provides an estimate of 7,882 tons. Overall, my estimates of total air freight emissions from the EU, total air freight emissions globally, total sea CO_2, and total sea tons shipped are extremely close to the estimates of international organizations. My estimates for international air freight, international air ton-km, and sea ton-miles are slightly larger than the estimates of international organizations. This suggests that my detailed data replicate the global stylized facts about these forms of shipping.[21]

5 Estimation of Trade Elasticities

5.1 Methodology: Trade Elasticities

Substituting equation (3a) into (5a) and taking logs gives an equation like the following:

$$\log \lambda^j_{ody} = \theta^j \log(1 + s^j_{ody}) + c^j_{oy} + p^j_{dy} + \delta^j_{od} + \epsilon^j_{ody} \tag{7}$$

This equation builds on the model by allowing trade flows and prices to vary by year y. It also allows for idiosyncratic innovations ϵ_{ody} in the unobserved component of trade costs, δ_{od}. Additionally, s_{ody} here represents the total shipping cost (including fuel and non-fuel components), which can be proportional to fuel costs under assumptions (3a) and (3c).[22]

An OLS estimate of equation (7) faces has two challenges. First, it omits variables like nonpecuniary trade barriers, wages, and prices. Such barriers associate with greater shipping costs and lower trade flows, introducing negative bias in the OLS estimate of θ^j.[23] A second

[21] Cristea et al. (Forthcoming) also compile sector-level CO_2 emissions from international shipping. Unlike their paper, I also calculate fuel consumption for domestic shipping. Domestic shipping data are important because international trade only accounts for 12 percent of global production (domestic trade represents the remaining 88 percent). Domestic shipping data are also important because any change in international trade will affect intranational trade, and it would violate GATT Article III for a region to regulate international but not domestic shipping (Bartels 2012, Meltzer 2012). Compared to Cristea et al., this section also uses a different statistical methodology (fractional multinomial logit) and somewhat different assumptions and data. In aggregate these differences matter—for example, Cristea et al's estimate of CO_2 emissions from airplane trade is about three times the values implied by data from the International Energy Agency or other organizations, while my estimate is close to these organizations' estimates. The estimate in Cristea et al. matches published estimates of total CO_2 from all air transportation, but the estimate only represents freight, which accounts for only 33.6 percent of all air ton-km transportation (IATA 2009).

[22] The data used in this section do not distinguish fuel and non-fuel costs or have all the necessary data to use assumption (3c) to distinguish fuel from non-fuel costs.

[23] Omitting these terms actually means that OLS estimates the wrong elasticity: because OLS does not

is measurement error in shipping costs s_{ody}, which occurs due to sector, exporter, and date misclassification, inaccurate currency conversion, and simple reporting errors.[24] Classical measurement error attenuates OLS estimates of θ.

To address omitted variables bias, I estimate equation (7) while including exporter-by-year fixed effects to control for production costs c^j_{oy}, importer-by-year fixed effects to control for destination prices p^j_{dy}, and country-pair fixed effects δ^j_{od} to control for time-invariant components of trade costs like distance. While the end of this section discusses related estimates, it is worth highlighting that to the best of my knowledge this estimator has not been applied with panel data, observed shipping costs, and the full fixed effects to recover θ^j.

Unfortunately, using fixed effects with panel data can decrease the signal-to-noise ratio and thereby exacerbate attenuation bias (Griliches and Hausman 1986). While fixed effects can address omitted variables bias, they can exacerbate the effects of measurement error.

Instrumental variables provide an appealing way to obtain consistent parameter estimates in the presence of classical measurement error (Durbin 1954, Freeman 1984, Ashenfelter and Krueger 1994).[25] I define the instruments as follows. For each year of data, I compile two measures of each variable: one measure containing data aggregated from quarters 2 and 3 of the year, and a second measure containing data aggregated from quarters 1 and 4. For each year, I then use mean reported shipping costs from quarters 2 and 3 as an instrumental variable for reported shipping costs from quarters 1 and 4.

This approach essentially uses leads and lags of shipping cost variables as instruments in order to address measurement error, which has the same spirit as using additional lags as instruments in models with lagged dependent variables (Arellano and Bond 1991). Many papers use multiple contemporaneous reports of a variable to address measurement error (Black et al. 2000), and Dustmann and Soest (2002) use a related approach to mine, albeit in a labor economics setting.

If measurement error in the two samples is independent, then the following instrumental

control for production costs and destination prices, it obtains a general equilibrium elasticity combining direct effects of trade costs on trade flows and indirect general equilibrium effects operating through the prices p^j_{dy} and c^j_{oy}. By contrast, θ^j in the model is a partial equilibrium elasticity which is purged of these general equilibrium effects.

[24] Many researchers document or attempt to address measurement error in trade volume data, unit cost data, or trade cost data which is estimated by comparing value reports across importers and exporters (Bowen, Leamer and Sveikauskas 1987, Harrigan 1993, Feenstra 1994, Trefler 1995, Limão and Venables 2001, Hummels and Lugovskyy 2006).

[25] A literature in labor and health economics examines the prevalence and implications of non-classical measurement error (Card 1996, Bound, Brown and Mathiowetz 2002). In the simple case of negative covariance between measurement error and a variable's true value, the asymptotic value of a univariate regression lies between OLS and IV estimates (Black, Berger and Scott 2000).

variables model will provide a consistent estimator of θ^j:

$$\log \lambda^j_{ody} = \theta^j \log(1 + s^{j,B}_{ody}) + \eta^{j,B}_{oy} + \zeta^{j,B}_{dy} + \delta^{j,B}_{od} + \epsilon^{j,B}_{ody} \quad (8)$$

$$\log(1 + s^{j,B}_{ody}) = \beta^j \log(1 + s^{j,A}_{ody}) + \eta^{j,A}_{oy} + \zeta^{j,A}_{dy} + \delta^{j,A}_{od} + \epsilon^{j,A}_{ody} \quad (9)$$

Here $s^{j,A}_{ody}$ represents a measure of shipping costs from quarters 2 and 3 and $s^{j,B}_{ody}$ represents a measure of shipping costs from quarters 1 and 4. The Appendix reports estimates using other quarter definitions. This assumption that the two reports of shipping costs have independent measurement error is strong. If this assumption fails then (8) will still suffer from some attenuation bias, albeit less severe than in the fixed effects estimates (Black et al. 2000).

In equation (8), the variation in s_{ody} which the fixed effects do not eliminate includes all components of the gravity equation varying at the *o-d-y* level. For example, fees for crossing the Suez canal and different efficiency growth of plane versus sea transportation are sources of variation which could contribute to identify s^B_{ody} (Feyrer 2009a, Feyrer 2009b).[26]

Finally, these panel data may have autocorrelation, so I report standard errors adjusted for clustering within trading partners (Bertrand, Duflo and Mullainathan 2004).

5.2 Results: Trade Elasticities

OLS regression without controls or fixed effects obtains the estimate $\theta = -21.0$ (Table 2). This implies that a 10 percent decrease in trade costs causes a 210 percent increase in bilateral trade flows. This represents extraordinarily elastic demand. This estimate may be so negative because it does not control for other trade costs. Using detailed fixed effects as in equation (7) helps address omitted variables bias but may exacerbate attenuation bias (Table 2). This fixed effect estimate for the entire economy is $\theta = -3.7$.

In the instrumental variables regressions, most instruments have a first-stage F-statistic above the rule-of-thumb cutoff of 10 for weak instruments (Staiger and Stock 1997). Instrumental variable estimates of the trade elasticity all have the expected negative signs and moderate magnitudes (Table 2, columns 7-8). The economywide estimate is $\theta = -7.91$. Averaging over the 13 sector-specific elasticities gives a roughly similar value of -8.1 for all goods. The literature reports conflicting evidence on the bias from aggregation over sectors—Imbs and Méjean (2011) conclude that aggregation over sectors can bias estimates of trade elasticities, while Feenstra, Obstfeld and Russ (2010) find little bias from aggregation.

Alternative assumptions – generalized least squares, controlling for tariffs, a simple alternative to zero values for the response variable, or other specifications of the instrument – obtain similar patterns of point estimates (Appendix Table 2).

[26] In principle, one could use these changes as instrumental variables for $1 + s_{ody}$. However, apart from the shipping cost instruments I use, I am not aware of strong instruments for the 13 tradable sectors and two importers in the 20 years I analyze.

5.3 How Reasonable are these Trade Elasticities?

Rauch Test. I evaluate these IV estimates with a simple test: theory predicts that demand should be more elastic for more homogenous goods.[27] I find that the pattern of elasticities across sectors is consistent with this theoretical prediction.

I implement this test using a classification from Rauch (1999), who separates traded goods into three classifications: goods traded on listed exchanges ("homogenous"); goods with reference prices; and all other goods ("differentiated"). Rauch classifies nearly all traded goods by product based on several printed volumes listing prices.

This test provides sensible results (Appendix Table 3). All three types of goods have strong instruments, with first stage F-statistics between 26.4 and 90.3. Differentiated goods have the smallest trade elasticity in absolute value (-5.75), and homogenous goods have the largest elasticity (-9.18). Although theoretical predictions for reference-priced goods are less clear, but those goods have an intermediate elasticity of -5.81. All three elasticities are precisely estimated.[28]

Comparison to Literature. Researchers have used several strategies to estimate these elasticities for multiple sectors. Omitted variables and measurement error remain potentially important sources of bias. Hummels (2001) uses cross-sectional shipping costs for the year 1992 with importer and exporter fixed effects and with proxies for distance and shared language. Caliendo and Parro (2011) compare tariffs and trade flows across two directions in triads of countries. Anderson and van Wincoop (2004) discuss other methods to estimate these parameters for the global economy as a whole. Existing estimates in the literature for the global economy or for manufacturing generally lie in the range -4 to -10 (Anderson and van Wincoop 2004). My estimate of $\theta = -7.33$ for manufactured goods lies in this range. This estimate is also between the $\theta = -4.14$ value of Simonovska and Waugh (2011) and the $\theta = -8.28$ value of Eaton and Kortum (2002).

My sector-by-sector range of estimates vary somewhat from other estimates at similar aggregation levels. My most homogenous sector has an elasticity of only -18.55, whereas Caliendo and Parro (2011) find elasticities of -51 to -69, and Hummels (2001) obtains an elasticity of -79. My most differentiated sector has an elasticity of -0.77, which is more negative than Caliendo and Parro's -0.37.

[27] Broda and Weinstein (2006) implement a similar test for product-level elasticities.

[28] Table 3 reports the "conservative" classification of Rauch (1999), which minimizes the number of commodities classified as homogenous or reference priced. Using Rauch's "liberal" classification, which maximizes those numbers, obtains estimates (and standard errors) of -7.26 (2.37), -4.61 (1.58), and -10.5 (1.89) for the differentiated, reference-priced, and homogenous goods, respectively.

6 Counterfactual 1: Costs and Benefits of International Trade

This section uses the model together with the data described in the last two sections to measure the full welfare effects of international trade.

6.1 Methodology: Costs and Benefits of International Trade

I consider a counterfactual which closes off all countries from international trade. This is not a proposed policy, but it represents an important benchmark which recurs throughout the trade literature because it provides a starting point for thinking about real-world policies. Recall that x' denotes the value of the variable x under a counterfactual policy, x denotes the initial value, and $\hat{x} \equiv x'/x$ denotes the proportional change due to a policy. Autarky is equivalent to imposing infinite international trade costs but changing no other variables.

The gains from international trade for country d equal the negative of the change in real income due to autarky as in equation (6). The gains from trade can also be written as the change in the share of goods which are purchased from domestic producers, $\hat{I}_d/\hat{P}_d = \prod_{j=1}^{J}(\hat{\lambda}_{dd}^{j})^{\alpha_d^j/\beta_d^j\theta_d^j}$ (Arkolakis et al. 2012).

Autarky would then produce the following proportional change in welfare for country d:

$$A_d = \left[\prod_{j=1}^{J}\left(\lambda_{dd}^{j}\right)^{-\frac{\alpha_d^j}{\beta_d^j\theta_d^j}}\right]\left[\frac{1+\left(\mu_d^{-1}\sum_{o=1}^{N}E_o\right)^2}{1+\left(\mu_d^{-1}\sum_{o=1}^{N}E_o'\right)^2}\right] \tag{10}$$

In equation (10), the effect of moving a country to autarky equals the diminished gains from trade multiplied by the change in the environmental costs of trade. I aggregate across countries to measure the global welfare effect if all of the world's countries went to autarky.

Equation (10) has an appealing feature: all terms in it are observed in the data. The counterfactual of autarky permits this straightforward calculation because the domestic expenditure share under autarky is one by definition ($\lambda_{dd}' = 1$).

The only term in equation (10) which I have not previously explained is E_o', representing the CO_2 emissions from country o in autarky. However, $E_o^{'}$ can also be calculated as a function of observed data. This calculation for E_o' reflects the following algebra. By assumption (4) and the counterfactual of autarky, we have $E_d' = \Sigma_j(\gamma_3 f_{dd}^j + \chi_d^j)X_{dd}^j\hat{X}_{dd}^j/(p_{dd}^j\hat{p}_{dd}^j)$. Choosing the wage in country d as numéraire, we have $\hat{X}_{dd}^j = X_d^j/X_{dd}^j$. The proportional change in domestic prices due to autarky is $\hat{p}_{dd}^j = (\hat{w}_d)^{\beta_d^j}(\hat{p}_d^j)^{1-\beta_d^j}\hat{\tau}_{dd}^j$. The choice of numéraire and assumption that autarky does not change domestic trade costs imply $\hat{p}_{dd}^j = (\hat{p}_d^j)^{1-\beta_d^j}$. The methodology behind equation (10) implies $\hat{p}_{dd}^j = (\lambda_{dd}^j)^{(1-\beta_d^j)/(\beta_d^j\theta_d^j)}$. Substituting $\hat{X}_{dd}^j$ and $\hat{p}_{dd}^j$

into equation (5b) gives

$$E'_d = \sum_j (\gamma_3 f^j_{dd} + \chi^j_d)(X^j_d)(\lambda^j_{dd})^{-(1-\beta^j_d)/(\beta^j_d \theta^j_d)}$$

It may clarify how this framework measures the welfare effects of international trade to walk through four mechanisms by which international trade can affect pollution emissions. First, international trade increases global output. This effect will tend to increase total CO_2 emissions. Second, because international trade requires allows goods to be produced in countries other than where they are consumed, trade changes each country's production overall and by sector. Because CO_2 emissions rates differ by country and sector, this effect can increase or decrease CO_2 emissions from production. Third, international trade requires international goods transportation, which increases CO_2 emissions. Fourth, international trade can increase or decrease domestic goods transportation and the associated CO_2 emissions.

To perform inference, I conduct a bootstrap over the stochastic term of the model, θ^j, and report the resulting 95-percent confidence interval. The trade literature largely has not performed inference on welfare calculations. I report the bias-corrected bootstrap estimate, which can provide an accurate finite-sample approximation (Efron 1987) (see the Appendix).

6.2 Results: Costs and Benefits of International Trade

The analysis provides several results (Figure 1 and Table 3). First, several papers in the trade-environment literature ask, "Is trade good for the environment?" This analysis shows that international trade harms the environment. International trade increases global CO_2 emissions by 5 percent (1.55 gigatons of CO_2 annually or about $32 billion of global damages). Globally this effect is almost equally driven by production and transportation. This is notable since autarky only directly affects shipping.

Second, the gains from international trade exceed the environmental costs of international trade by a factor of 180 (i.e., by two orders of magnitude). The gains from international trade exceed the environmental costs of trade in every country (Table 3). The global gains from international trade, at $5.8 trillion, equal 10 percent of global GDP. The environmental costs of international trade equal $32 billion.

Third, a global analysis masks heterogeneity across countries. Not surprisingly, as a share of GDP, the gains from trade are greatest in countries like Belgium where international trade is a large share of gross output, and smallest in relatively closed countries like the US. Also as a share of GDP, climate change is predicted to have the largest negative effects on poor regions like Sub-Saharan Africa and on India, and the smallest impacts on high-income countries like the US. Finally, all of these results are precisely estimated.

6.3 Discussion: How Sensitive are these Model Calculations?

One useful check on the sensitivity of these results is to ask: how large must the social cost of carbon be to overturn the finding that the gains from trade greatly exceed the environmental cost of trade? I calculate that autarky decreases global welfare if the social cost of CO_2 emissions is any value below \$3,292 per ton of CO_2. This cutoff is over a hundred times the ninety-fifth percentile estimate of the social cost of carbon reported in Greenstone et al. (Forthcoming), and several times larger than the estimate under a dynamic climate model that incorporates severe risk aversion, potential climate disasters, tipping points, and uncertain climate damages (Cai et al. 2012). It is larger than any estimate of the social cost of carbon I have seen in any source. This calculation provides fairly strong evidence that under any plausible social cost of carbon, trade's benefits vastly exceed its environmental costs.

Should we be surprised that trade's benefits exceed trade's environmental costs? Perhaps not in aggregate, though I believe no previous research has established this fact, and the vast difference between these two quantities in all countries is not obvious without the kind of analysis this paper undertakes. But this finding is useful because it provides an empirical basis for most trade research which ignores the environment. Broad trade reforms, improvements in transport technology, or other advances in globalization may advance climate change, but the welfare effects due to climate change are likely to be second-order in most countries.

7 Counterfactual 2: EU, US, and Global Carbon Taxes

I now turn to a very different type of counterfactual—regional and global regulations which use targeted policy to address the environmental externalities of trade. While this paper's framework could be applied to many types of regulation, I study transportation for three reasons. First, the policies I study are under active debate, but so far untested. Second, almost all existing research on climate change regulations focuses on production and not transportation. Third, international air and sea transportation represents the single fastest-growing anthropogenic source of greenhouse gas emissions, and CO_2 from this sector is growing at nearly double the rate of the rest of the global economy.

7.1 Methodology: Effects of Regional and Global Carbon Taxes

Measuring the effects of untested climate change regulations requires constructing an empirical analogue to the equivalent variation in equation (6). Algebra using the model's assumptions can express the model as the following system of $N-1$ nonlinear equations (one per

country, excluding a numéraire due to Walras' Law) in $N-1$ unknown wage changes $\hat{w}_d$:

$$\sum_{o,j} \frac{X_{od}^{j\prime}\left(\hat{w}_d\right)}{1+t_{od}^{j}} = \sum_{o,j} \frac{X_{do}^{j\prime}\left(\hat{w}_d\right)}{1+t_{do}^{j}} + \phi_d^{j\prime} + T_d \tag{11}$$

Here the matrix $X_{od}^{j\prime}\left(\hat{w}_d\right)$ is a known function of observed data and of the wage changes $\hat{w}_d$ (see the Appendix). Every term in (11) is observed in data or is a known function of the vector of country-level wage changes due to a carbon tax, $\hat{w}_d$.

I solve this system for equilibrium wages, with numéraire chosen so $\sum_d w_d L_d = \sum_d w_d' L_d$. Given the candidate wage vector $\hat{w}_d$ at an iteration of the algorithm, I estimate the price vector $\hat{p}_d^j$ by using a contraction map which iterates over the price equation, as described in the Appendix. After recovering the $N-1$ values of $\hat{w}_d$ from this algorithm, calculating $\hat{X}_d$, $\hat{P}_d$, and E_d' requires arithmetic. Finally, I substitute these values into (6) to find the effect of a counterfactual carbon tax on social welfare in each country. Because this method analyze proportional changes, it assumes that country pairs and sectors with no reported trade will have no trade in the counterfactual.

For each carbon tax, I introduce a shock by changing the value of the carbon tax $(t_{odm}^{jX}, t_{odm}^{j,M})$ from 0 to \$19.96 per $MtCO_2$. As discussed in section 3.3, \$19.96 reflects a leading estimate of the social cost of CO_2 emissions.

The paper reports the total effects of each policy over its first decade of implementation. This follows standard practice—the EU has planned aviation ETS allowances for the period 2012 through 2020, and many evaluations of proposed US regulations use budget scoring over a 10-year time horizon. The main results hold global aggregates fixed over the decade, so they equal ten times a policy's annual effects.[29]

In these calculations, I conduct inference using a bias-corrected bootstrap with 200 replications over IV estimates of θ^j, as described in section 6.1.

7.2 Regulation Details

I use the model to analyze stylized versions of the real-world policies. The EU's Emissions Trading System (ETS) sets an EU-wide cap for regulated CO_2 emissions, distributes CO_2 "allowances" to firms, then lets firms trade those allowances. Each year, firms must provide the EU with allowances to cover their regulated CO_2 emissions. In 2011, the ETS regulated CO_2 emissions from electricity generation; oil refining; iron and steel; cement, glass, lime, brick, and ceramics; and pulp, paper, and boards. In January 2012, the ETS attempted to add a sixth industry, air transportation. This paper's EU counterfactual represents a stylized version of the EU ETS. Like the ETS, I consider the regulation of CO_2 emissions from airplane

[29] Allowing for trends in global aggregates would require credible forecasts of bilateral trade between all countries for each sector and year (λ_{od}^j), which are difficult to obtain.

flights involving the 30 countries participating in the EU ETS. The ETS regulates all airplane transportation, whereas I include only shipping. Finally, the EU is initially distributed 85 percent of permits for free to airlines, whereas I treat the ETS as a carbon tax.

The second counterfactual analyzes the regulation of CO_2 emissions from all US shipping. This analysis reflects the Waxman-Markey Bill, which passed the US House but not Senate in 2009, and would have created a cap-and-trade market for US CO_2 emissions. The bill included refineries' petroleum products and fuel imports in the CO_2 emissions cap, though did not regulate shipping firms directly. Like this bill, this paper's US counterfactual analyzes the regulation of all shipping. Unlike the bill, I study a carbon tax which affects CO_2 emissions from imports and exports. Moreover, I focus on the regulation of goods and not passenger transportation.

Article 2.2 of the 1997 Kyoto Protocol called for UN agencies to develop a cap-and-trade policy for plane and sea emissions for 41 industrialized countries. This remains under negotiation but has never been implemented. My global counterfactual analyzes the regulation of all domestic and international airborne and maritime shipping.

These policies – regulation of a global externality by only some countries or sectors – are far from optimal. Research needs dynamic, long-run climate-economy models to identify the optimal carbon tax, which can be applied all sectors and countries, with the tax rate equal to the marginal social cost of CO_2 emissions (Nordhaus and Boyer 2000, Golosov, Hassler, Krusell and Tsyvinski Forthcoming). But a political economy constraint – a several global collective action problem – has prevented implementation of such a policy. Instead, climate change regulations are being implemented country-by-country and industry-by-industry. Because such incomplete regulation can distort economic activity towards unregulated regions and hence have ambiguous welfare consequences, it is important to develop tools to evaluate second-best environmental regulation. That is the task this paper undertakes. Indeed, all trade policy is second-best, and the large body of research analyzing trade policy underscores the economic insights available from analyzing suboptimal policy.

7.2.1 Global Welfare

All three counterfactuals increase global welfare because they each decrease the global environmental costs of trade more than they decrease the global gains from trade (Figure 2, Tables 4-6, and Appendix Table 4). In total, the EU, US, and global policies increase welfare by \$0.7, \$5.2, and \$5.2 billion over a decade, respectively. These effects are proportionally larger for the US and global policy because those regulations affect more trade.

These welfare results occur because all of these policies cause both international trade and CO_2 emissions fall. For the EU policy, they fall 49 $MtCO_2$ over a decade, respectively. Again the US and global policies have proportionally larger effects because they regulate

more trade.

Recall that because these policies regulate only transportation, they have theoretically ambiguous effects on CO_2 emissions from production: they could relocate output to countries where production is more CO_2-intensive, or they could decrease global production overall. In practice, regulating CO_2 emissions from transportation does not increase the CO_2 emissions from production, and in fact decreases CO_2 from production by amounts which account for between 2 and 31 percent of the policies' total environmental benefits.

7.2.2 Regressivity

All of these regulations are regressive and actually decrease welfare in poor countries (Figure 2, Tables 4-6, and Appendix Table 4). The EU policy increases welfare in the richest third of countries (measured by GDP per capita) by a tenth of a basis point, decreases welfare in the middle third of countries by two tenths of a basis point, and decreases welfare in the poorest third of countries by half of a basis point. These effects occur largely because airplane trade takes place with distant countries (and countries far from the EU are poorer than are countries near to the EU); and poor countries tend to trade goods that have high weight-to-value ratios, which are fuel-intensive to transport. The US and global regulations generate similar patterns.

7.2.3 Private Gains from Trade

A third finding is that the EU and US regulations increase the implementing region's gains from trade, even before accounting for environmental benefits (Figure 2, Tables 4-6, and Appendix Table 4). This result occurs because these regulations act like a unilateral tariff which improves a country's terms of trade.

In total, the EU policy increases the EU's gains from trade rise by $7.7 billion. This policy decreases welfare for most countries outside the EU. Again, the US policy has similar patterns but larger magnitudes.

Appendix Figure 3 plots the welfare effects of the EU policy against the air carbon tax that the EU imposes, assuming that the true social cost of carbon is $\$20/tCO_2$. These graphs makes clear that the optimal carbon tax from the EU perspective is about $\$3000/tCO_2$, which is larger than any estimate of the social cost of carbon emissions. This is comparable to a 25 percent tariff.[30] Global welfare, however, is maximized at a carbon tax rate closer to $\$50/tCO_2$. This globally optimal EU tariff is modestly higher than the social cost of carbon in part because the EU regulation decreases CO_2 from unregulated sources like production.

[30] Fuel costs represent about 1.4 percent of the value of goods for international trade, and a $\$19.96/tCO_2$ carbon tax equals a 12 percent increase in fuel costs.. The tariff-equivalent comes from the calculation 0.014*.12*3000/19.96.

7.2.4 Trade Diversion and Leakage

A fourth finding is that these policies generate small amounts of trade diversion and leakage (Figure 2, Tables 4-6, and Appendix Table 4). About 23 percent of the EU's decrease in international trade is offset by international trade increases elsewhere in the world. Hardly any leakage occurs for the environment—transportation CO_2 emissions fall for the EU and nearly do not change elsewhere, and production CO_2 emissions actually fall elsewhere. The US regulation generates slightly more trade diversion and leakage: a third of the US decline in international trade is offset by increases in international trade elsewhere in the world. Also for the US policy, leakage from transportation elsewhere in the world is relatively unimportant. For the US policy, production CO_2 emissions do rise in the rest of the world.

7.3 How Robust Are These Model Calculations?

This section has used a gravity model to evaluate several potential climate change regulations. I now assess how the results compare against a simpler model—a textbook Harberger (1964) triangle analysis of the demand for shipping fuels. Overall, the two models estimate similar global effects of the taxes. This provides one piece of evidence that the gravity model obtains plausible estimates. The exact numbers differ, however, and the gravity model estimates many results which the textbook partial equilibrium model does not.

To calculate the area of Harberger triangles, I assume the social planner imposes a tax rate of t on all shipping fuels; that all shipping fuels have the demand elasticity η, and that they have perfectly elastic supply.

Harberger triangles differ from the gravity model in several ways. First, Harberger triangles apply the elasticity η to all shipping, but the demand elasticities may differ by good and policy design.[31] Second, Harberger triangles ignore potential increases in consumption of unregulated fuels. Third, Harberger triangles ignore CO_2 emissions from production. Fourth, Harberger triangles do not measure incidence. Finally, Harberger triangles do not ensure market clearing, so ignore general equilibrium effects.

I consider two demand elasticities η which bracket estimates in the literature: -0.02, and -0.50 (Dargay and Gately 2010, Faber et al. 2010, Mazraati 2011). The gravity estimate of how the EU, US, and global carbon taxes affect the global gains from trade is roughly equidistant from the Harberger estimates corresponding to these two elasticities (Appendix Figure 2). For the EU tax, the gravity model predicts a decline in the gains from trade of $210 million over a decade, while the textbook model predicts a change in the gains from shipping of between $20 million and $440 million. For the US and global taxes, the gravity

[31] The demand elasticity is also difficult to estimate credibly—the few papers which report a parameter like a global demand elasticity for shipping fuels use time-series variation in global oil prices for identification (Dargay and Gately 2010, Faber, Markowska, Eyring, Cionni and Selstad 2010, Mazraati 2011).

model again lies roughly in the middle of the two corresponding Harberger estimates. Overall, this provides one independent piece of evidence that the gravity model provides reasonable results.

8 Extensions and Robustness

This section of the paper assesses how the model's results change with its assumptions (Appendix Table 5). I first assess how results change under low and high possible values for the social cost of CO_2: \$4.10/tonCO_2, and \$1170/tonCO_2. Under the lower social cost of carbon, the environmental costs of trade are \$8 billion/year; while under the greater social cost of carbon, the environmental costs of trade are much larger. Under either assumption, the gains from trade remain substantially larger larger than the environmental costs of trade (Appendix Table 6).

The social cost of carbon is more relevant to evaluating climate change regulations. Under a low social cost of carbon (\$4.10/tonCO_2), a global tax on air and sea shipping produces a welfare gain over a decade of \$1.7 billion. Under a higher social cost of carbon, the welfare gain is far larger. Interestingly, the far larger social cost of carbon makes these policies become progressive and benefit poor countries. The reason is that decreasing CO_2 emissions disproportionately benefits poor countries, while these kind of carbon regulations disproportionately hurt poor countries. For large enough taxes, the progressive structure of the environmental benefits overshadows the regressive structure of the regulations' costs. This value of \$1150 is far larger than any other estimate, but it makes the point that once climate change becomes harmful enough, even these policies begin to benefit poor countries.

I also consider how changing the model's trade assumptions affect the paper's main findings. First I consider an elasticity for each sector of $\theta = -4.14$, or alternatively an elasticity for each sector of $\theta = -8.28$. These represent leading estimates from the literature (Eaton and Kortum 2002, Simonovska and Waugh 2011), and they roughly bracket my estimates. The results reflect the fact that the gains from trade are exactly proportional to this parameter. Because an elasticity of $\theta = -8.28$ reflects a world where goods are more homogenous, the global gains from trade are smaller, at \$1.8 trillion per year. By contrast, the value $\theta = -4.14$ reflects a world with more differentiated goods, and the gains from trade are relatively larger, at \$3.4 trillion per year. These modifications do not substantially affect the counterfactual analysis of global air and sea shipping.

9 Conclusion

This paper seeks to contribute to research on trade and the environment in three ways. First, it draws on trade theory to develop a new approach to evaluating regulation. The paper weds

a structural general equilibrium model with reduced-form estimates of key parameters.[32] Although the full theory depends on numerous parameters which are difficult to identify and estimate, measuring the effects of policies on social welfare depends on only one set of elasticities which I estimate. This framework accounts for general equilibrium effects and analyzes untested policies while using straightforward econometric tools to estimate key parameters. A bootstrap allows for statistical inference on the model's welfare calculations.

Second, this paper compares international trade's benefits against its environmental costs in a unified theoretical and empirical framework. The gains from international trade exceed the environmental international costs of trade by two orders of magnitude, and they are precisely estimated. Third, this paper analyzes the incidence and aggregate welfare effects of proposed climate change regulations. I study policies under the EU's Emissions Trading System, the US Waxman-Markey Bill, and the 1997 Kyoto Protocol, which would each regulate the CO_2 emissions from some forms of shipping. Poor countries specialized in trading raw materials like grain and iron ore, particularly those in Sub-Saharan Africa, lose the most from these policies. Because they regulate shipping for only some countries or modes of transportation, these policies increase unregulated CO_2 emissions and divert trade to unregulated routes. These policies also create unequal incidence by increasing welfare in the implementing region and decreasing welfare elsewhere, even before accounting for environmental benefits. Nonetheless, all three of these policies increase global welfare because they decrease the environmental costs of trade more than they decrease the gains from trade.

This paper demonstrates one way in which new ideas in international economics can clarify the links between trade and the environment. Such links are widespread—arguably, most environmental policies affect trade and most trade policies affect the environment. Similar approaches that may shed light on other questions in trade and the environment provide a good basis for building on this paper. For example, this paper focuses on climate change to the exclusion of other pollutants like particulate matter. Accounting for these other pollutants could increase or decrease the estimated environmental costs of trade. Using a framework which accounts for heterogeneity across firms, it is possible to use extensive US plant-level data on these pollutants to analyze the benefits and costs of regulations which affect both trade and the environment.

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[32] This approach has similar spirit to the literature on "sufficient statistics for welfare analysis" (Chetty 2009).

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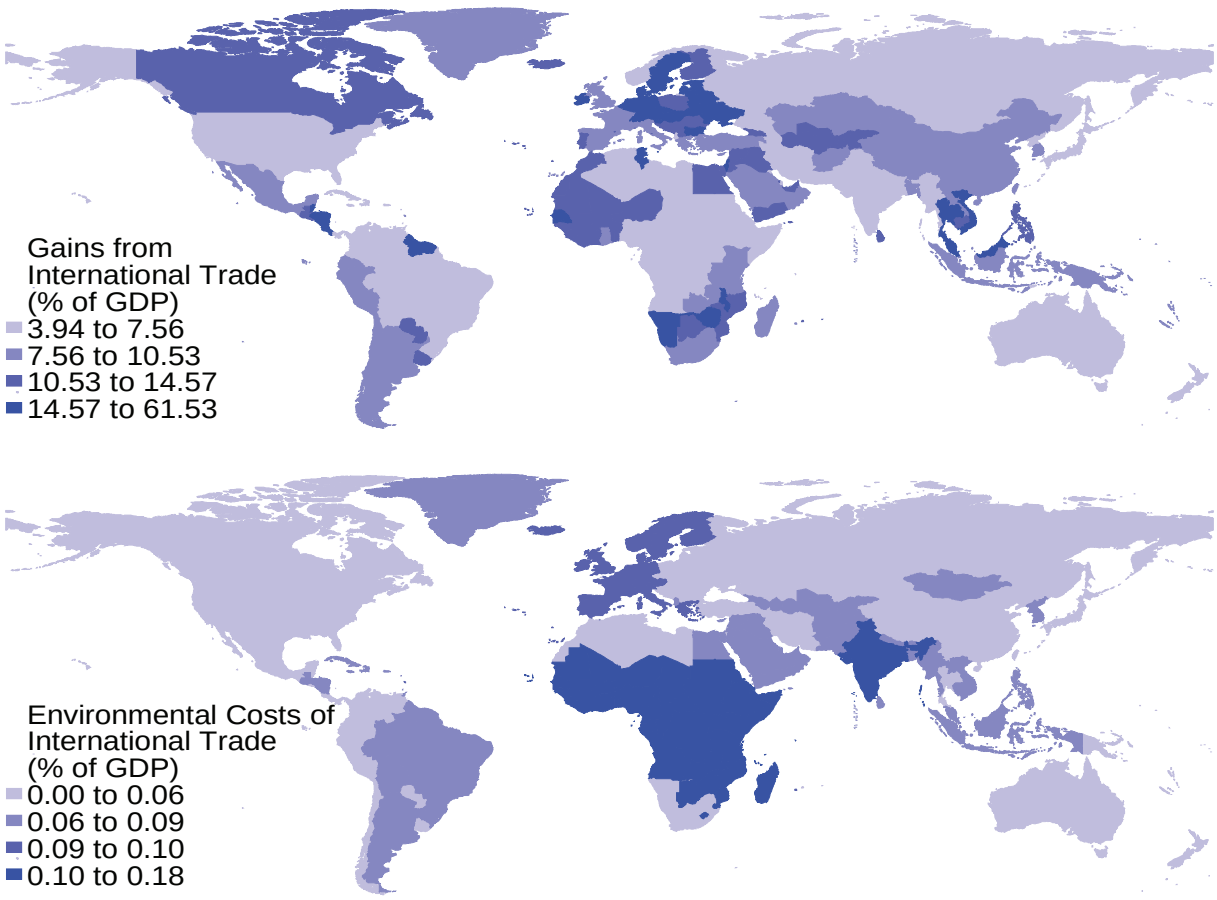


Figure 1: Benefits and Environmental Costs of International Trade, by Country

Notes: Figures plot empirical analogues of equation (10). See main text for details on data sources.

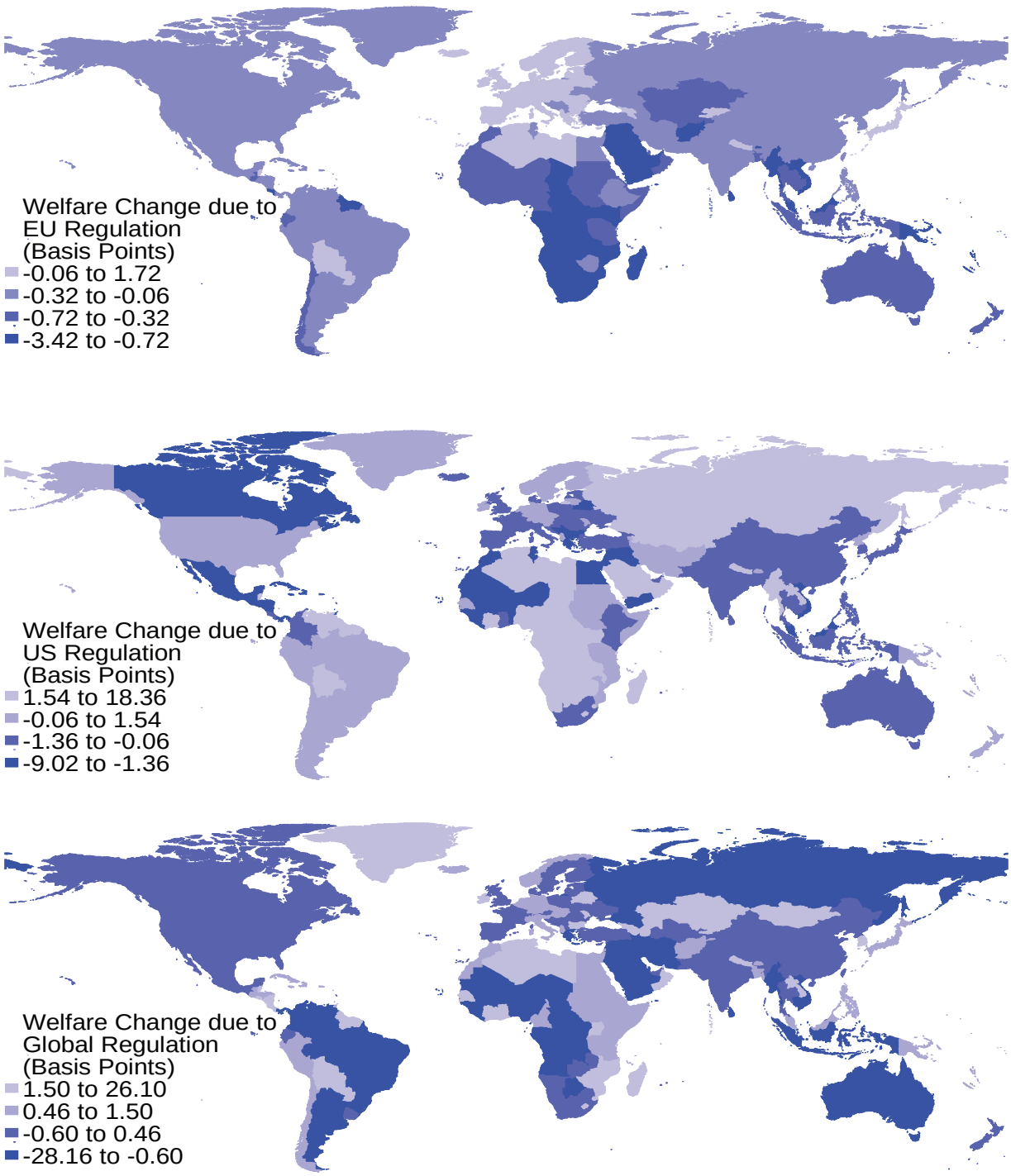


Figure 2: Impact of EU, US, and Global Climate Change Regulations on Social Welfare in Basis Points

Notes: Each regulation imposes a $19.96/ton carbon tax on intranational and international shipping. Revenue is rebated to the country imposing the tariff (or, for the global tax, to the importer). EU tax applies only to air shipping; US tax applies to all modes of shipping (air, sea, rail, road, and other); and global tax applies to air and sea shipping.

Table 1: Total Greenhouse Gas Emissions in 2007

Source	International (1)	Domestic (2)	Total (3)
Panel A: CO_2 Emissions by Transport Mode and Type			
Shipping: Air	200	35	235
Shipping: Sea	648	114	762
Shipping: Rail	23	20	43
Shipping: Road	594	1,740	2,334
Shipping: Total	1,465	1,909	3,374
Production: Total	1,192	25,333	26,525
Global Total	2,657	27,242	29,899
Panel B: CO_2 Emissions by Region			
US	363	6,189	6,552
EU	849	4,368	5,217
Other	1,445	16,684	18,129

Notes: All values represent MtCO2 in the year 2007. Section 3 of the paper describes data sources. International production represents production of internationally traded goods. Household consumption (e.g., passenger transportation) is included in domestic production. Panel B combines production and shipping emissions. Table summarizes direct emissions from fossil fuels consumed by each economic activity.

Table 2: Trade Elasticities, Instrumental Variables Estimates

Response Variable:	Log Freight Costs	Log Trade Costs	Log Shipping Costs	Log Import Shares	N
Regression Type	OLS	FE	FS	IV	
	(1)	(2)	(3)	(4)	(5)
Panel A: Economy-Wide Estimates					
Overall	-20.947***	-3.709**	0.207***	-7.908**	4,830
	(2.614)	(1.822)	(0.052)	(3.643)	
Overall: Manufacturing	-24.637***	-4.237***	0.218***	-7.326**	4,800
	(1.855)	(1.082)	(0.044)	(3.411)	
Panel B: Sector-Specific Estimates, Non-Manufacturing					
Agriculture, Forestry	-4.705**	-3.412***	0.289***	-3.335	3,316
	(1.855)	(1.044)	(0.068)	(3.396)	
Mining	-5.003***	-2.125**	0.441***	-3.450***	2,150
	(1.334)	(0.964)	(0.056)	(1.314)	
Panel C: Sector-Specific Estimates, Manufacturing					
Food, Beverages, Tobacco	-15.817***	-5.044***	0.464***	-5.361***	3,570
	(1.823)	(1.275)	(0.060)	(1.726)	
Textiles	-19.765***	-6.378***	0.192***	-18.552***	3,558
	(1.407)	(0.965)	(0.065)	(5.056)	
Apparel, Leather	-18.193***	-3.469***	0.287***	-9.949***	3,612
	(1.456)	(1.256)	(0.061)	(2.893)	
Wood	-12.684***	-2.568***	0.321***	-5.901***	3,206
	(1.075)	(0.658)	(0.046)	(1.818)	
Paper, Printing	-14.499***	-1.813***	0.198***	-5.623*	2,778
	(1.377)	(0.606)	(0.038)	(2.936)	
Petroleum, Coal, Minerals	-13.498***	-3.057***	0.240***	-8.949**	2,972
	(1.211)	(0.822)	(0.062)	(3.766)	
Chemicals, Rubber, Plastics	-16.251***	-3.411***	0.356***	-0.769	3,586
	(1.694)	(1.086)	(0.054)	(2.557)	
Metals	-19.666***	-5.522***	0.204**	-12.926*	3,204
	(1.381)	(0.719)	(0.083)	(6.737)	
Machinery, Electrical	-28.444***	-7.945***	0.237***	-10.908***	3,910
	(2.085)	(0.955)	(0.043)	(2.795)	
Transport Equipment	-23.524***	-4.505***	0.235***	-6.868**	2,544
	(2.566)	(1.105)	(0.072)	(3.448)	
Other	-16.656***	-4.425***	0.157***	-12.768**	3,626
	(1.135)	(0.637)	(0.054)	(5.374)	
Exporter-by-Year Fixed Effects	No	Yes	Yes	Yes	
Importer-by-Year Fixed Effects	No	Yes	Yes	Yes	
Exporter-by-Importer Fixed Effects	No	Yes	Yes	Yes	

Notes: Each table entry represents a separate regression. An observation represents a good-exporter-importer-time. The data include two importers: the US and Australia. Data have two observations per year: one aggregating quarters 2 and 3, and the other aggregating quarters 1 and 4. In IV, shipping costs measured from quarters 2 and 3 of a year are used as an instrument for freight costs measured in quarters 1 and 4 of that year. Standard errors clustered by importer-exporter pair. *** $p<0.01$, ** $p<0.05$, * $p<0.10$.

Table 3: Annual Effects of International Trade on Social Welfare

	Gains from Trade	Enviromental Costs of Trade	Social Welfare	Ratio: (1)/(2)
		Panel A: Global		
World	5780	-32.0	5809	-180
	[3374 , 17373]	[-41 , -16]	[3515 , 15209]	[-1770 , -87]
		Panel B: By Region		
US	640	-2.3	642	-275
	[412 , 11150]	[-3 , -1]	[415 , 11150]	[-10040 , -141]
EU	2279	-17.4	2294	-131
	[1336 , 6283]	[-22 , -9]	[1357 , 6292]	[-1743 , -59]
		Panel C: By GDP Per Capita		
Richest Third	3773	-22.7	3793	-166
	[2330 , 11689]	[-29 , -11]	[2295 , 10181]	[-2960 , -82]
Middle Third	1498	-5.0	1502	-299
	[805 , 4419]	[-6 , -3]	[762 , 3761]	[-3077 , -128]
Poorest Third	510	-4.3	513	-119
	[295 , 1265]	[-5 , -2]	[300 , 1268]	[-921 , -54]

Notes: All columns represent US 2007$ billions. The first three columns show (GFT-1)*GDP, (ECT-1)*GDP, and (GFT*ECT-1)*GDP where GFT is gains from trade in percentage terms and ECT is environmental cost of trade in percentage terms. Bracketed numbers represent bootstrapped ninety-five percent confidence intervals; see Appendix for details.

Table 4: EU Carbon Tax on Air Shipping: Effects on Social Welfare

	Gains from Trade	Environmental Costs of Trade	Social Welfare: Total	Social Welfare: Basis Points
		Panel A: Global		
World	-0.3	-1.0	0.7	0.01
	[-0.4 , -0.3]	[-1.2 , -0.8]	[0.5 , 0.8]	[0.01 , 0.01]
		Panel B: By Region		
US	-2.0	-0.1	-1.9	-0.13
	[-2.1 , -2.0]	[-0.1 , -0.1]	[-2.0 , -1.9]	[-0.14 , -0.13]
EU	7.7	-0.5	8.2	0.46
	[7.3 , 8.2]	[-0.7 , -0.4]	[7.6 , 8.8]	[0.42 , 0.49]
		Panel C: By GDP Per Capita		
Richest Third	3.7	-0.7	4.4	0.11
	[3.4 , 4.1]	[-0.9 , -0.5]	[3.9 , 4.8]	[0.09 , 0.12]
Middle Third	-2.5	-0.1	-2.3	-0.21
	[-2.9 , -2.2]	[-0.2 , -0.1]	[-2.7 , -2.1]	[-0.25 , -0.19]
Poorest Third	-1.6	-0.1	-1.4	-0.46
	[-1.7 , -1.5]	[-0.2 , -0.1]	[-1.6 , -1.3]	[-0.50 , -0.42]

Notes: First three columns represent the total effect in US 2007$ billions over a decade. The counterfactual policy applies a carbon tax of $19.96 per metric ton of CO_2 to all airborne imports, exports, and intranational trade of the 30 countries that are part of the EU Emissions Trading System (ETS). Bracketed numbers represent bootstrapped ninety-five percent confidence intervals; see Appendix for details.

Table 5: US Carbon Tax on All Shipping: Effects on Social Welfare

	Gains from Trade	Costs of Trade	Social Welfare:	Social Welfare:
		Panel A: Global		
World	-1.6	-6.9	5.2	0.09
	[-1.8 , -1.4]	[-7.1 , -6.6]	[4.8 , 5.6]	[0.08 , 0.10]
		Panel B: By Region		
US	16.9	-0.5	17.4	1.16
	[12.3 , 21.2]	[-0.6 , -0.5]	[12.9 , 21.8]	[0.86 , 1.45]
EU	-6.3	-3.8	-2.5	-0.14
	[-7.2 , -5.2]	[-3.9 , -3.6]	[-3.5 , -1.4]	[-0.20 , -0.08]
		Panel C: By GDP Per Capita		
Richest Third	5.8	-4.9	10.6	0.25
	[3.2 , 8.1]	[-5.1 , -4.7]	[8.5 , 12.8]	[0.20 , 0.31]
Middle Third	-4.5	-1.0	-3.5	-0.31
	[-6.8 , -2.3]	[-1.1 , -1.0]	[-5.9 , -1.3]	[-0.53 , -0.11]
Poorest Third	-2.9	-0.9	-1.9	-0.61
	[-5.8 , -2.1]	[-1.0 , -0.9]	[-4.9 , -1.4]	[-1.56 , -0.43]

Notes: First three columns represent the total effect in US 2007$ billions over a decade. The counterfactual policy applies a carbon tax of $19.96 per metric ton of CO2 to all US imports, exports, and intranational trade. Bracketed numbers represent ninety-five percent confidence intervals, estimated using the bias-corrected bootstrap of Efron (1987) with B=200 draws from the θ_j distributions of Table 2, excluding draws of $\theta_j>0$.

Table 6: Global Carbon Tax on Air & Sea Shipping: Effects on Social Welfare

	Gains from Trade	Environmental	Social Welfare:	Social Welfare:
		Panel A: Global		
World	-3.4	-8.6	5.2	0.09
	[-4.2 , -3.0]	[-9.9 , -7.8]	[4.0 , 5.8]	[0.07 , 0.10]
		Panel B: By Region		
US	2.3	-0.7	3.0	0.20
	[1.4 , 3.0]	[-0.8 , -0.6]	[2.3 , 3.4]	[0.16 , 0.23]
EU	6.1	-4.7	10.8	0.60
	[4.3 , 7.2]	[-5.4 , -4.3]	[8.1 , 13.0]	[0.45 , 0.72]
		Panel C: By GDP Per Capita		
Richest Third	8.8	-6.1	14.9	0.36
	[8.0 , 9.5]	[-7.0 , -5.6]	[12.8 , 16.3]	[0.31 , 0.39]
Middle Third	-7.7	-1.3	-6.4	-0.57
	[-10.2 , -6.5]	[-1.5 , -1.2]	[-8.9 , -5.4]	[-0.80 , -0.49]
Poorest Third	-4.5	-1.2	-3.3	-1.06
	[-5.0 , -4.3]	[-1.4 , -1.1]	[-3.7 , -3.2]	[-1.18 , -1.00]

Notes: All columns except (4) represent values in US 2007$ billions. All estimates summarize the total effect over a decade. The counterfactual policy applies a carbon tax of $19.96 per metric ton of CO2 to all airborne and maritime imports, exports, and intranational trade. Bracketed numbers represent ninety-five percent confidence intervals, estimated using the bias-corrected bootstrap of Efron (1987) with B=200 draws from the θ_j distributions of Table 2, excluding draws of $\theta_j>0$.

For Online Publication: Appendix to Trade, CO_2, and the Environment

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A Data Appendix

A.1 Transport Modes

I use a few general rules to compile the transportation data. I exclude observations with unknown trading partners or products. I convert all foreign currencies to dollars using the mean period exchange rate from the IMF's International Financial Statistics, then deflate values to the year 2007 using the US Bureau of Labor Statistics Consumer Price Index. Where possible, I use importer reports. When a trade flow reports currency but not weight, I impute weight using the mode-specific weight-to-value ratio from all other countries reporting transportation modes. If a landlocked country reports trade by sea, I measure the sea distance according to the population-weighted distance from its trading partner (using CEPII data).

Some decisions are specific to each data source. For EU trade, I treat "inland waterway" trade as maritime trade. For US imports, I sum freight charges and product values to obtain the goods' value, since I use importer-reported trade values elsewhere. Japan only distinguishes transport mode for airborne and container ship trade, so I assign additional Japanese trade values (obtained from the same Trade Statistics of Japan source) to sea shipment. I use the HS-to-14-sector concordance file described below to link these HS codes to the 14 sectors I analyze.

I obtain EU data at the 2-digit HS code level, so I use the procedure described below for the Australian freight data. In mapping 2-digit trade data to the 14 sectors I analyze, I apply value shares to the trade value data and weight shares to the trade weight data.

I impute transportation mode shares for remaining 17-26 percent of trade using fractional multinomial logit. Let x_{od} denote the covariates used to impute mode shares. x_{od} includes 11 variables: log importer and exporter GDP per capita and their squares, log bilateral distances

by air and by sea and their squares, and dummy variables identifying landlocked, contiguous, and island countries.

In a fractional multinomial logit, the share of the *o-d* trade flow transported by mode m is

$$\sigma_{odm} = \begin{cases} \frac{1}{1+\sum_{\tilde{m}=2}^{M} \exp(x_{od}\gamma_{\tilde{m}})} & \text{if } m = 1 \\ \frac{\exp(x_{od}\gamma_m)}{1+\sum_{\tilde{m}=2}^{M} \exp(x_{od}\gamma_{\tilde{m}})} & \text{if } m > 1 \end{cases} \tag{A.1}$$

One mode is arbitrarily chosen as the base category $m = 1$. The corresponding log likelihood for observation odm is

$$\ln(L_{odm}) = \sum_{\tilde{m}=1}^{M} \ln(\tilde{\sigma}_{od\tilde{m}})\, \sigma_{od\tilde{m}} \tag{A.2}$$

where $\tilde{\sigma}_{odm}$ represents the fitted value from (A.1).

I use a secondary reference to impose mode shares in one case—UNECA (2010, p. 214) reports that 80 percent of intra-African freight transportation moves by road. I impose this statistic on all intra-African trade, then estimate the division of remaining trade between sea, rail, and air using equation (A.2).[1]

For Assumption 3 in the main text, I impute weight-to-value ratios (W) for the quarter of world trade where weight is missing. Using data from global trade, I measure W separately for each of the 13 tradable sectors and 4 observed transport modes, then apply these values to the missing data.

A.2 Freight Costs

I use a few rules to compile the Australian and US data. The Australian data report the value of goods at their port of origin and port of destination, and I define the shipping cost as the difference between these values. I exclude the few observations where shipping costs are negative, or outlying observations where the shipping cost exceeds the goods' value (which represent about a tenth of a percent of the aggregated data). For both importers, I exclude observations which list the exporter as unknown or where the exporter is not a country. I use a quarterly price deflator for these data from the Bureau of Labor Statistics Consumer Price Index. I do not use US files from four months which had corrupted data in two independent sets of files I checked: April 2003, February 2004, August 2008, and May 2010.

Defining the 14 sectors in these data requires constructing one concordance file for the US data and a separate concordance file for the Australian data. The US data use different revisions of the Harmonized Commodity Description and Coding System (HS) codes (1992, 1996, 2002, and 2007). I construct a concordance file which links HS codes from each revision to the 14 sectors I analyze. For the 2002 revision, I use a dataset created by Thomas

[1] Cristea, Hummels, Puzzello and Avetisyan (Forthcoming) make a similar adjustment.

Hutcheson as part of GTAP which links each 6-digit HS code to the 14 sectors I analyze. For the 2007 HS revision, I invert a 2002-to-2007 concordance which the UN Statistics Division created, and I then apply the 2002 concordance described above. For the 1996 HS revision, I use a concordance file created by Robert McDougall and Mark Gehlhar as part of GTAP. For the 1992 revision, I invert the UN's 1992-to-1996 HS concordance file then apply the 1996 concordance described above. I find 21 6-digit HS codes which appear in the US trade data but not in this concordance file. I assign these codes to a sector based on the concordance for the same code in a different HS revision, or based on the assignment of adjacent HS codes.[2]

The Australian data are only available at the 2-digit HS code level. To link these data to the 14 sectors I analyze, I construct a concordance linking each year of the Australian data to a sector. Using 6-digit HS code trade value data from each year of UN-Comtrade (a source which reports trade value and weight but not mode) for Australian imports only, for each HS code-by-trading partner-by year cell, I measure the share of value which falls in each of the 14 sectors I analyze. I then apply these shares to the Australian data.

The Rauch (1999) classification of homogenous, reference-priced, and differentiated goods is defined in terms of SITC Revision 2 codes. To estimate trade elasticities according to this classification, I use concordances published by the UN Statistics Division for all four HS revisions which link 6-digit HS codes to SITC Revision 2 codes. I use this approach to define all the US trade data in SITC Revision 2 codes. I apply the same approach I use for the main data to define the Australian shipping cost data in terms of the three Rauch categories.

In the freight cost data and in the calculation of fuel costs for the counterfactual analyses, I top-code freight and fuel costs at 100 percent of product values to address outliers. In the counterfactual analyses, this affects a twentieth of a percentage point of observations.

A.3 Trade and Production Data

To calculate value-added (GDP) by country and sector from the GTAP data, I sum the value of payments to all factors together with total taxes (McDonald and Thierfelder 2004). I exclude taxes devoted to producing capital goods, since these are not assigned to individual sectors. I measure gross output in cost including insurance and freight terms (CIF; equivalently, I measure it at world prices) so gross output is comparable with international exports in the model (which are described in CIF terms). I top-code country-by-sector value-added (GDP) data at 98.5 percent of gross output and bottom-code GDP data at 1.5 percent of gross output, which each affect a handful of observations with outlying values.

[2] In inverting the 2002-to-2007 concordance file, for the few cases where one year 2007 code links to multiple year 2002 codes, I uniquely link it to the first 2002 code ordered numerically. I use the same procedure to invert the 1992-to-1996 HS concordance file. Unclassified trade (HS=999999) are mapped to the "Other" sector.

A.4 Additional Cleaning

In all datasets, I exclude observations where the partner country cannot be identified (e.g., "Africa", "areas not elsewhere specified," etc.). For calculating damages from the RICE model, I include Mozambique and Tanzania in the Africa region, and I combine Western Sahara with Morocco.

For commodity-specific data, I exclude observations with commodity codes that are missing or that do not correspond to Harmonized System values.

The preceding sections described the concordance of the 13 tradable sectors in this paper to Harmonized System codes. The 13 sectors represent the following groupings of GTAP sector codes (Version 8): 1 to 14 (Agriculture, Forestry); 15 to 18 (Mining); 19 to 26 (Food, Beverages, Tobacco); 27 (Textiles); 28 and 29 (Apparel, Leather); 30 (Wood); 31 (Paper, Printing); 32 and 34 (Petroleum, Coal, Minerals); 33 (Chemicals, Rubber, Plastics); 35 to 37 (Metals); 40 to 41 (Machinery, Electrical); 38 to 39 (Transport Equipment); 42 (Other).

B Comparison to Estimates by International Organizations

This section discusses the assumptions required to compare my estimates of air and sea CO_2 emissions to the estimates of international organizations. For air travel, the global organization for airlines (IATA 2009) reports that all air transportation moved 498.7 billion ton-km in 2007 and that 167.7 billion of this represented freight. (The remainder is mail, passengers, and passenger baggage.) So globally, 33.6 percent of air transportation ton-km represents freight.

The EU air estimate is calculated as follows. To add air transportation to the ETS, the EU collected data indicating that in the years 2004-2006, flights to and from the EU emitted an annual mean of 221.4 $MtCO_2$. Applying the 0.336 freight/transportation ratio described above implies annual EU air freight emissions of 74.61 $MtCO_2$. Applying the 5.7 percent 2005-2007 growth in international air transportation CO_2 emissions (IEA 2011) implies an EU-reported total of 78.86 $MtCO_2$.

The IEA international air estimate is calculated as follows. The IEA reports that international air transportation emitted 431 $MtCO_2$ in the year 2007. Assuming again that 33.6 percent of this represents we have an IEA estimate for air freight of 145 $MtCO_2$.

The ICAO total air estimate is calculated as follows. The ICAO (2009) estimates that domestic and international aviation emitted a total of 632 $MtCO_2$ in the year 2006. I inflate this by the 2006-2007 5% growth in global air ton-km reported by IATA (2009), then multiply by the IATA freight/total ton-km ratio of 0.336 to obtain an ICAO estimate of 223 $MtCO_2$ for international plus domestic air freight.

C Inference

This section describes the methodology for bias-corrected bootstrap estimates of the 95-percent confidence intervals for counterfactual calculations. This bootstrap takes $B = 200$ draws of the 13×1 vector θ from the 13 independent normal distributions that have mean and standard deviation given by the instrumental variables parameter estimates and standard errors of Table 2, columns 7-8. If any element of the bth draw $\theta(b)$ is positive and so economically infeasible, I re-draw the $\theta(b)$ vector until I obtain negative values. This procedure consistently estimates the true confidence interval under the null hypothesis that $\theta^j < 0$. For each draw $\theta(b)$, I calculate the model's estimate $\zeta(b)$ of the parameter of interest. $\zeta(b)$ for different table entries represents welfare, international trade, or pollution.

Given these draws, I report the bias-corrected bootstrap estimate of the 95-percent confidence region, which can provide an accurate finite-sample approximation (Efron 1987). The bootstrap estimate of the confidence region is given by the pair $(\zeta^{(\alpha_1)}, \zeta^{(\alpha_2)})$, where $\zeta^{(\alpha)}$ denotes the $100 \cdot \alpha$th percentile of the B estimates $\zeta(1), \ldots, \zeta(200)$. The unadjusted percentiles for the 95-percent confidence interval are $\alpha_1 = 0.025$ and $\alpha_2 = 0.975$. The bias-corrected percentiles are

$$\begin{aligned} \alpha_1 &= \Phi\left(2z_0 + z^{(\alpha)}\right) \\ \alpha_2 &= \Phi\left(2z_0 + z^{(1-\alpha)}\right) \end{aligned}$$

Here $\Phi(\cdot)$ represents the standard normal cumulative distribution function (CDF) and $z^{(\alpha)}$ represents the $100 \cdot \alpha$th percentile of a standard normal CDF. The bias correction coefficient z_0 is calculated from the share of bootstrap estimates $\zeta(1), \ldots, \zeta(200)$ which are less than the full-sample estimate ζ:

$$z_0 \equiv \Phi^{-1}\left(B^{-1}\sum_{b=1}^{B} 1[\zeta(b) < \zeta]\right)$$

Here $1[\cdot]$ represents the indicator function, which takes the value one if its argument is true and zero otherwise, and $\Phi^{-1}(\cdot)$ represents the inverse of a standard normal CDF.

D Welfare Effects of Climate Change Regulation

Measuring the effect of climate change regulations requires calculating $X_{od}^{j\prime}$ as a function of $\hat{w}_d$ and known data. I calculate $X_{od}^{j\prime}$ from

$$X'(\hat{w}_d) = [I - F(\hat{w}_d)]^{-1} \Psi(\hat{w}_d)$$

To explain these matrices, I begin with three terms which are easiest to derive. The budget constraint, trade balance, and gravity equation imply the following three equations:

$$\hat{c}_o^j = (\hat{w}_d)^{\beta_d^j} \left(\hat{p}_d^j\right)^{1-\beta_d^j}$$

$$\hat{p}_d^j = \left[\sum_{o=1}^{N} \lambda_{od}^j (\hat{c}_o^j \hat{\tau}_{od}^j)^{\theta^j}\right]^{1/\theta^j} \tag{D.1}$$

$$\hat{\lambda}_{od}^j = \left(\frac{\hat{c}_o^j \hat{\tau}_{od}^j}{\hat{p}_d^j}\right)^{\theta^j} \tag{D.2}$$

These relationships represent the proportional effect of a regulation on production costs, prices, and trade flows.

I now turn to explain the main calculation. X' is an $NJ \times 1$ vector representing expenditures after a carbon tax is imposed.[3] The vector X' is ordered by country then sector, so that the first 14 entries represent the values for the first country; the second 14 entries represent values for the second country, etc. I is an $NJ \times NJ$ identity matrix. $\Psi(\hat{w}_d)$ is an $NJ \times 1$ vector defined as follows:

$$\Psi(\hat{w}_d) \equiv \alpha_d^j \hat{w}_d (w_d L_d) - (1-\beta_d^j) T_d^j + \alpha_d^j T_d$$

Finally, the $NJ \times NJ$ matrix $F(\hat{w}_d)$ is the sum of four separate $NJ \times NJ$ matrices:

$$F = A + B + C + D$$

These four matrices are defined as follows, where $G_{od} = 1$ if the importer receives the tariff revenue and $G_{od} = 0$ otherwise:

$$\begin{aligned} A &= diag\left((1-\beta_d^j)\sum_{o=1}^{N} \frac{\lambda_{od}^{j\prime}}{1+t_{od}^j}\left[1+t_{od}^j(1-G_{od})\right]\right) \\ &= \begin{bmatrix} \left(1-\beta_1^1\right)\sum_o \frac{\lambda_{o1}^{1\prime}\left[1+t_{o1}^1(1-G_{o1})\right]}{1+t_{o1}^1} & & & 0 \\ & \left(1-\beta_1^2\right)\sum_o \frac{\lambda_{o1}^{2\prime}\left[1+t_{o1}^2(1-G_{o1})\right]}{1+t_{o1}^2} & & \\ & & \ddots & \\ 0 & & & \left(1-\beta_N^J\right)\sum_o \frac{\lambda_{oN}^{J\prime}\left[1+t_{oN}^J(1-G_{oN})\right]}{1+t_{oN}^J} \end{bmatrix} \end{aligned}$$

[3] As in the main text, x' represents the value of the variable x after a regulation is imposed. No vectors or matrices in this section are transposed.

$$
\begin{aligned}
B &\equiv diag\left(\begin{bmatrix} \rho_d^{j,k=1} & \dots & \rho_d^{j=1,k=J} \\ \vdots & \ddots & \vdots \\ \rho_d^{j=J,k=1} & \dots & \rho_d^{j=K,k=J} \end{bmatrix}\right) \\
&= \begin{bmatrix} \begin{bmatrix} \rho_{d=1}^{j=1,k=1} & \dots & \rho_{d=1}^{j=1,k=J} \\ \vdots & \ddots & \vdots \\ \rho_{d=1}^{j=J,k=1} & \dots & \rho_{d=1}^{j=K,k=J} \end{bmatrix} & & 0 \\ & \ddots & \\ 0 & & \begin{bmatrix} \rho_{d=N}^{j=1,k=1} & \dots & \rho_{d=N}^{j=1,k=J} \\ \vdots & \ddots & \vdots \\ \rho_{d=N}^{j=J,j=1} & \dots & \rho_{d=N}^{j=J,k=J} \end{bmatrix} \end{bmatrix} \\
\rho_d^{j,k} &= \alpha_d^j \sum_{o=1}^{N} \frac{t_{od}^k G_{od}^k \lambda_{od}^{k\prime}}{1+t_{odj}}
\end{aligned}
$$

$$
\begin{aligned}
C &\equiv \left(\alpha_o^j \frac{t_{od}^k \left(1-G_{od}^k\right) \lambda_{on}^{k\prime}}{1+t_{od}^k}\right) \\
&= \begin{bmatrix} \alpha_1^1 \frac{t_{11}^1 (1-G_{11}^1)\lambda_{11}^{1\prime}}{1+t_{11}^1} & \dots & \alpha_1^1 \frac{t_{11}^J (1-G_{11}^J)\lambda_{11}^{J\prime}}{1+t_{11}^J} & \dots & \alpha_1^1 \frac{t_{1N}^J (1-G_{1N}^J)\lambda_{1N}^{J\prime}}{1+t_{1N}^J} \\ \vdots & & \vdots & & \vdots \\ \alpha_1^J \frac{t_{11}^1 (1-G_{11}^1)\lambda_{11}^{1\prime}}{1+t_{11}^1} & \dots & \alpha_1^J \frac{t_{11}^J (1-G_{11}^J)\lambda_{11}^{J\prime}}{1+t_{11}^J} & \dots & \alpha_1^J \frac{t_{1N}^J (1-G_{1N}^J)\lambda_{1N}^{J\prime}}{1+t_{1N}^J} \\ \vdots & & \vdots & & \vdots \\ \alpha_N^J \frac{t_{N1}^1 (1-G_{N1}^1)\lambda_{N1}^{1\prime}}{1+t_{N1}^1} & \dots & \alpha_N^J \frac{t_{N1}^J (1-G_{N1}^J)\lambda_{N1}^{J\prime}}{1+t_{N1}^J} & \dots & \alpha_N^J \frac{t_{NN}^J (1-G_{NN}^J)\lambda_{NN}^{J\prime}}{1+t_{NN}^J} \end{bmatrix}
\end{aligned}
$$

$$
\begin{aligned}
D &= \begin{bmatrix} \begin{bmatrix} D_{11}^1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & D_{11}^J \end{bmatrix} & \begin{bmatrix} D_{12}^1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & D_{12}^J \end{bmatrix} & \begin{bmatrix} D_{1N}^1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & D_{1N}^J \end{bmatrix} \\ \vdots & \ddots & \vdots \\ \begin{bmatrix} D_{N1}^1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & D_{N1}^J \end{bmatrix} & \dots & \begin{bmatrix} D_{NN}^1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & D_{NN}^J \end{bmatrix} \end{bmatrix} \\
D_{od}^j &= \left(1-\beta_d^j\right)\left[t_{od}^j \left(1-G_{od}\right)\right] \frac{\lambda_{od}^j}{1+t_{od}^j} X_d^j
\end{aligned}
$$

These matrices can be derived by solving the budget constraint after a regulation is imposed so as to obtain X' as a function of other parameters and variables of the model.

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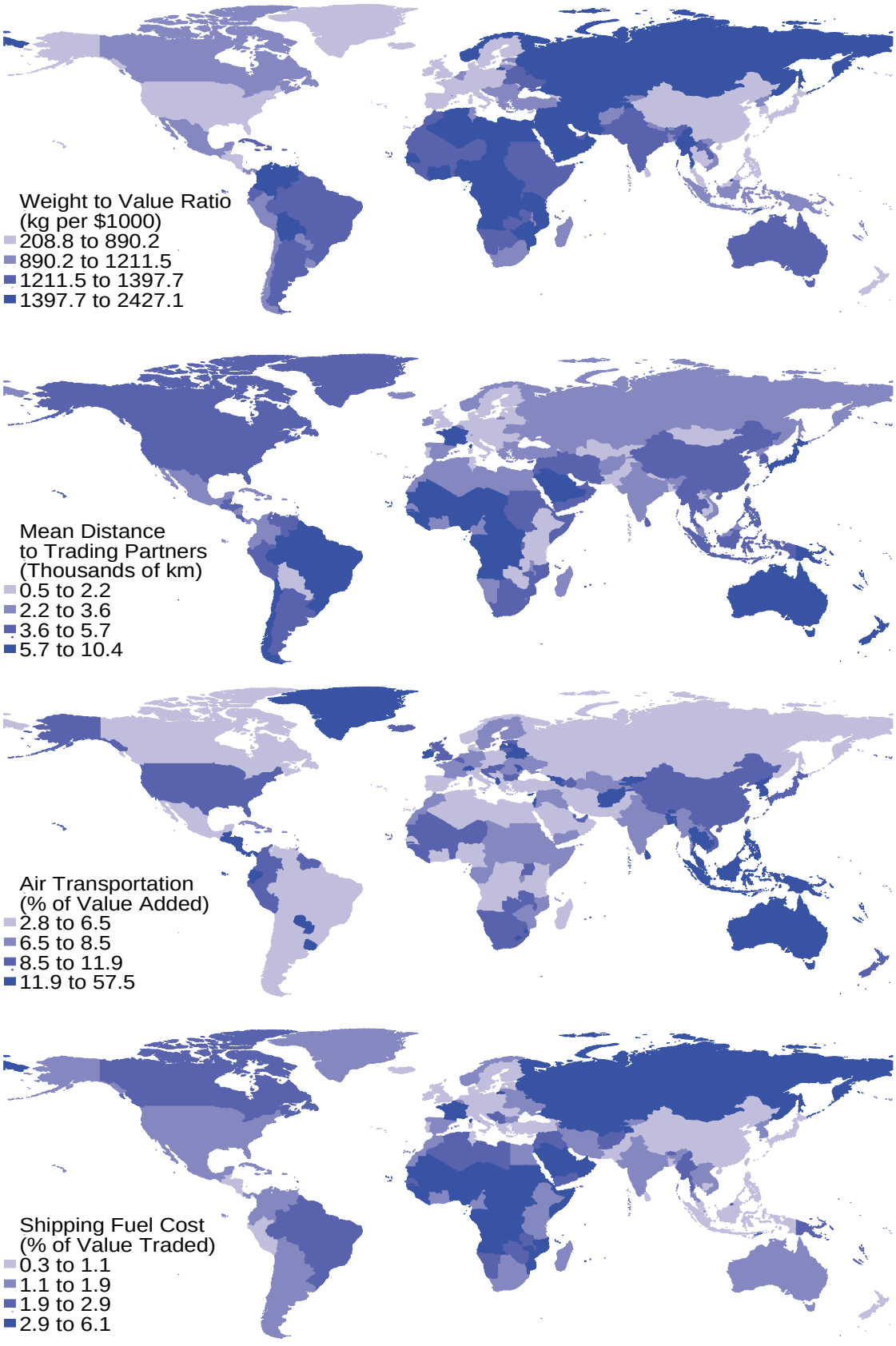
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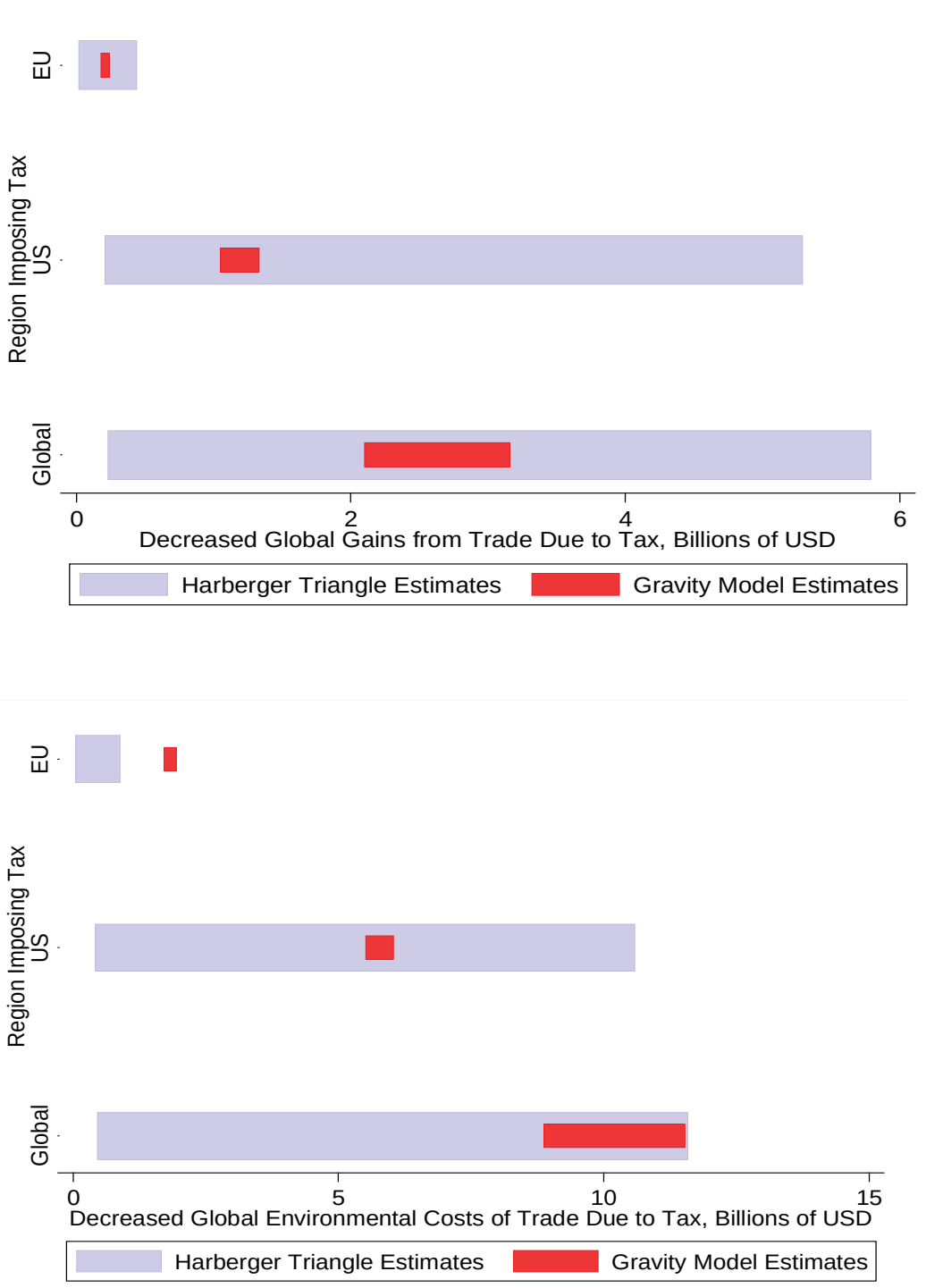
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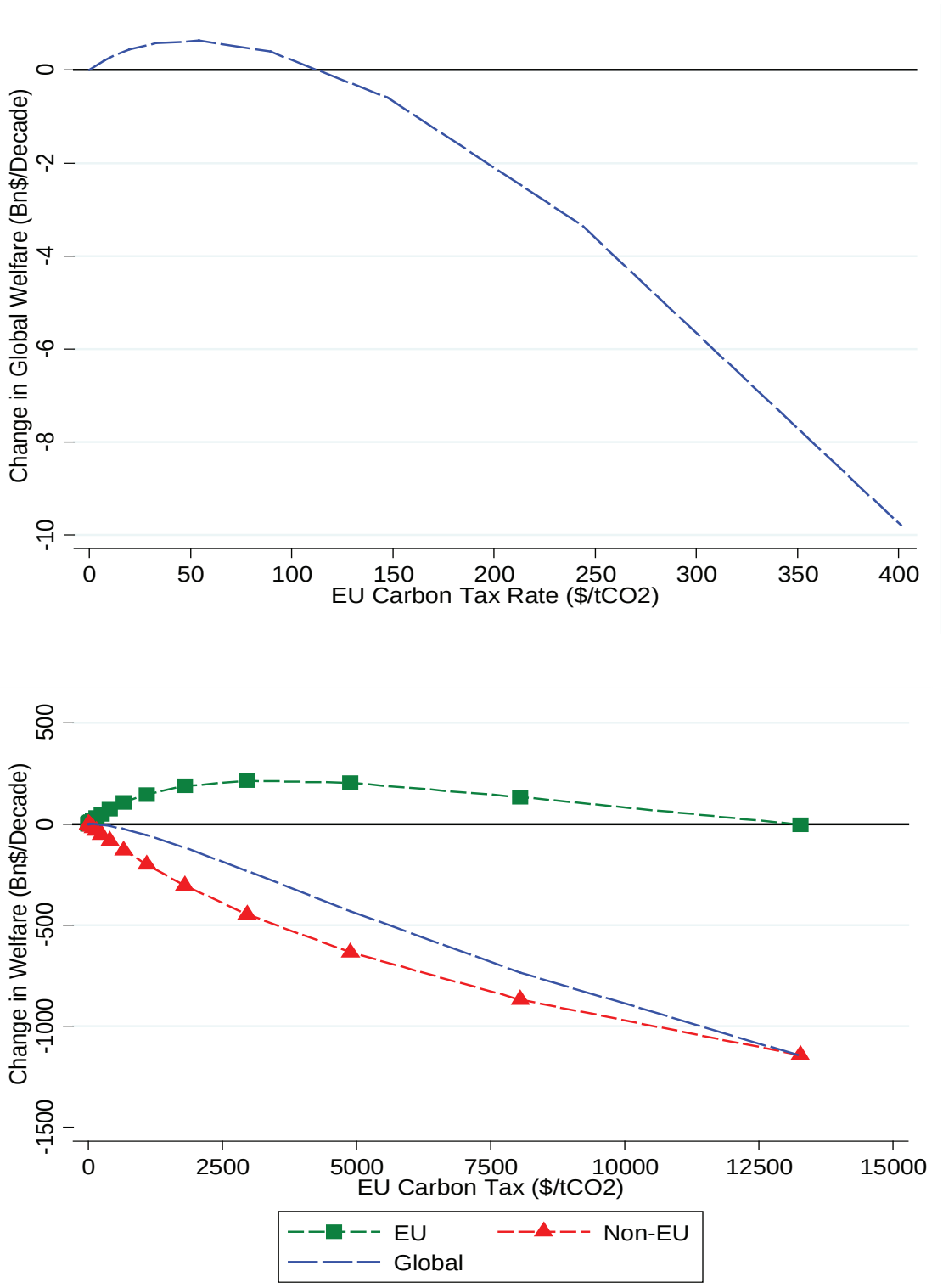
Appendix Figure 1: Shipping Fuel Intensity of Traded Goods

Notes: Data aggregate over intranational trade, international imports, and international exports. Mean distance is weighted by kg. Fuel cost is calculated by equation (3c).



Appendix Figure 2. Comparing Estimates from the Gravity Trade Model and from Harberger Triangles

Notes: The gravity model is described in section 2 of the paper. Harberger triangles describe a partial equilibrium model of the demand for shipping fuels; see paper text for details. For the gravity model, the bar describes the 95% confidence interval, estimated using a bias-corrected bootstrap. For Harberger triangles, the bar represents the range implied by two possible demand elasticities: -0.02 and -0.50. Both models assume perfectly elastic oil supply. The EU, US, and Global carbon taxes of $19.96/tonCO2 are applied to international and intranational shipping; see paper text for details.



Appendix Figure 3: Optimal EU Tariffs: Regional and Global Welfare as Function of EU Carbon Tax Rate

Notes: Graphs depict the welfare effect of an EU carbon tax at different tax rates, all assuming the marginal social cost of CO2 emissions is $19.96/ton.

Appendix Table 1: Review of Fuel Economy Estimates, by Transportation Mode

Mode	Value (gCO_2/ton-km)	Method	Region	Source
Air	985.97	Fuel consumption divided by ton-km	Global	This paper, IATA (2009)
Air	540	n.a.	Boeing 747	NTM (2012)
Air	912 to 963.45	Calculations from published data	US	Cristea et al. (2011)
Air	595-1916	Engineering estimates	UK	Defra (2009)
Sea	9.53	Global CO_2 emissions from IEA (2011) divided by original ton-km freight estimates	Global	This paper
Sea	4.5 to 16.3	Engineering estimates aggregated over ship fleet registeries	Global	Psaraftis and Kontovas (2009)
Sea	15 to 21	n.a.	n.a.	NTM (2012)
Sea	4 to 20	Engineering estimates	UK	Defra (2009)
Rail	23	Summary of studies listed below	Global	This paper
Rail	23	n.a.	Asia	ADB (2010)
Rail	22.7	n.a.	EU15	Giannouli et al. (2006)
Rail	7.3 to 26.3	Literature review	EU	Cefic (2011)
Rail	27.6	Fuel consumption divided by freight transport	UK	ORR (2009)
Rail	10-119	Literature review	Various	IMO (2009)
Road	119	Summary of studies listed below	Global	This paper
Road	119.7	n.a.	EU	Giannouli et al. (2006)
Road	61	n.a.	Asia	ADB (2010)
Road	118.6	Fuel consumption divided by freight transport	UK	Defra (2009)
Road	80-181	Literature review	Various	IMO (2009)
Other	0	Assumption	Global	This paper

Notes: n.a.=not available.

Appendix Table 2: Trade Elasticities, Instrumental-Variables Estimates, Sensitivity Analysis

	(1)	(2)	(3)	(4)	(5)
	Panel A: Economy-Wide Estimates				
Overall	-10.099**	1.221	-7.627**	-2.009*	-2.009*
	(4.662)	(3.230)	(3.190)	(1.185)	(1.185)
Overall: Manufacturing	-6.590**	-1.789	-6.734**	-2.309**	-2.309**
	(3.149)	(5.108)	(2.702)	(1.104)	(1.104)
	Panel B: Sector-Specific Estimates, Non-Manufacturing				
Agriculture, Forestry	-3.440*	-4.740**	-3.021	-0.046	-0.046
	(2.003)	(2.120)	(1.854)	(2.300)	(2.300)
Mining	-3.212**	-2.405*	-2.943**	-3.338***	-3.338***
	(1.260)	(1.365)	(1.183)	(1.271)	(1.271)
	Panel C: Sector-Specific Estimates, Manufacturing				
Food, Beverages, Tobacco	-6.991***	-6.887**	-6.529***	-5.122*	-5.122*
	(2.261)	(3.120)	(2.113)	(2.720)	(2.720)
Textiles	-24.106***	-13.957***	-21.487***	-34.504***	-34.504***
	(6.802)	(4.104)	(5.999)	(10.128)	(10.128)
Apparel, Leather	-6.328***	-9.757***	-5.988***	-14.039***	-14.039***
	(2.175)	(2.588)	(1.994)	(3.629)	(3.629)
Wood	-6.067***	-7.259**	-5.712***	-6.981***	-6.981***
	(1.806)	(3.575)	(1.690)	(1.832)	(1.832)
Paper, Printing	-4.428	-4.11	-4.196	-3.777	-3.777
	(2.849)	(4.556)	(2.601)	(2.720)	(2.720)
Petroleum, Coal, Minerals	-8.612***	-12.256***	-7.855***	-10.583***	-10.583***
	(2.754)	(3.158)	(2.589)	(3.313)	(3.313)
Chemicals, Rubber, Plastics	-7.700***	-3.212*	-4.947***	-8.016***	-8.016***
	(2.497)	(1.937)	(1.755)	(2.636)	(2.636)
Metals	-13.840***	-21.809**	-12.129***	-16.858***	-16.858***
	(4.878)	(9.577)	(4.194)	(5.191)	(5.191)
Machinery, Electrical	-10.998***	-4.57	-8.794***	-12.279***	-12.279***
	(3.002)	(4.645)	(2.243)	(3.118)	(3.118)
Transport Equipment	-6.429	-10.355	-5.336	-6.72	-6.72
	(4.102)	(6.752)	(3.288)	(4.503)	(4.503)
Other	-6.835*	-8.21	-7.055**	-8.354**	-8.354**
	(3.670)	(6.306)	(3.475)	(3.547)	(3.547)
Correlation with Table 2, Column 7	0.93	0.94	0.97	0.98	0.98
Quarters 1,4 instrument quarters 2,3	Yes	No	No	No	No
Quarters 1,2 instrument quarters 3,4	No	Yes	No	No	No
GLS weights	No	No	Yes	No	No
log(x+0.00001)	No	No	No	Yes	No
Include tariffs in freight cost	No	No	No	No	Yes

Notes: Data include two importers: the US and Australia. Columns (5) uses log(1+s+k) as explanatory variable, where k is tariff rate reported in US and Australian data. Each table entry represents a separate regression. "Correlation with Table 2" reports the correlation coefficient between the 13 sector-specific elasticities reported in a given column of this table and the 13 elasticities reported in Table 2, column 7. An observation represents a good-exporter-importer-year. The data include two importers: the US and Australia. Standard errors clustered by importer-exporter pair. *** p<0.01, ** p<0.05, * p<0.10.

Appendix Table 3: Trade Elasticities, by Rauch (1999) Classification

	Log Shipping Costs (FS)	Log Import Shares (IV)	N
	(1)	(2)	(3)
Differentiated	0.26***	-5.75**	4,750
	(0.05)	(2.29)	
Reference Priced	0.38***	-5.81**	4,104
	(0.04)	(2.28)	
Homogenous	0.36***	-9.18***	3,374
	(0.07)	(3.00)	

Notes: See notes to Table 2.

Appendix Table 4--Policy Effects on International Trade and on CO_2

	Intl Trade ($bn)	CO_2 (Mn. Tons)				CO_2: Share From Transport
		Air	Sea	Other Transport	Total	
	(1)	(2)	(3)	(4)	(5)	(6)
EU Policy	-9.7	-33.5	-6.3	-1.5	-48.6	0.85
	[-10.7 , -8.3]	[-44.2 , -27.2]	[-8.6 , -5.2]	[-2.3 , -0.8]	[-61.6 , -38.7]	[0.83 , 0.86]
US Policy	-16.2	-11.8	-61.3	-176.5	-344.7	0.72
	[-19.6 , -13.4]	[-12.6 , -10.2]	[-70.4 , -52.0]	[-187.5 , -170.3]	[-359.5 , -330.2]	[0.68 , 0.74]
Global Policy	-66.3	-85.1	-263.6	-25.9	-430.3	0.87
	[-79.8 , -59.9]	[-114.7 , -69.5]	[-359.5 , -230.3]	[-37.4 , -18.8]	[-496.8 , -393.0]	[0.82 , 0.89]

Notes: see main text for details and Tables 4-5 for associated welfare calculations.

Appendix Table 5. Sensitivity to Model Assumptions, Full Welfare Effects of International Trade

	Gains from Trade	Environmental Costs of Trade	Social Welfare	Welfare (Percentage Points)		
				Richest	Middle	Poorest
Model	(1)	(2)	(3)	(4)	(5)	(6)
1. Detailed Model	5,678	-51	5,706	9	13	16
2. Social Cost of CO_2=$4.10/ton	5,678	-10	5,684	9	13	16
3. Social Cost of CO_2=$1170/ton	5,678	-2,969	7,338	12	15	23
4. Homogenous Damage Function	5,678	-51	5,707	9	13	16
5. Trade Elasticity = -4.12	4,357	-52	4,391	7	8	12
6. Trade Elasticity = -8.28	2,237	-54	2,281	4	4	6

Notes: See paper text for additional details on each row.

Appendix Table 6. Sensitivity to Model Assumptions, Carbon Taxes

	Gains from Trade	Environmental Costs of Trade	Welfare			Welfare (Basis Points)		
			Global	EU	US	Richest	Middle	Poorest
Model	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A: EU Carbon Tax for Air Shipping								
1. Main Results	-0.31	-0.97	0.65	8.24	-1.94	0.11	-0.21	-0.46
2. Carbon Tax=$4.10/ton	-0.02	-0.05	0.03	1.69	-0.41	0.02	-0.05	-0.10
3. Carbon Tax=$1170/ton	-1.96	-132.53	130.57	94.24	4.15	2.48	1.17	4.34
4. Trade Elasticity = -4.12	-0.31	-1.05	0.73	8.04	-1.73	0.11	-0.20	-0.48
5. Trade Elasticity = -8.28	-1.43	-1.68	0.26	25.17	-6.26	0.31	-0.72	-1.42
Panel B: US Carbon Tax for All Shipping								
1. Main Results	-1.61	-6.85	5.24	-2.49	17.44	0.25	-0.31	-0.61
2. Carbon Tax=$4.10/ton	-0.07	-0.30	0.23	-1.17	3.88	0.04	-0.08	-0.18
3. Carbon Tax=$1170/ton	-13.10	-1,116.64	1,103.45	596.78	124.85	19.17	13.99	46.06
4. Trade Elasticity = -4.12	-1.61	-7.43	5.82	-3.88	18.90	0.27	-0.27	-0.77
5. Trade Elasticity = -8.28	-14.71	-19.02	4.30	-6.53	34.28	0.42	-0.76	-1.52
Panel C: Global Carbon Tax for Air & Sea Shipping								
1. Main Results	-3.37	-8.55	5.18	10.82	2.98	0.36	-0.57	-1.06
2. Carbon Tax=$4.10/ton	-0.16	-0.39	0.23	1.66	0.53	0.06	-0.13	-0.26
3. Carbon Tax=$1170/ton	-24.70	-1,302.62	1,277.82	729.99	106.79	22.53	15.35	51.99
4. Trade Elasticity = -4.12	-3.37	-9.28	5.91	9.08	4.80	0.38	-0.52	-1.26
5. Trade Elasticity = -8.28	-22.47	-20.01	-2.47	26.59	6.18	0.87	-2.22	-4.46

Notes: Numbers represent total effects over a decade. Except where listed as basis points, all table entries represent billions of 2007 US$.