

# Trade Costs, CO<sub>2</sub>, and the Environment

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## Abstract

This paper quantifies how international trade affects CO<sub>2</sub> emissions and analyzes the welfare consequences of regulating the CO<sub>2</sub> emissions from shipping. To this end the paper describes a model of trade and the environment, compiles new data on the CO<sub>2</sub> emissions from shipping, and estimates key parameters using panel data regressions. Results show that the benefits of international trade exceed trade's environmental costs due to CO<sub>2</sub> emissions by two orders of magnitude. While proposed regional carbon taxes on the CO<sub>2</sub> emissions from shipping would increase global welfare and increase the implementing region's GDP, they would also harm poor countries.

JEL Codes: F18, F64, H23, Q56

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# 1 Introduction

This paper builds a theoretical and empirical framework that can quantify the environmental costs of international trade due to CO<sub>2</sub> and analyze the welfare consequences of counterfactual policies that would regulate the CO<sub>2</sub> emissions from shipping. To this end the paper describes a model of trade and the environment, compiles new data on CO<sub>2</sub> emissions from international and intranational shipping, and estimates the model's key parameters via panel data regressions. 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. This study finds that international trade increases CO<sub>2</sub> emissions by 5 percent. Several influential papers ask whether international trade is good for the environment (Copeland and Taylor 1994, Antweiler, Copeland and Taylor 2001, Copeland and Taylor 2003, Frankel and Rose 2005). I find that the global gains from international trade, equal to \$5.5 trillion annually, exceed the costs of international trade due to CO<sub>2</sub> emissions by a factor of 161.

Second, this paper assesses the welfare consequences of several proposed regulations on the carbon emissions from shipping. I analyze only goods transportation, though the EU has sought to regulate both passenger and goods transportation by air. I also analyze US regulations of CO<sub>2</sub> 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. Finally, I analyze a global tax on the CO<sub>2</sub> emissions from air and sea shipping, which the 1997 Kyoto Protocol required and which is under discussion at two UN fora (the International Maritime Organization and the International Civil Aviation Organization) 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 rate of CO<sub>2</sub> emissions from international transportation exceeds the CO<sub>2</sub> emissions growth rate from any other sector (IEA 2011); and because international trade issues play a prominent role in policy debates on climate change.

I find that these policies all increase global welfare but have two surprising properties. First, these policies increase welfare in wealthy countries but decrease welfare in poor countries. This is surprising because poor countries suffer the largest proportional damages from climate change. Poor countries, however, tend to export 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 the 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 world price (i.e., the foreign

exporter price) of targeted goods. The idea originates in Bickerdike (1907) and is now standard in textbooks and research. 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.

This paper is built around an 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 Rodriguez-Clare 2012).

To estimate this model’s key parameters, the paper uses panel data regressions to estimate trade elasticities separately for 13 sectors. These parameters represent the bilateral elasticity of trade in dollars with respect to bilateral trade costs. These elasticities play a central role 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, Caliendo and Parro 2015). This paper uses panel data on the reported cost of shipping all types of goods from each of the 128 countries analyzed in the rest of the paper to Australia and the US, which both have panel data on shipping costs. Hertel, Hummels, Ivanic and Keeney (2007) use a similar cross-sectional dataset on shipping costs to estimate these parameters, though I believe this is the first time any researcher has exploited panel data on shipping costs to estimate these parameters. The only other estimate of the trade elasticity I know that exploits the panel structure of trade data by including origin-by-destination fixed effects in regressions is Donaldson (Forthcoming), who estimates the trade elasticity for agricultural commodities in Colonial India. Panel data are important because so many variables like currency and expropriation risk, culture, regulation, and many others create bilateral trade frictions. Panel data have the advantage over these cross-sectional studies that they can use country pair fixed effects to sweep out all time-invariant bilateral trade frictions, thereby decreasing potential bias from omitted variables. The regressions include origin-by-year, destination-by-year, and origin-by-destination fixed effects. The parameters are identified from all remaining sources of variation in trade costs which are not removed by these fixed effects. Potential sources of such variation include the effects of shipping fuel changes that differ by route distance; varying costs for crossing the Panama or Suez canals; and many others.

Because trade costs are likely to suffer from measurement error, I use instrumental variables to estimate these elasticities. I 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  $-1.55$  to  $-18.56$  for thirteen sectors. I emphasize that this is an elasticity of bilateral trade with respect to bilateral trade costs.

To take the model to the data, I combine data from national commerce offices and public records to obtain what I believe it is the most comprehensive set of files ever compiled on international and intranational shipping costs, transportation mode choice, pollution emissions, and trade flows. I also construct intranational and international distances by air and sea using a three million gridpoint database describing the distribution of the world's distribution of population (Goldewijk, Beusen, van Drecht and de Vos 2011). For 13 sectors of production, five modes of transportation, and 128 countries, these data measure how economic activity affects carbon emissions, representing nearly one million carbon emission estimates. Together, these provide a complete accounting of carbon emissions from the global economy. These data show that CO<sub>2</sub> emissions from international and intranational shipping account for about 4 and 5 percent, respectively, of total global CO<sub>2</sub> emissions. Data on international trade 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 Article III of the General Agreement on Tariffs and Trade (GATT) for a region to regulate international but not domestic shipping (Bartels 2012, Meltzer 2012).

I test each set of results against independent estimates to assess their accuracy. When aggregated to broad categories that are comparable, my aggregate CO<sub>2</sub> emissions estimates resemble those of international organizations. For my regression estimates of trade elasticities, estimated bilateral demand is more elastic for more homogenous goods (Rauch 1999). I also report numerous sensitivity analyses to other ways of measuring the social cost of climate change; to other ways of estimating trade elasticities; to other ways of measuring intranational transport mode shares; to other ways for accounting for transport mode substitution; and to detailed links between industries. In each of these alternatives, the paper's main conclusions persist—rich countries benefit more than poor countries from the proposed carbon emissions regulations; the EU and US benefit disproportionately from unilateral regulation; and international trade's benefits are orders of magnitude larger than international trade's environmental costs due to CO<sub>2</sub>.

This paper builds on existing research in several ways. The methodology builds on a burgeoning "structural gravity" literature in trade that combines a parsimonious general equilibrium model with reduced-form estimates of a few key elasticities (Eaton and Kortum 2002, Head and Mayer 2014). This type of approach is not commonly used in environmental economics. It occupies a middle ground between existing methods—reduced-form studies abstract from general-equilibrium forces, papers in the trade-environment literature typically focus on Heckscher-Ohlin models, and computable general equilibrium models require a huge number of assumptions (Mestelman 1982, Copeland and Taylor 2003, Böhringer, Carbone

and Rutherford 2013, Davis and Hausman Forthcoming). For example, the Global Trade and Analysis Project (GTAP) CGE model uses over 150 equations and hundreds of parameters, while this paper’s model has 5 equations and one parameter per sector. My finding that measurement error biases conventional estimates of the trade elasticity towards zero (and thus biases estimates of the gains from trade upwards) provides new support in panel data for a classic idea (Orcutt 1950).

The paper proceeds as follows. Section 2 outlines the theory. Section 3 describes the paper’s data. Section 4 describes measures of the CO<sub>2</sub> 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 EU, US, 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 agent. Production requires only one factor (“labor”). In this Armington (1969) model, each country produces one variety per sector. Varieties are differentiated by country of origin.

The rationale for this simple model is expositional: versions of several Ricardian models with more realistic microfoundations (Eaton and Kortum 2002, Bernard, Eaton, Jensen and Kortum 2003) would generate equivalent welfare calculations to this model. The equivalence between these models and Armington models is clear in standard trade settings (Arkolakis et al. 2012). That equivalence persists in this framework because the equations determining equilibrium production and consumption, as described in Section 2.2, are the same in this model as in richer Ricardian models. Moreover, carbon emissions in this framework, as shown in equation (5), depend only on equilibrium production and consumption decisions, and not on the microfoundations giving rise to them.

### 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 carbon emissions:

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

The first bracketed term in (1) represents the utility from consuming goods, and the second bracketed term in (1) represents the disutility from carbon emissions. 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  $\alpha_d^j$  of its expenditure on sector  $j$ . Total CO<sub>2</sub> emissions due to country  $o$  are  $E_o$ , and the parameter  $\mu_d$  dictates the social cost of CO<sub>2</sub> emissions.<sup>1</sup> CO<sub>2</sub> emissions are a pure 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 carbon emissions do not affect trade directly.

These preferences imply the following 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 national price index is then  $P_d \equiv \prod_{j=1}^J (p_d^j)^{\alpha_d^j}$ . These price indices do not incorporate environmental damages because I assume carbon emissions are a pure externality.

The functional form for climate damages is common in environmental economics (e.g., Nordhaus 2008), with two exceptions. First, many papers describe damages as a function of climate and use atmospheric science to determine how CO<sub>2</sub> emissions affect climate. Assumption (1) approximates those models by using a quadratic damage function to summarize both how CO<sub>2</sub> 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

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<sup>1</sup>Recent explanations of the social cost of carbon and the integrated assessment models from which it originates include Greenstone, Kopits and Wolverton (2013), Nordhaus (2014), and Pizer, Adler, Aldy, Anthoff, Cropper, Gillingham, Greenstone, Murray, Newell, Richels, Rowell, Waldhoff and Wiener (2014). These parameters represent the following thought experiment: if the world marginally increased CO<sub>2</sub> emissions, this would change CO<sub>2</sub> concentrations over future centuries, which in turn would change the climate over future centuries, which would then affect sea level rise, human health, agricultural productivity, and extreme weather. These effects must be monetized, assigned to specific countries or regions of the world, and discounted back to the present.

constant. For changes in CO<sub>2</sub> emissions much larger than this paper considers, the social marginal cost of carbon would change by larger amounts. But for the moderate deviations of a few percentage points for autarky or less than one percentage point for carbon emissions regulations (which this paper analyzes), the marginal cost of carbon remains close to the main value this paper analyzes. Second, many papers describe climate as affecting output rather than utility. I use the reduced-form approximation of describing climate damage as affecting utility directly.

The parameter  $\mu_d$  quantifies the magnitude of climate damages such as diminished human health. I rely on the large climate change literature to measure  $\mu_d$ ; 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 Dynamic Integrated Climate-Economy (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  $\alpha_d^j$  and climate damages  $\mu_d$  to vary across countries. This assumption does not allow elasticities of substitution  $\sigma^j$  to vary by country. I make this restriction for tractability: models with heterogeneous trade elasticities do not generally lead to the simple gravity equation which has an appealing empirical and theoretical basis. I calibrate the environmental damages parameter  $\mu_d$  to match leading estimates of the global distribution of climate change’s costs, as described in section 3.

What does this utility function imply about the substitutability between environmental goods (carbon emissions) and regular consumption goods? The indirect utility function for this model is

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

Here a country’s social welfare equals the product of real income and environmental damage. This utility function allows each country to have different willingness-to-pay for avoiding carbon emissions, summarized by the  $d$  subscript on the climate damages parameter  $\mu_d$ . A country’s willingness to substitute real income for avoiding carbon emissions is drawn from the climate change literature, and summarized by the number  $\mu_d$ . But for a given country, the value of a one-ton change in carbon emissions as a proportion of real income does not change with a given country’s real income.

**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:

$$c_o^j = (w_o)^{\beta_o^j} (p_o^j)^{1-\beta_o^j} \quad (3a)$$

$$p_{od}^j = c_o^j \tau_{od}^j \quad (3b)$$

Labor has price  $w_o$  and share  $\beta_o^j$ . 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  $\tau_{od}^j$ . 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 (3a). Assumption A3 shows that the trade costs combine tariffs, which are lump-sum rebated, with genuine iceberg trade costs which are lost, so one could also describe this assumption as multiplicative rather than iceberg trade costs.

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

$$\tau_{od}^j = (1 + t_{od}^j)(1 + f_{od}^j) \exp(\delta_{od}^j) \quad (4a)$$

$$t_{od}^j = \sum_{m=1}^M D_{odm} \kappa_{odm}^j W_{odm}^j \xi_m \gamma_1 (t_{odm}^{j,X} + t_{odm}^{j,M}) \quad (4b)$$

$$f_{od}^j = \sum_{m=1}^M D_{odm} \kappa_{odm}^j W_{odm}^j \xi_m \gamma_2 P^{oil} \quad (4c)$$

Here  $t_{od}^j$  represents the carbon tax per dollar of expenditure,  $f_{od}^j$  represents the fuel cost per dollar of expenditure, and  $\delta_{od}^j$  represents all other bilateral trade frictions. Equation (4a) summarizes two types of trade costs: an “iceberg” component  $(1 + f_{od}^j) \exp(\delta_{od}^j)$ ; and a carbon tax  $t_{od}^j$  which is rebated lump-sum to consumers. The carbon tax can apply to both international trade and intranational trade which has the same origin and destination country, i.e., where  $o = d$ . The costs  $\delta_{od}^j$  are difficult to observe and include tariffs, border effects, language differences, informational barriers, and other barriers to trade (Anderson and van Wincoop 2004). This functional form for fuel costs originates in Cristea, Hummels, Puzzello and Avetisyan (2013).

Equations (4b) and (4c) 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  $\kappa_{odm}$  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  $\xi_m$  represents the fuel efficiency of transportation mode  $m$ , defined in grams of CO<sub>2</sub> emitted per ton-km transported. The variable  $P^{oil}$  represents the global

oil price in dollars per barrel of crude. The variable  $t_{odm}^{j,X}$  represents the carbon tax rate for exports, measured in dollars of tax per ton of CO<sub>2</sub>, and  $t_{odm}^{j,M}$  represents the carbon tax rate for imports. The constants  $\gamma_1$  and  $\gamma_2$  convert units of measurement.<sup>2</sup> 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  $D_{odm}$ ,  $\kappa_{odm}$ ,  $W_{odm}$ , and  $\xi_{odm}$  as fixed.

This assumption allows transportation mode shares to differ by country pair and sector. So in response to increasing transport costs, consumers can purchase goods from other countries which use other transport modes. For a given country pair and sector, however, mode shares are fixed in counterfactuals. Appendix Table 5 reports the sensitivity of the paper's results to allow endogenous changes in mode shares for a country-pair-sector. The natural way to relax this assumption within this framework would be to describe multiple transport modes as a form of quality differentiation, as in Lux (2012). This approach requires data on the level of trade costs, price indices, and other model variables for all countries and sectors, which are difficult to obtain. Subsequent sections of this paper adapt an approach from Dekle, Eaton and Kortum (2008), which makes these data unnecessary, but this simplification requires holding mode shares fixed within country-pair-sector observations.

**A4. Environment.** Trade and production generate CO<sub>2</sub> emissions as follows:

$$E_d = \sum_{o,j} (\gamma_3 f_{od}^j + \chi_o^j) \frac{X_{od}^j}{p_{od}^j} \quad (5)$$

Equation (5) shows how trade contributes to carbon emissions by incorporating CO<sub>2</sub> emissions from both production and transportation. Here,  $\chi_o^j$  represents the CO<sub>2</sub> emissions per unit of output for sector  $j$  in country  $o$ , and the constant  $\gamma_3$  represents tons of CO<sub>2</sub> emitted per dollar of fuel. The ratio  $X_{od}^j/p_{od}^j$  represents the units of goods produced in country  $o$  and consumed in country  $d$ . Trade generates an environmental externality through shipping ( $f_{od}^j$ ) and through relocating production to countries with differing CO<sub>2</sub> emissions rates from production ( $\chi_o^j$ ). 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 (5) accounts for CO<sub>2</sub> emissions from all economic activity, and not merely from international trade.

Equation (5) implies that trade can affect pollution intensity (pollution emitted per unit of output) through changing the types of transportation used for trade and the locations where goods are produced. Equation (5), however, assumes there are no economically viable

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

end-of-pipe abatement technologies for CO<sub>2</sub> emissions. In response to rising shipping costs, consumers and producers can change what goods they consume, where they buy from, and how they are transported. While local pollutants like sulfur dioxide and particulate matter have end-of-pipe abatement technologies like scrubbers or bag filters, though, no such technologies exist for carbon dioxide.

## 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  $\alpha_d^j$  on sector  $j$ . In the second stage, countries allocate this expenditure across varieties within a sector according to the following “gravity” demand:

$$\lambda_{od}^j = \left( \frac{c_o^j \tau_{od}^j}{p_d^j} \right)^{\theta^j} \quad (6a)$$

Here  $\lambda_{od}^j$  represents the share of country  $d$ 's expenditure on sector  $j$  which is devoted to goods from producing country  $o$ . I use the notation  $\theta^j \equiv 1 - \sigma^j$  to highlight that the elasticity in equation (6a) does not merely represent a preference parameter, but represents the key trade elasticity of a large family of gravity models.<sup>3</sup>

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,  $R_d = \sum_{o,j} [t_{do}^{j,X} X_{do}^j / (1 + t_{do}^{j,X}) + t_{od}^{j,M} X_{od}^j / (1 + t_{od}^{j,M})]$ , 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:

$$\sum_{o,j} \frac{X_{od}^j}{1 + t_{od}^j} = \sum_{o,j} \frac{X_{do}^j}{1 + t_{do}^j} + T_d + \phi_d \quad (6b)$$

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<sup>3</sup>In Armington (1969) models, the trade elasticity represents the elasticity of substitution across national 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).

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. The parameter  $\phi_d$  measures international financial flows due to carbon taxes on exports. Formally,  $\phi_d = \sum_{o,j} X_{do}^j t_{do}^{j,X} / (1 + t_{do}^{j,X}) - \sum_{o,j} X_{od}^j t_{od}^{j,M} / (1 + t_{od}^{j,M})$ , 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

Because 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  $[I_d/P_d][\hat{V}_d - 1]$ , where

$$\hat{V}_d = \left[ \frac{\hat{I}_d}{\hat{P}_d} \right] \left[ \frac{1 + \left( \mu_d^{-1} \sum_{o=1}^N E_o \right)^2}{1 + \left( \mu_d^{-1} \sum_{o=1}^N E'_o \right)^2} \right] \quad (7)$$

The equivalent variation represents the amount a country would accept, ex ante, to end up with the same utility level that a policy change would provide. I evaluate counterfactuals by constructing empirical analogues to equation (7). I calculate the global equivalent variation of each policy as the unweighted sum of  $I_d/P_d[\hat{V}_d - 1]$  across countries.

### 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 ( $\theta^j$ ); and bilateral expenditure shares ( $\lambda_{od}^j$ ). 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 (4a). The elasticities  $\theta^j$  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  $\theta^j$  with data from specific countries and years, under assumption (1),  $\theta^j$  describes the effects of trade costs for any country and years. The data  $\lambda_{od}^j$  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 (4a), the gravity equation (6a), trade balance (6b), and social welfare (7). 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  $\theta^j$ .

Trade balance defines market equilibrium, which pins down the effect of a policy on wages. The measure of welfare is used to evaluate counterfactuals.

## 2.5 Comparison to Literature

Because this model takes an unconventional approach to analyzing environmental policy, it is useful to compare this approach to the literature. Existing approaches include reduced-form and computable general equilibrium studies. Reduced-form studies use policy evaluation methods to assess how specific regulations affected CO<sub>2</sub> emissions, then apply an estimate of the “social cost of carbon” to measure environmental benefits (Li, Linn and Spiller 2013, Holland, Hughes, Knittel and Parker 2014, Davis and Hausman Forthcoming). Compared to these analyses, the framework provides theoretical microfoundations and can analyze a wide variety of counterfactual policies. Computable general equilibrium models use substitution, supply, and demand elasticities, and assumptions to analyze comparative statics (Babiker 2005, Nijkamp, Wang and Kremers 2005, Böhringer et al. 2013). Compared to these analyses, this paper’s approach is parsimonious and its regressions and data are collected consistently with the model. Another difference is that this model uses a “gravity” framework with iceberg trade costs, which can provide equivalent welfare calculations to several richer Ricardian models, while most CGE models use a transport sector. Finally, this model builds in environmental damages, which makes it possible to analyze the incidence of environmental regulations while accounting for both differences in costs and benefits across countries.

This model also builds on studies at the intersection of trade and the environment (Antweiler et al. 2001, Copeland and Taylor 2003, Frankel and Rose 2005) by using a structural “gravity” model of trade and focusing on transportation. Much of the trade and the environment literature uses Heckscher-Ohlin or reduced-form models, analyzes pollutants like SO<sub>2</sub> which primarily affect the region where they are emitted, and focuses on production. Unlike much of this literature, this model does not describe environmental regulations as endogenous to income. I make this modelling choice both because the empirical literature on its importance is mixed (Harbaugh, Levinson and Wilson 2002) and because most benefits of abating CO<sub>2</sub> emissions accrue to foreign countries, so the effects of income growth on CO<sub>2</sub> regulations is likely to be smaller than for local pollutants like SO<sub>2</sub> (Cole and Elliott 2003).

Finally, the model uses methods from a literature which develops robust approaches to measuring the gains from international trade, and is sometimes described as the “structural gravity” literature (Eaton and Kortum 2002, Alvarez and Lucas 2007, Dekle et al. 2008, Head and Mayer 2014). The model builds on this literature by accounting for the environmental costs of trade due to CO<sub>2</sub>.

### 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<sub>2</sub> Emissions from Trade

Measuring CO<sub>2</sub> emissions as described in equations (4c) and (5) requires data on distances, transport mode shares, weight-to-value ratios, fuel efficiency, and production emission rates.

**Intranational and International Distances** I measure intranational and international distances by applying geographic information system techniques to a detailed dataset of population locations. The History Database of the Global Environment (HYDE) Version 3.1 measures population data for the year 2000 (Goldewijk et al. 2011). HYDE combines a variety of underlying datasets to measure population separately for about 3 million gridded points across the Earth’s landmasses.

I measure distances between and within countries with a single method. For both international and intranational trade, the distance is measured as  $D_{od} = \sum_{i \in G_o} \sum_{j \in G_d} \frac{p_i}{P_o} \frac{p_j}{P_d} d_{ij}$ . Here  $p_i$  and  $p_j$  are the total population of grid cells  $i$  and  $j$ ,  $G_o$  and  $G_d$  are the sets of cells in countries  $o$  and  $d$ ,  $P_o$  and  $P_d$  are the total populations of countries  $o$  and  $d$ , and  $d_{ij}$  is the shortest path on the Earth’s surface (the “great circle” distance) between points  $i$  and  $j$ . This calculation represents the most accurate approach that I can discern to measure population-weighted distances between each country pair and within each country. Many researchers use international and international distance data from the Center for International Prospective Studies (CEPII), which provides data on intranational and international distances ( $D_{odm}$ ) for air, rail, and road trade (Mayer and Zignago 2005). These data account for define intranational distances as  $0.67\sqrt{area/\pi}$  (Head and Mayer 2010) or account for the largest cities in each country.

Measuring transportation fuel costs requires estimates of distances for maritime trade. These distances differ from the  $D_{od}$  measure described above because ships travel through ports, cannot go overland, and hence do not follow the shortest paths on the Earth’s surface (they do not reflect great circle distances). Geographic information system (GIS) files from the Environmental Systems Research Institute (ESRI) describe the locations of all major global ports and land masses. To measure distances between ports 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 pair of ports in the world, which measures the sea distance between their respective countries. A country can have many sea ports. I assume that the share of a country’s trade which flows through a given port equals the share of the country’s population for which that port is closest. Finally,

I apply the same equation  $D_{od} = \sum_{i \in G_o} \sum_{j \in G_d} \frac{p_i}{P_o} \frac{p_j}{P_d} d_{ij}$ , but now  $d_{ij}$  measures distances by sea (as measured by the Floyd-Warshall algorithm),  $p_i$  and  $p_j$  the population closest to ports  $i$  and  $j$ , and  $G_o$  and  $G_d$  are the set of ports within a country.

**Mode Shares.** Data on the share of goods transported by each mode ( $\kappa_{odm}^j$ ) 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 international 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 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 and for all intranational trade flows where data do not report them, and for intranational trade mode shares (see Appendix A.1 for details). 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. OLS and Tobit fitted values for each mode, for example, need not lie in the  $[0, 1]$  interval, even when adding-up constraints require shares to sum to one. Beta and Dirichlet distributions are not used because they exclude the values 0 and 1, but those values appear regularly in the data.

**Other Data for CO<sub>2</sub> Emissions from Trade.** Appendix C describes several other components of these data which are more common to the literature. These include weight-to-value ratios, fuel efficiency, and CO<sub>2</sub> emissions from production. One important paper (Cristea et al. 2013) has compiled similar data, and this study builds on their work in several ways. I calculate fuel consumption for both international and domestic shipping. 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<sub>2</sub> emissions from airplane trade is about three times the values from the International Energy Agency or other organizations estimate, while my estimate is close to these organizations’ estimates. The number in Cristea et al. matches published estimates of total CO<sub>2</sub> from all air transportation, but their estimate only represents freight, which accounts for only a third of all air ton-km transportation (IATA 2009).

### 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. 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. 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<sub>2</sub> emissions from production for the year 2007 from GTAP. These data report values for 128 countries and 57 sectors. The data include all world production, but small countries are combined due to data limitations. 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 this paper cannot estimate is  $\mu_d$ , which is isomorphic to the social marginal cost of CO<sub>2</sub> emissions. Equivalently, this parameter represents the present discounted value of the change in current and future welfare due to emitting one additional ton of CO<sub>2</sub>. The paper does not estimate this parameter because  $\mu_d$  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<sub>2</sub> emissions into climate change, and the trends and discounting of these values over future centuries to obtain their present value.

I choose the values of  $\mu_d$  so that a one ton increase in CO<sub>2</sub> emissions decreases global GDP by \$29. Specifically, I differentiate equation (2) with respect to  $\sum E_o$ , then solve for the values of  $\mu_d$  which make the marginal global social cost of carbon equal \$29. Appendix Table 5 studies alternative numbers for this value. The \$29 figure reflects the most recent estimate of the marginal social cost of CO<sub>2</sub> emissions by an interagency panel of the US government (Interagency Working Group on the Social Cost of Carbon 2013), which bases its analysis on three integrated assessment models (FUND, DICE, and PAGE). The calculation assumes a 3 percent discount rate. For each counterfactual, I set the carbon tax rate equal to this social cost of carbon. I also investigate how key results for each of the paper's counterfactuals change with a social cost of carbon of \$11 or \$77. The low value of \$11 per ton of CO<sub>2</sub> reflects a 5% discount rate, and the high value of \$77 represents the top quantile of values measured from the integrated assessment models with a discount rate of 3% Interagency Working Group on the Social Cost of Carbon (2013). For comparison, I also investigate the

consequences of assuming that climate damages  $\mu_d$  are homogenous across countries. Finally, I investigate the consequences of a version of the DICE model with risk-averse policymakers, tipping points, and large and uncertain potential impacts of climate change (Cai, Judd and Lontzek 2012), who obtain an estimate of the social cost of carbon of \$200.

To assign the global cost of carbon emissions to individual countries, I choose  $\mu_d$  so that the global impact of marginal increases in CO<sub>2</sub> emissions is \$29/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) (see Appendix A.6 for details). I also report results assuming that the damages of carbon emissions are proportional across countries.

## 4 CO<sub>2</sub> Emissions from Trade

This paper compiles data on the CO<sub>2</sub> emissions from shipping because these data are necessary to apply the model. This section describes salient facts from these data because they provide novel evidence on how shipping contributes to carbon emissions.

The CO<sub>2</sub> emissions due to production of traded goods and due to international transportation have similar orders of magnitude. International shipping emitted 1.3 gigatons of CO<sub>2</sub> in the year 2007, domestic shipping emitted 1.6 gigatons, the production of traded goods emitted 1.2 gigatons, and the production of nontraded goods emitted 25.4 gigatons (Table 1). In total, I calculate global CO<sub>2</sub> emissions in 2007 of 29.4 gigatons. Other sources report similar global estimates (Boden, Marland and Andres 2010, IEA 2011). Goods production is responsible for about 90 percent of global CO<sub>2</sub> emissions.

Differences in CO<sub>2</sub> 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 disproportionately trade technological goods with low weight-to-value ratios. Poorer regions generally trade in heavy mining and agricultural goods. 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 may experience the largest relative effects of rising shipping costs.

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. Airplanes emit nearly 100 times as much CO<sub>2</sub> as ships do to move one ton-km (Appendix Table 1). In part because air shipment is so costly, road trade accounts for most freight—trucks account for 63 percent of all CO<sub>2</sub> emissions due to shipping (Table 1).

These estimates build on existing work. Some research uses reports of shipping costs (Hertel et al. 2007), 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 et al. 2013). A literature focused on multi-region input-output matrices provides accounting measures of international CO<sub>2</sub> flows (e.g., (Davis and Caldeira 2010)), but does not allow prices or wages to change in counterfactuals.

## 5 Estimation of Trade Elasticities

### 5.1 Methodology: Trade Elasticities

Substituting equation (4a) into (6a) and taking logs gives an equation like the following:

$$\log \lambda_{ody}^j = \theta^j \log(1 + s_{ody}^j) + c_{oy}^j + p_{dy}^j + \delta_{od}^j + \epsilon_{ody}^j \quad (8)$$

This equation builds on the model by allowing trade flows and prices to vary by year  $y$ . It also allows for idiosyncratic innovations  $\epsilon_{ody}$  in the unobserved component of trade costs,  $\delta_{od}$ . Additionally,  $s_{ody}$  here represents the total shipping cost (including fuel and non-fuel components), which can be proportional to fuel costs under assumptions (4a) and (4c).

An OLS estimate of equation (8) has two challenges. First, it omits variables like non-pecuniary trade barriers, wages, and prices. Such barriers are associated with greater shipping costs and lower trade flows, introducing negative bias in the OLS estimate of  $\theta^j$ . A second is measurement error in shipping costs  $s_{ody}$ , which occurs due to sector, exporter, and date misclassification, inaccurate currency conversion, and simple reporting errors. 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, Trefler 1995, Limao and Venables 2001, Hummels and Lugovskyy 2006). Note that many bilateral trade frictions are not part of the shipping cost  $s_{ody}$ , and are contained in the bilateral terms  $\delta_{od}$  and  $\epsilon_{ody}$ . Such multiplicative trade frictions do not represent a source of measurement error in shipping costs  $s$ , but rather represent separate terms of the total multiplicative trade cost. Classical measurement error attenuates OLS estimates of  $\theta$ .

To address omitted variables bias, I estimate equation (8) while including exporter-by-year fixed effects to control for production costs  $c_{oy}^j$ , importer-by-year fixed effects to control for destination prices  $p_{dy}^j$ , and country-pair fixed effects  $\delta_{od}^j$  to control for time-invariant components of trade costs like distance. While the end of this section discusses related estimates, I am not aware of other studies using panel data and observed trade barriers to estimate the trade elasticity  $\theta^j$ .

Unfortunately, using fixed effects with panel data can exacerbate attenuation bias (Griliches

and Hausman 1986). In classic errors-in-variables, the problem is that the OLS estimator converges to the true parameter times the signal-to-noise ratio, and fixed effects can decrease the signal-to-noise ratio. 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). 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. These instrumental variables do not represent a natural experiment, but rather they are exclusively designed to address measurement error (Ashenfelter and Krueger 1994). Any quarters can be used as instruments, though in the presence of trends in shipping costs, using the second and third quarters to construct instruments may be stronger since they are centered around the middle of the year. Later I discuss use of alternative quarters as instruments.

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, Berger and Scott 2000), and Dustmann and Soest (2002) use a related approach to mine, albeit in a labor economics setting. I emphasize that this use of instrumental variables is not a natural experiment designed to address reverse causality or omitted variables bias; rather, it uses multiple reports of a variable to address measurement error.

If measurement error in the two samples is independent, then the following instrumental variables model will provide a consistent estimator of  $\theta^j$ :

$$\log \lambda_{ody}^j = \theta^j \log(1 + s_{ody}^{j,B}) + \eta_{oy}^{j,B} + \zeta_{dy}^{j,B} + \delta_{od}^{j,B} + \epsilon_{ody}^{j,B} \quad (9)$$

$$\log(1 + s_{ody}^{j,B}) = \beta^j \log(1 + s_{ody}^{j,A}) + \eta_{oy}^{j,A} + \zeta_{dy}^{j,A} + \delta_{od}^{j,A} + \epsilon_{ody}^{j,A} \quad (10)$$

Here  $s_{ody}^{j,A}$  represents a measure of shipping costs from quarters 2 and 3, and  $s_{ody}^{j,B}$  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 (9) will still suffer from some attenuation bias, albeit less severe than in the fixed effects estimates (Black et al. 2000).

These fixed effects address several important threats to internal validity. One is reverse causality: the scale of a country's trade may affect its shipping costs. Another is omitted variables: distance, port quality, prices, wages, and other variables may affect trade and

correlate with shipping costs. The fixed effects control for all sources of reverse causality or omitted variables which operate at the origin-by-year, destination-by-year, and origin-by-destination levels.

The variation in shipping costs which identifies the trade elasticities include all components of the gravity equation that vary at the origin-by-destination-by-year 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  $s_{ody}^B$  (Feyrer 2009a, Feyrer 2009b). In principle, one could use these changes as instrumental variables for  $1 + s_{ody}$ . Apart from the shipping cost instruments I use, however, I am not aware of strong instruments for the 13 tradable sectors and two importers in the 20 years I analyze. Any force which varies at the origin-by-destination-by-year level, affects trade flows, and correlates with shipping costs also represents a remaining potential threat to internal validity. One example is time-varying bilateral trade policies like tariffs. Appendix Table 3 finds that controlling for tariffs obtains sector-by-sector estimates which have a correlation of 88 percent with the main results. Appendix Table 5 finds that the paper’s welfare analysis is extremely similar when based on trade elasticity regressions that include tariff controls.

Overall, a benefit of the empirical strategy is that the estimates of the trade elasticity are not specific to one event where trade costs changed, and hence can increase external validity. Because I do not use a natural experiment to estimate these elasticities, however, I cannot specify the exact source of variation which drives them.

Finally, these panel data may have autocorrelation, so I report standard errors adjusted for clustering within trading partners (Bertrand, Dufflo 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 1 percent decrease in trade costs causes a 21 percent increase in bilateral trade flows. This represents extraordinarily elastic bilateral demand. This OLS estimate is so negative because it does not control for any other trade costs—it is a correlation of bilateral trade costs with bilateral trade flows. It suffers from cross-sectional omitted variables like distance and language barriers which are correlated with shipping costs and which directly decrease trade flows. It also suffers from time-series omitted variables, since trade costs have been falling over time but trade flows have been rising over time. These omitted variables all suggest that the OLS estimate of  $\theta$  is biased downwards (i.e., too negative).

Using detailed fixed effects as in equation (8) helps address omitted variables bias but may exacerbate attenuation bias (Table 2). The bilateral origin-by-destination fixed effects remove all time-invariant determinants of trade flows like distance and language which are correlated with bilateral shipping costs. The origin-by-year and destination-by-year fixed

effects adjust for all time-series omitted variables such as changes in global trade costs or country-specific trade costs. As discussed earlier, however, if shipping costs are measured with error, then including origin-by-year, destination-by-year, and origin-by-destination fixed effects will decrease the signal-to-noise ratio of the fixed effects regression and obtain an estimate which suffers from attenuation bias (i.e., less negative than the truth). The fixed effect estimate for the entire economy is  $\theta = -3.7$ , which is much less negative than the OLS.

In the instrumental variables regressions, most instruments have a first-stage F-statistic above the 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, column 4). The mean across sectors is  $\theta = -8.16$ .

Alternative assumptions obtain similar patterns of point estimates (Appendix Table 3). In these analyses, the first-stage regressions for an economy-wide elasticity are weaker, and the reduced-form estimates range more widely. Since I only use sector-specific estimates in counterfactuals, I focus on those here. The main results use the second and third quarters to construct the instruments. Using the first and fourth quarter to construct the instruments (i.e., switching the set of instruments and the endogenous variable) obtains an average elasticity across sectors of -8.3 (compared to the main estimate of -8.2) and sector-by-sector correlation with the main estimates of 0.85 (Appendix Table 3, Column 1). Using other quarters for the regression gives similar results (Appendix Table 3, Column 2). I also re-estimate the regressions using generalized least squares with weights proportional to total expenditures (i.e., proportional to the denominator of the dependent variable), which provides an efficient response to heteroskedasticity but which estimates an elasticity for the mean dollar of expenditure rather than for the mean trade flow. This also obtains a mean elasticity across sectors of -8.97 and a sector-by-sector correlation with the main estimates of 0.87 (Appendix Table 3, Column 3).

I also consider two other sensitivity analyses. Replacing the dependent variable for cases with no trade flows with the log of a small number obtains a mean elasticity across sectors of -8.97, and a sector-by-sector correlation with the main estimates of 0.88 (Appendix Table 3, Column 4). Additionally, I investigate including tariffs in shipping costs, and in a separate set of regressions, by controlling for tariffs in the regressions (Appendix Table 3, columns 5 and 6). These regressions obtain a mean across sectors of -9.90 and -8.45, with sector-by-sector correlations with the main estimates of 0.88 and 0.86.

I investigate the importance of the instrumenting strategy by taking a simpler approach to address measurement error—I aggregate the data to the full year and estimate the fixed effects model of equation (8), without instruments (Appendix Table 3, Column 7). These regressions give an average elasticity across sectors of -3.95 and a range from -1.19 to -7.33. Additionally, I consider a pooled cross-section estimate of the trade elasticity, which I obtain by estimating the full-year dataset while including origin fixed effects, destination fixed effects,

and year fixed effects. In this cross-sectional estimate, the mean elasticity across sectors is -6.26 and a sector-by-sector correlation of 76 percent with the main results.

Section 8.2 re-estimates all the counterfactuals separately using each of the elasticities in columns (1) through (6) and finds that the paper’s main qualitative conclusions and the magnitude of the welfare calculations are similar with these alternatives estimates of the trade elasticities.

I evaluate the estimates of trade elasticities with a simple test: theory predicts that demand should be more elastic for more homogenous goods. I find that the pattern of elasticities across sectors is consistent with this theoretical prediction. See Appendix B for additional detail.

## 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. This autarky counterfactual is unrealistic, but provides an important benchmark which is common in research. The autarky counterfactual is also useful because it provides a sense of the magnitudes of the environmental costs of trade reform due to CO<sub>2</sub>. A leading undergraduate trade textbook, for example, laments how China’s opening to trade has contributed to climate change but hypothesizes that those environmental costs due to CO<sub>2</sub> are small relative to trade’s economic benefits (Krugman, Obstfeld and Melitz 2012, p. 287). Without studying every possible counterfactual of interest, looking at autarky provides a starting point for this kind of question to think about the relative magnitudes of international trade liberalization’s benefits and its environmental costs due to CO<sub>2</sub>.

### 6.1 Methodology: Costs and Benefits of International Trade

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 (7). 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  $d$ :

$$A_d = \left[ \prod_{j=1}^J \left( \lambda_{dd}^j \right)^{-\frac{\alpha_d^j}{\beta_d^j \theta_d^j}} \right] \left[ \frac{1 + \left( \mu_d^{-1} \sum_{o=1}^N E_o \right)^2}{1 + \left( \mu_d^{-1} \sum_{o=1}^N E'_o \right)^2} \right] \quad (11)$$

In equation (11), the effect of moving a country to autarky equals the diminished gains from trade multiplied by the change in the environmental costs of trade due to CO<sub>2</sub>. I aggregate across countries to measure the global welfare effect if all of the world's countries went to autarky.

It may be useful to explain conceptually how equation (11) interprets the vast changes in production and consumption that would take place because of autarky. The key insight is that in a model with one sector and no intermediate goods, the share of a country's expenditure which comes from domestic production,  $\lambda_{dd}$ , combined with the trade elasticity,  $\theta$ , is sufficient to describe how sending a country to autarky affects its real income. This share  $\lambda_{dd}$  equals one minus the import penetration ratio. This idea is emphasized in Eaton and Kortum (2002) and expanded in Arkolakis et al. (2012). This result applies to both the Armington model described in this paper and also for a variety of other gravity models. The other terms in equation apply to the more detailed features of this model—the multiplying across sectors  $j$  each with exponent  $\alpha$  accounts for multiple sectors, and dividing by the sector-specific ratio of intermediate to final goods  $\beta$  accounts for intermediate goods. The first term in brackets represents the change in real income due to autarky, and the second term in brackets represents the change in environmental damages due to autarky.

Equation (11) has an appealing feature: all terms in it are parameters or simple-to-calculate numbers, as opposed to complicated equilibrium objects that require solving a fixed point problem. The counterfactual of autarky permits this straightforward calculation because the domestic expenditure share under autarky is one by definition (i.e.,  $\lambda'_{dd} = 1$ ).

The only term in equation (11) which I have not previously explained is  $E'_o$ , representing the CO<sub>2</sub> emissions from country  $o$  in autarky. But  $E'_o$  can also be calculated as a function of observed data. This calculation for  $E'_o$  reflects the following algebra. By assumption (5) and the counterfactual of autarky, we have  $E'_d = \sum_j (\gamma_3 f_{dd}^j + \chi_d^j) X_{dd}^j \hat{X}_{dd}^j / (p_{dd}^j \hat{p}_{dd}^j)$ . With the wage in country  $d$  as numéraire, we have  $\hat{X}_{dd}^j = \beta_d^j X_d / X_{dd}^j$ . 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 (11) 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 (5) gives

$$E'_d = \sum_j (\gamma_3 f_{dd}^j + \chi_d^j) (\beta_d^j X_d) (\lambda_{dd}^j)^{-(1-\beta_d^j)/(\beta_d^j \theta_d^j)} \quad (12)$$

Economic intuition for this measure of CO<sub>2</sub> emissions in autarky is as follows. The emissions data  $f_{dd}^j$  and  $\chi_d^j$  indicate the intensity of carbon emissions from domestic transportation and production, respectively. The remaining terms describe the level of production in autarky.  $\beta_d^j X_d$  describes expenditure in the baseline data, and the  $\lambda_{dd}$  term summarizes the effect on output of going to autarky. The role of the term  $\lambda_{dd}^j$  is similar to that in Arkolakis et al. (2012). Importantly, all of the terms on the right-hand side of equation (12) are observed

in the baseline data, i.e., none has an apostrophe (') or represents a number only observed in a counterfactual. Consequently, calculating CO<sub>2</sub> emissions in autarky requires substituting the data and parameters into the right-hand side of equation (12).

To perform inference on outputs of the model (e.g., on the effects of a counterfactual on output, trade, or welfare), I conduct a bootstrap over the term of the model which has an estimated sampling distribution,  $\theta^j$ , and report the resulting 95-percent confidence interval. In practice, separately for each sector  $j$ , I take 200 draws from a normal distribution which has mean equal to the estimated trade elasticity for that sector  $\theta^j$  and standard deviation equal to the estimated standard error of the trade elasticity for that sector. I then obtain 200 estimates of the model output of interest (e.g., a welfare change), each corresponding to one of the 200 sets of trade elasticities. Finally, I report the 95 percent confidence region implied by those 200 model outputs. I report the bias-corrected confidence region, which provides a more accurate finite-sample approximation than the unadjusted 95 percent confidence region does. Efron (1987) describes the rationale and methodology for the bias-corrected bootstrap; Appendix C describes this paper's implementation of this methodology in more detail.

## 6.2 Results: Costs and Benefits of International Trade

Table 3 lists global and regional aggregates, Figure 1 shows a map depicting values for each country in the world, and Appendix Table 6 lists country-by-country values. The analysis provides three results. 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<sub>2</sub> emissions by 5 percent (1.7 gigatons of CO<sub>2</sub> annually). Globally this effect is almost equally driven by production and transportation. This is notable since autarky only directly affects shipping. I emphasize that while much of this paper focuses on CO<sub>2</sub> emissions from international shipping, the autarky counterfactual in this section accounts for changes in CO<sub>2</sub> emissions from international shipping, domestic shipping, and production which result from shutting off international trade.

Second, the gains from international trade exceed the environmental costs of international trade due to CO<sub>2</sub> emissions by a factor of 161 (i.e., by two orders of magnitude; see Figure 1). The gains from international trade exceed the environmental costs of trade due to CO<sub>2</sub> in every country. The global gains from international trade, at \$5.5 trillion, equal 10 percent of global GDP. The environmental costs of international trade due to CO<sub>2</sub> equal \$34 billion. At a country level, the smallest gains from trade exceed the biggest environmental costs of trade due to CO<sub>2</sub>.

Because international shipping accounts for a relatively small share of global CO<sub>2</sub> emissions, it might seem unsurprising that international trade has such small effects on carbon emissions. But international trade affects the location and magnitude of both production

and transportation, which collectively account for most of the world’s CO<sub>2</sub> emissions. So ex ante, there is considerable potential for international trade to have large effects on climate change.

Third, a global analysis masks heterogeneity across countries (Figure 1). Unsurprisingly, 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 confidence regions exclude zero.

It is worth commenting on the confidence regions here, since none of the burgeoning recent “structural gravity” literature in trade provides confidence regions for welfare calculations. Lai and Treffer (2002) and Hertel et al. (2007), which use different frameworks from this gravity literature, use other methods than those described here to calculate confidence regions for the gains from trade. Confidence regions are important because a recent debate has emerged about the magnitude of the gains from trade (Arkolakis et al. 2012, Ossa 2014), and the confidence region indicate whether one can conclude that welfare calculations from one model differ from another.

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

I now turn to a very different type of counterfactual—EU, US, and global regulations which use targeted policy to address the environmental externalities of trade. As discussed in the introduction, while this paper’s framework could be applied to many types of regulation, this paper studies transportation for three reasons. First, these policies 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<sub>2</sub> from this sector is growing at nearly double the rate of the rest of the global economy.

### 7.1 Regulation Details

I use the model to analyze stylized versions of the EU, US, and global policies. The EU’s Emissions Trading System (ETS) sets an EU-wide cap for regulated CO<sub>2</sub> emissions, distributes CO<sub>2</sub> “allowances” to firms, then lets firms buy and sell those allowances. Each year, a regulated firm must provide the EU with allowances to cover their regulated CO<sub>2</sub> emissions. In 2011, the ETS regulated CO<sub>2</sub> emissions from five industries: 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. Each airline

with flights landing in or departing from a country affected by the EU ETS would have to record its carbon emissions from the each flight leg that landed in or departed from the EU. At the end of each year, each airline would then have to provide the EU with allowance to cover their regulated CO<sub>2</sub> emissions. Challenges from other countries delayed the addition of airplane emissions to the ETS.

This paper’s EU counterfactual represents a stylized version of the EU ETS. Like the ETS, I consider the regulation of CO<sub>2</sub> emissions from airplane flights involving the 30 countries participating in the EU ETS. The ETS regulates all airplane transportation, whereas I include only shipping. Globally, the International Air Transportation Association estimates the shipping accounts for about a third of global ton-km, while passengers account for about two-thirds. Finally, the EU 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<sub>2</sub> 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<sub>2</sub> emissions. The bill included refineries’ petroleum products and fuel imports in the CO<sub>2</sub> 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<sub>2</sub> emissions from imports and exports. Moreover, I focus on the regulation of goods and not passenger transportation.

The third counterfactual analyzes the regulation of all domestic and international airborne and maritime shipping. The EU has vocally advocated for the implementation of such a policy in the last few years, and the relevant UN agencies (the International Civil Aviation Organization and the International Maritime Organization, or ICAO and IMO) have been negotiating the details of such policies. In October 2013, ICAO members committed to implement a global market-based mechanism to regulate airplane carbon emissions by the year 2020. These plans are not new—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.

## **7.2 Methodology: Effects of EU, US, and Global Carbon Taxes on Shipping**

Measuring the effects of these climate change regulations requires constructing an empirical analogue to the equivalent variation from equation (7). 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  $\hat{w}_d$ :

$$\sum_{o,j} \frac{X_{od}^{j'}(\hat{w}_d)}{1 + t_{od}^j} = \sum_{o,j} \frac{X_{do}^{j'}(\hat{w}_d)}{1 + t_{do}^j} + \phi_d^{j'} + T_d \quad (13)$$

Here the matrix  $X_{od}^{j'}(\hat{w}_d)$  is a known function of observed data and of the wage changes  $\hat{w}_d$  (see Appendix D). Every term in (13) is observed in data or is a known function of the vector of country-level wage changes due to a carbon tax,  $\hat{w}_d$ . The carbon tax  $t_{od}$  can apply to both international trade, where  $o \neq d$ , and to intranational trade, where  $o = d$ .

I solve this system for equilibrium wages, with numéraire chosen so  $\sum_d w_d L_d = \sum_d w'_d L_d$ . Appendix D shows the step-by-step algorithm. Conceptually, this algorithm resembles that of many general equilibrium models—it solves a system of nonlinear equations to find the prices which achieve a competitive equilibrium in a counterfactual. Trade, production, pollution and welfare are functions of those prices which are derived earlier (and referenced in the algorithm).

For each carbon tax, a shock is introduced by changing the value of the carbon tax ( $t_{odm}^{jX}, t_{odm}^{jM}$ ) from \$0 to \$29 per ton of CO<sub>2</sub>. As discussed in section 3.3, \$29 reflects a leading estimate of the social cost of CO<sub>2</sub> emissions. Appendix A.6 explains how I allocate the global damage to each country—essentially I use estimate from the RICE model of region-specific damages of climate change, and scale these estimates so the global damage is \$29 per ton but the region-specific damages are proportional to those estimated in the RICE model. An important reason for this regional scaling is to reflect the idea that climate change may disproportionately hurt India, Africa, and certain other regions of the world (see also Figure 1).

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

In these calculations, inference is conducted using a bias-corrected bootstrap with 200 replications over IV estimates of  $\theta^j$ , as described in section 6.1.

An interesting question is whether this model has a unique equilibrium. Numerically, I studied this by trying a variety of starting values for the candidate wage vector  $\hat{w}_d$ . All converged to the same equilibrium. While the main results use a trust-region dogleg algorithm to solve the system of equations in step 4, I also tried a trust-region reflexive algorithm and a Levenberg-Marquardt algorithm. These also converged to the same equilibrium. Algebraically, a general version of this model with a single sector and no intermediates is known to have a unique competitive equilibrium (Alvarez and Lucas 2007).

### 7.3 Results: EU, US, and Global Policy Counterfactuals

Table 4 describes the effects of the three policies in three separate panels, Figure 2 plots these results, and Appendix Table 6 lists values country-by-country. Each panel of Table 4 lists the effect on welfare for several groups of countries: the world; the EU and US; and the richest, middle, and poorest third of countries, measured according to their GDP per capita in 2007. Table 4 suggests three interesting conclusions.

First, Column 3 of Table 4 shows that all three counterfactual policies increase social welfare globally, albeit by small amounts. In each case, the gains from trade fall slightly, but the environmental costs of trade due to CO<sub>2</sub> fall even more. In total, social welfare increases by about \$1 billion over a decade for the EU policy, \$7 billion for the US policy, and \$10 billion for a global policy. While these effects are positive, they are small in magnitude and do not exceed two tenths of a basis point relative to baseline levels of global income. While the median country is actually harmed by the regional policies (as can be seen by the negative values for Figure 2, Panels A and B), the positive benefits to GDP in the implementing region more than offset these losses elsewhere.

Second, Column 1 of Table 4 shows that the EU policy increases the EU's gains from trade and the US policy increases the US' gains from trade, even before accounting for environmental benefits. This means that these regions are obtaining direct economic benefits from these environmental policies. This feature makes these policies unlike almost any other environmental regulation. Many environmental policies decrease manufacturing activity or increase energy prices, and those economic costs can then be weighed against cleaner air, healthier children, and other environmental benefits. But the private benefits of the EU and US counterfactuals in this paper show that these policies do not behave like other environmental regulations—these policies provide economic benefits to the implementing region, even ignoring environmental consequences. This result occurs because these regulations act like a unilateral tariff which improves a country's terms of trade at the expense of its trading partners. While it has been long known in trade that strategic trade policy can redistribute income, Table 4 shows that these environmental policies are achieving the same result.

Because the US and EU policies provide a terms-of-trade gain to wealthy countries, they are predisposed to benefit rich countries more than poor countries. Hence, it is likely that if a large but poor country like China or India imposed the kind of policy I analyze, it would obtain a terms-of-trade gain at the expense of its trading partners. I do not analyze such policies because no country has seriously proposed them. But it is possible that such policies, like small tariffs, could benefit poor countries at the expense of their wealthier trading partners.

The terms-of-trade argument applies to international tariffs, but this is a policy which applies to both international and intranational trade. The reason the terms-of-trade effects appear here is that international trade is far more fuel-intensive than is intranational trade.

This is both because the mean distance that goods travel (either averaged across countries and sectors, or using a trade value-weighted average) is several times greater for international than for intranational trade, and because international trade is several times more likely to use air transportation than is intranational trade. Air transportation consumes far more fuel per ton-km than any other mode. So although the carbon regulations appear neutrally applied both to intranational and to international trade, they have much larger effective rates on international trade since it is more fuel-intensive.

Third, Table 4 shows that these regulations benefit wealthy countries but actually decrease welfare in poor countries. This table, like several others, demarcates three groups of countries: the richest third, which had 2007 GDP per capita above \$14,000; the middle third, which had 2007 GDP per capita of \$2,400 to \$14,000; and the bottom third, which had 2007 GDP per capita below \$2,400. The global policy increases welfare in the richest third of countries by half a basis point, decreases welfare in the middle third of countries by three quarters of a basis point, and decreases welfare in the poorest third of countries by 1.3 basis points. The EU and US counterfactual policies generate similar patterns but with smaller magnitude effects.

Existing literature to compare these results against is limited. 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.

The findings of this paper's two sets of counterfactuals contrast somewhat. The first counterfactual suggests that international trade's total benefits exceed trade's total environmental costs due to CO<sub>2</sub>. The second counterfactual suggests that modest climate change regulations focused on international trade have environmental benefits that exceed their economic costs. Two reasons account for this contrast. One is that the climate change regulations are proportional to the environmental externality generated, whereas broad and unfocused changes to trade like autarky are not. An efficient Pigouvian tax should equal the marginal external cost of an activity, and the climate change regulations approximate this tax (although they do not cover all sectors) while broad changes to trade do not. A second reason is that the climate change regulations behave like a small tariff. Standard analysis from international trade argues that modest levels of such tariffs up to some optimum increase welfare for the country imposing the tariff, but tariffs that are too large decrease the country's welfare. This second reason suggests that climate change policies have nonlinear consequences for welfare.

## 8 Extensions and Robustness

I consider several types of sensitivity analyses, which largely reaffirm the paper's general conclusions. The paper's main qualitative conclusions persist under these alternatives – in

each case, countries with high GDP per capita benefit more than countries with low GDP per capita do, and the implementing region (EU or US) experiences a welfare gain while other countries experience a welfare loss. Appendix Tables 4 and 5 present results for autarky and for the specific regulations, respectively. For environmental assumptions, I consider the range of social costs of CO<sub>2</sub> from \$11 to \$77 estimated in the Interagency Working Group on the Social Cost of Carbon (2013), the assumption that climate damages  $\mu_d$  are proportional across countries, and an estimate of the social cost of carbon of \$200 from a model with tipping points and potential catastrophe (Cai et al. 2012). Because we have no measures of the geographic incidence of climate change costs in that counterfactual, I assume the costs are proportional across countries.

I also analyze the effects of alternative trade assumptions. The magnitudes of these patterns do vary across the alternatives. For example, the welfare benefit to the EU of including airplanes in the EU ETS is about \$29 billion in the main estimates. This figure jumps slightly to \$32 billion with trade elasticities of -4.1 in every sector rather than by using the main trade elasticity estimates. This table considers a variety of such alternatives, including trade elasticities for each sector of  $\theta = -4.14$  or  $\theta = -8.28$  (Simonovska and Waugh 2014, Eaton and Kortum 2002), the range of trade elasticities estimated in Appendix Table 3, the sensitivity of model results to allowing endogenous changes in mode shares,<sup>4</sup> and a counterfactual which accounts for complete detailed input-output links between industries (Caliendo and Parro 2015). The last sensitivity analysis incorporates the full input-output matrix for each country as reported in the GTAP data.<sup>5</sup>

## 9 Conclusion

This paper seeks to contribute to research on trade and the environment in three ways. First, it builds on recent trade research to develop a new approach to evaluating environmental regulation. The paper wed a structural general equilibrium model with reduced-form estimates of key parameters. This approach has similar spirit to the literature on “sufficient statistics

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<sup>4</sup>Row 15 of Appendix Table 5 assumes that the elasticity of a mode’s share with respect to its price is minus one, and that transportation is reallocated across other modes in proportion to their baseline shares.

<sup>5</sup>It is worth mentioning some features of the global economy which are left for future work. Research on outsourcing and environmental regulation is in its infancy (though see work by Li and Zhou (2015)) and an important future question is how they interact. A related issue is market structure—how would allowing for endogenous markups or more general market structure affect this kind of analysis? A third abstraction is feedback from climate to economic activity. In some sectors, such as agriculture, the effect of climate on trade and production is relatively well understood (Costinot, Donaldson and Smith Forthcoming). In others like extreme weather and manufacturing, this relationship is poorly understood. In still others like human health, it is natural to think of climate directly affecting utility, consumption, or labor supply, but the effect by sector and country is unclear. Finally, this analysis abstracts from existing revenue-raising tariffs. While tariff revenue is a small portion of government revenue in most countries, the interaction of strategic trade policy and strategic environmental policy is a potentially fruitful area for future study.

for welfare analysis” (Chetty 2009). 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.

Second, this paper compares international trade’s benefits against its environmental costs due to CO<sub>2</sub> in a unified theoretical and empirical framework. The gains from international trade exceed the environmental costs of international trade by two orders of magnitude. These magnitudes have not been previously compared, and they suggest that while broad liberalization of international may create environmental costs due to additional CO<sub>2</sub> emissions, the magnitude of those costs are small relative to trade’s benefits.

Third, this paper analyzes the incidence and aggregate welfare effects of proposed regulations on the carbon emissions from shipping. 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<sub>2</sub> emissions from some forms of shipping. Poor countries specialized in trading goods with high weight-to-value ratios, 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<sub>2</sub> 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. Because these policies increase global welfare, they represent a potential Pareto improvement, and there exists a set of transfers from rich to poor countries which would make these policies benefit all countries.

This paper focuses on climate change to the exclusion of other kinds of pollution, and it emphasizes Ricardian models focused on perfect competition and technology differences. The analysis of “local” pollutants like particulate matter or sulfur dioxide and the analysis of imperfectly competitive firms have the potential to reveal new insights about environmental regulation (Shapiro and Walker 2015).

## References

- Alvarez, Fernando and Robert E. Lucas**, “General equilibrium analysis of the Eaton-Kortum model of international trade,” *Journal of Monetary Economics*, 2007, 54, 1726–1768.
- Anderson, James E. and Eric van Wincoop**, “Trade Costs,” *Journal of Economic Literature*, 2004, 42(3), 691–751.
- Antweiler, Werner, Brian R. Copeland, and M. Scott Taylor**, “Is Free Trade Good

- for the Environment?,” *American Economic Review*, 2001, *91*(4), 877–908.
- Arellano, Manuel and Stephen Bond**, “Some Tests of Specification for Panel Data: Monte Carlo Evidence and an Application to Employment Equations,” *Review of Economic Studies*, 1991, *58*(2), 277–297.
- Arkolakis, Costas, Arnaud Costinot, and Andres Rodriguez-Clare**, “New Trade Models, Same Old Gains?,” *American Economic Review*, 2012, *102*(1), 94–130.
- Armington, Paul S.**, “A Theory of Demand for Products Distinguished by Place of Production,” *Staff Papers - International Monetary Fund*, 1969, *16*(1), 159–178.
- Ashenfelter, Orley and Alan Krueger**, “Estimates of the Economic Return to Schooling from a New Sample of Twins,” *American Economic Review*, 1994, *84*(5), 1157–1173.
- Babiker, Mustafa H.**, “Climate change policy, market structure, and carbon leakage,” *Journal of International Economics*, 2005, *65*(2), 421–445.
- Baier, Scott L. and Jeffrey H. Bergstrand**, “The growth of world trade: tariffs, transport costs, and income similarity,” *Journal of International Economics*, 2001, *53*(1), 1–27.
- Bartels, Lorand**, “The WTO Legality of the Application of the EU’s Emission Trading System to Aviation,” *European Journal of International Law*, 2012, *23*(2), 429–467.
- Bernard, Andrew B., Jonathan Eaton, J. Bradford Jensen, and Samuel Kortum**, “Plants and Productivity in International Trade,” *American Economic Review*, 2003, *93*(4), 1268–1290.
- Bertrand, Marianne, Esther Dufo, and Sendhil Mullainathan**, “How Much Should We Trust Differences-in-Differences Estimates?,” *Quarterly Journal of Economics*, 2004, *119*(1), 249–75.
- Bickerdike, Charles F.**, “Review of A. C. Pigou’s Protective and Preferential Import Duties,” *Economic Journal*, 1907, *17*, 98–108.
- Black, Dan A., Mark C. Berger, and Frank A. Scott**, “Bounding Parameter Estimates with Nonclassical Measurement Error,” *Journal of the American Statistical Association*, 2000, *95*(451), 739–748.
- Boden, T.A., G. Marland, and R.J. Andres**, “Global, Regional, and National Fossil-Fuel CO<sub>2</sub> Emissions,” Technical Report, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy 2010.
- Bowen, Harry P., Edward E. Leamer, and Leo Sveikauskas**, “Multicountry, Multifactor Tests of the Factor Abundance Theory,” *American Economic Review*, 1987, *77*(5), 791–809.

- Böhringer, Christoph, Jared C. Carbone, and Thomas F. Rutherford**, “Embodied Carbon Tariffs,” 2013. Working Paper, University of Calgary.
- Cai, Yongyang, Kenneth L. Judd, and Thomas S. Lontzek**, “The Social Cost of Stochastic and Irreversible Climate Change,” 2012. NBER Working Paper 18704.
- Caliendo, Lorenzo and Fernando J. Parro**, “Estimates of the Trade and Welfare Effects of NAFTA,” *Review of Economic Studies*, 2015, *82(1)*, 1–44.
- Chaney, Thomas**, “Distorted Gravity: The Intensive and Extensive Margins of International Trade,” *American Economic Review*, 2008, *98(4)*, 1707–1721.
- Chetty, Raj**, “Sufficient Statistics for Welfare Analysis: A Bridge Between Structural and Reduced-Form Methods,” *Annual Review of Economics*, 2009, *1*, 451–488.
- Cole, Matthew A. and Robert J. R. Elliott**, “Determining the trade-environment composition effect: the role of capital, labor and environmental regulations,” *Journal of Environmental Economics and Management*, 2003, *46(3)*, 363–383.
- Copeland, Brian R. and M. Scott Taylor**, “North-South Trade and the Environment,” *Quarterly Journal of Economics*, 1994, *109(3)*, 755–787.
- and ———, *Trade and the Environment: Theory and Evidence*, Princeton University Press, 2003.
- Costinot, Arnaud, Dave Donaldson, and Cory Smith**, “Evolving Comparative Advantage and the Impact of Climate Change on Agricultural Markets: Evidence from 1.7 million Fields Around the World,” *Journal of Political Economy*, Forthcoming.
- Cristea, Anca D., David Hummels, Laura Puzello, and Misak G. Avetisyan**, “Trade and the Greenhouse Gas Emissions from International Freight Transport,” *Journal of Environmental Economics and Management*, 2013, *65(1)*, 153–173.
- Davis, Lucas and Catherine Hausman**, “Market Impacts of a Nuclear Plant Closure,” *American Economic Journal: Applied Economics*, Forthcoming.
- Davis, Steven J. and Ken Caldeira**, “Consumption-based accounting of CO<sub>2</sub> emissions,” *Proceedings of the National Academy of Sciences*, 2010, *107(12)*, 5687–5692.
- Dekle, Robert, Jonathan Eaton, and Samuel Kortum**, “Global Rebalancing with Gravity: Measuring the Burden of Adjustment,” *IMF Staff Papers*, 2008, *55(3)*, 511–539.
- Donaldson, Dave**, “Railroads of the Raj: Estimating the Impact of Transportation Infrastructure,” *American Economic Review*, Forthcoming.
- Durbin, J.**, “Errors in Variables,” *Review of the International Statistical Institute*, 1954, *22(1-3)*, 23–32.

- Dustmann, Christian and Arthur Van Soest**, “Language and the Earnings of Immigrants,” *Industrial and Labor Relations Review*, 2002, *55*(3), 473–492.
- Eaton, Jonathan and Samuel Kortum**, “Technology, Geography, and Trade,” *Econometrica*, 2002, *70*(5), 1741–1779.
- Efron, Bradley**, “Better Bootstrap Confidence Intervals,” *Journal of the American Statistical Association*, 1987, *82*(397), 171–185.
- Faber, Jasper and Linda Brinke**, “The Inclusion of Aviation in the EU Emissions Trading System,” Technical Report, ICTSD 2011.
- Feyrer, James**, “Distance, Trade, and Income – The 1967 to 1975 Closing of the Suez Canal as a Natural Experiment,” 2009. Mimeograph, Dartmouth College.
- , “Trade and Income – Exploiting Time Series in Geography,” 2009. Mimeography, Dartmouth College.
- Floyd, Robert W.**, “Algorithm 97: Shortest Path,” *Communications of the ACM*, 1963, *5*(6), 345.
- Frankel, Jeffrey A. and Andrew K. Rose**, “Is Trade Good or Bad for the Environment? Sorting Out the Causality,” *Review of Economics and Statistics*, 2005, *87*(1), 85–91.
- Freeman, Richard B.**, “Longitudinal Analyses of the Effects of Trade Unions,” *Journal of Labor Economics*, 1984, *2*(1), 1–26.
- Goldewijk, Kees Klein, Arthur Beusen, Gerard van Drecht, and Martine de Vos**, “The HYDE 3.1 spspatial explicit database of human-induced global land-use change over the past 12,000 years,” *Global Ecology and Biogeography*, 2011, *20*(1), 73–86.
- Greenstone, Michael, Elizabeth Kopits, and Ann Wolverton**, “Developing a Social Cost of Carbon for US Regulatory Analysis: A Methodology and Interpretation,” *Review of Environmental Economics & Policy*, 2013, *7*(1), 23–46.
- Griliches, Zvi and Jerry A. Hausman**, “Errors in Variables in Panel Data,” *Journal of Econometrics*, 1986, *31*, 93–118.
- Harbaugh, William T., Arik Levinson, and David Molloy Wilson**, “Reexamining the Empirical Evidence for an Environmental Kuznets Curve,” *Review of Economics and Statistics*, 2002, *84*(3), 541–551.
- Harrigan, James**, “OECD imports and trade barriers in 1983,” *Journal of International Economics*, 1993, *35*, 91–111.
- Head, Keith and John Ries**, “Increasing Returns Versus National Product Differentiation as an Explanation for the Pattern of U.S.-Canada Trade,” *American Economic Review*, 2001, *91*(4), 858–876.

- \_\_\_\_\_ and **Theirry Mayer**, *Handbook of International Economics*, Elsevier,
- \_\_\_\_\_ and **Thierry Mayer**, *The Gravity Model in International Trade: Advances and Applications*, Cambridge University Press, 2010.
- Hertel, Thomas, David Hummels, Maros Ivanic, and Roman Keeney**, “How confident can we be of CGE-based assessments of Free Trade Agreements?,” *Economic Modelling*, 2007, *24*, 611–635.
- Holland, Stephen P., Jonathan E. Hughes, Christopher R. Knittel, and Nathan C. Parker**, “Some Inconvenient Truths About Climate Change Policy: The Distribution Impacts of Transportation Policies,” *Review of Economics and Statistics*, 2014.
- Hummels, David and Volodymyr Lugovskyy**, “Are Matched Partner Trade Statistics a Usable Measure of Transportation Costs?,” *Review of International Economics*, 2006, *14(1)*, 69–86.
- IATA**, “World Air Transport Statistics,” Technical Report, IATA 2009.
- IEA**, “CO2 Emissions from Fuel Combustion,” Technical Report, IEA 2011.
- Keen, Michael, Ian Perry, and Jon Strand**, “Market-Based Instruments for International Aviation and Shipping as a Source of Climate Finance,” 2012. World Bank Policy Research Working Paper 5950.
- Krugman, Paul R., Maurice Obstfeld, and Marc J. Melitz**, *International Economics: Theory and Policy*, Addison-Wesley, 2012.
- Lai, Huiwen and Daniel Treffer**, “The Gains from Trade with Monopolistic Competition: Specification, Estimation, and Mis-Specification,” 2002. NBER Working Paper 9169.
- Li, Shanjun, Joshua Linn, and Elisheba Spiller**, “Evaluating “Cash-for-Clunkers”: Program effects on auto sales and the environment,” *Journal of Environmental Economics and Management*, 2013, *65(2)*, 175–193.
- Li, Xiaoyang and Yue Maggie Zhou**, “Offshoring Pollution while Offshoring Production,” 2015. Fama-Miller Working Paper No. 1253.
- Limao, Nuno and Anthony J. Venables**, “Infrastructure, Geographical Disadvantage, Transport Costs, and Trade,” *World Bank Economic Review*, 2001, *15(3)*, 451–479.
- Lux, Matthias**, “Defying Gravity: The Substitutability of Transportation in International Trade,” 2012. Mimeograph, Cornerstone Research.
- Mayer, Thierry and Soledad Zignago**, “Market Access in Global and Regional Trade,” 2005. CEPP Working Paper 2.
- Melitz, Marc J.**, “The Impact of Trade on Intra-Industry Reallocations and Aggregate Industry Productivity,” *Econometrica*, 2003, *71(6)*, 1695–1725.

- Meltzer, Joshua**, “Climate Change and Trade—The EU Aviation Directive and the WTO,” *Journal of International Economic Law*, 2012, *15(1)*, 111–156.
- Mestelman, Stuart**, “Production Externalities and Corrective Subsidies: A General Equilibrium Analysis,” *Journal of Environment*, 1982, *9*, 186–193.
- Nijkamp, Peter, Shunli Wang, and Hans Kremers**, “Modeling the impacts of international climate change policies in a CGE context: the use of the GTAP-E model,” *Economic Modelling*, 2005, *22(6)*, 955–974.
- Nordhaus, William**, *A Question of Balance: Weighing the Options of Global Warming Policies*, Yale University Press, 2008.
- , “Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches,” *Journal of the Association of Environmental and Resource Economists*, 2014, *1(1/2)*, 273–312.
- Nordhaus, William D. and Joseph Boyer**, *Warming the World: Economic Models of Global Warming*, MIT Press, 2000.
- on the Social Cost of Carbon, United States Government Interagency Working Group**, “Technical Support Document: - Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis - Under Executive Order 12866 -,” Technical Report, US Government 2013.
- Orcutt, Guy H.**, “Measurement of Price Elasticities in International Trade,” *Review of Economics and Statistics*, 1950, *32(2)*, 117–132.
- Ossa, Ralph**, “Why Trade Matters After All,” 2014. Mimeo, University of Chicago.
- Papke, Leslie E. and Jeffrey M. Wooldridge**, “Econometric Methods for Fractional Response Variables with an Application to 401(k) Plan Participation Rates,” *Journal of Applied Econometrics*, 1996, *11(6)*, 619–32.
- Pizer, William, Matthew Adler, Joseph Aldy, David Anthoff, Maureen Cropper, Kenneth Gillingham, Michael Greenstone, Brian Murray, Richard Newell, Richard Richels, Arden Rowell, Stephanie Waldhoff, and Jonathan Wiener**, “Using and improving the social cost of carbon,” *Science*, 2014, *346(6214)*, 1189–1190.
- Rauch, James E.**, “Networks Versus Markets in International Trade,” *Journal of International Economics*, 1999, *48(1)*, 7–35.
- Shapiro, Joseph S. and Reed Walker**, “Why is Pollution from U.S. Manufacturing Declining? The Role of Trade, Regulation, Productivity, and Preferences,” 2015. Mimeo, Yale.

- Simonovska, Ina and Michael E. Waugh**, “The Elasticity of Trade: Estimates and Evidence,” *Journal of International Economics*, 2014, *92(1)*, 1–210.
- Staiger, Douglas and James H. Stock**, “Instrumental Variables Regression with Weak Instruments,” *Econometrica*, 1997, *65(3)*, 557–586.
- Trefler, Daniel**, “The Case of the Missing Trade and Other Mysteries,” *American Economic Review*, 1995, *85(5)*, 1029–1046.
- Warshall, Stephen**, “A theorem on Boolean matrices,” *Journal of the ACM*, 1962, *9(1)*, 11–12.

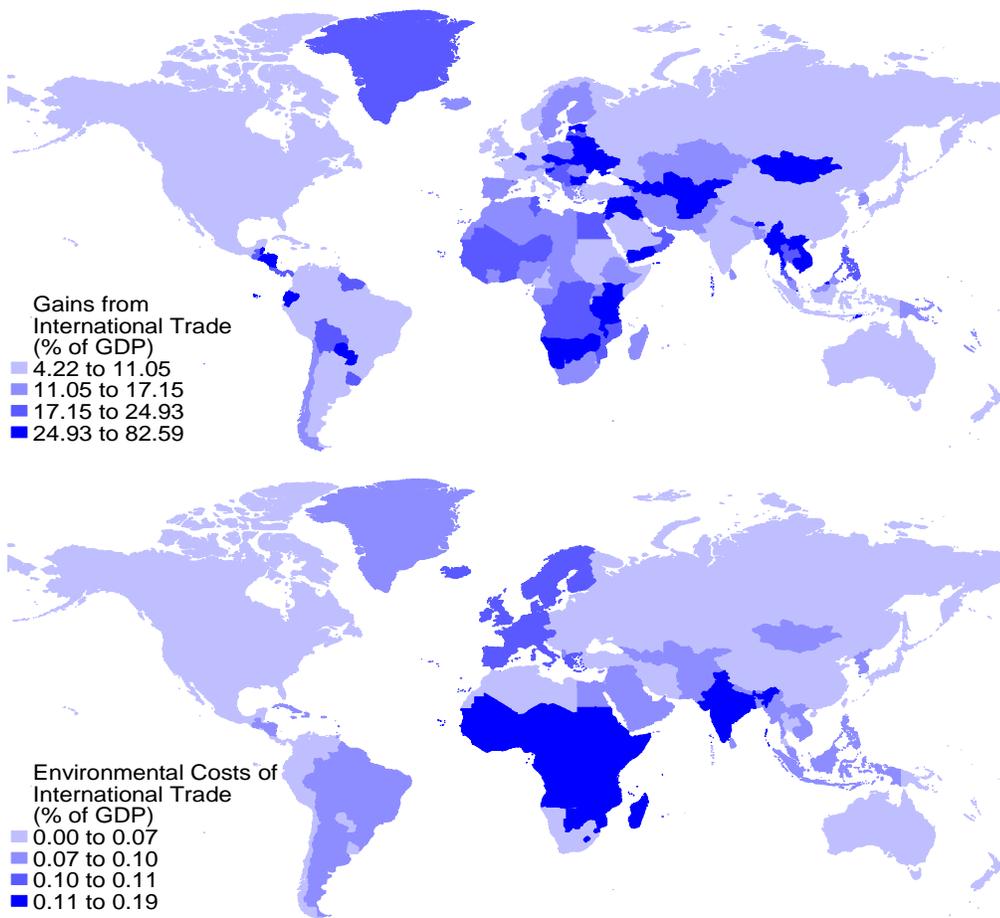


Figure 1: Benefits and Environmental Costs of International Trade, by Country (% of GDP)  
 Notes: Figures plot empirical analogues of equation (7). See main text for details on data sources.

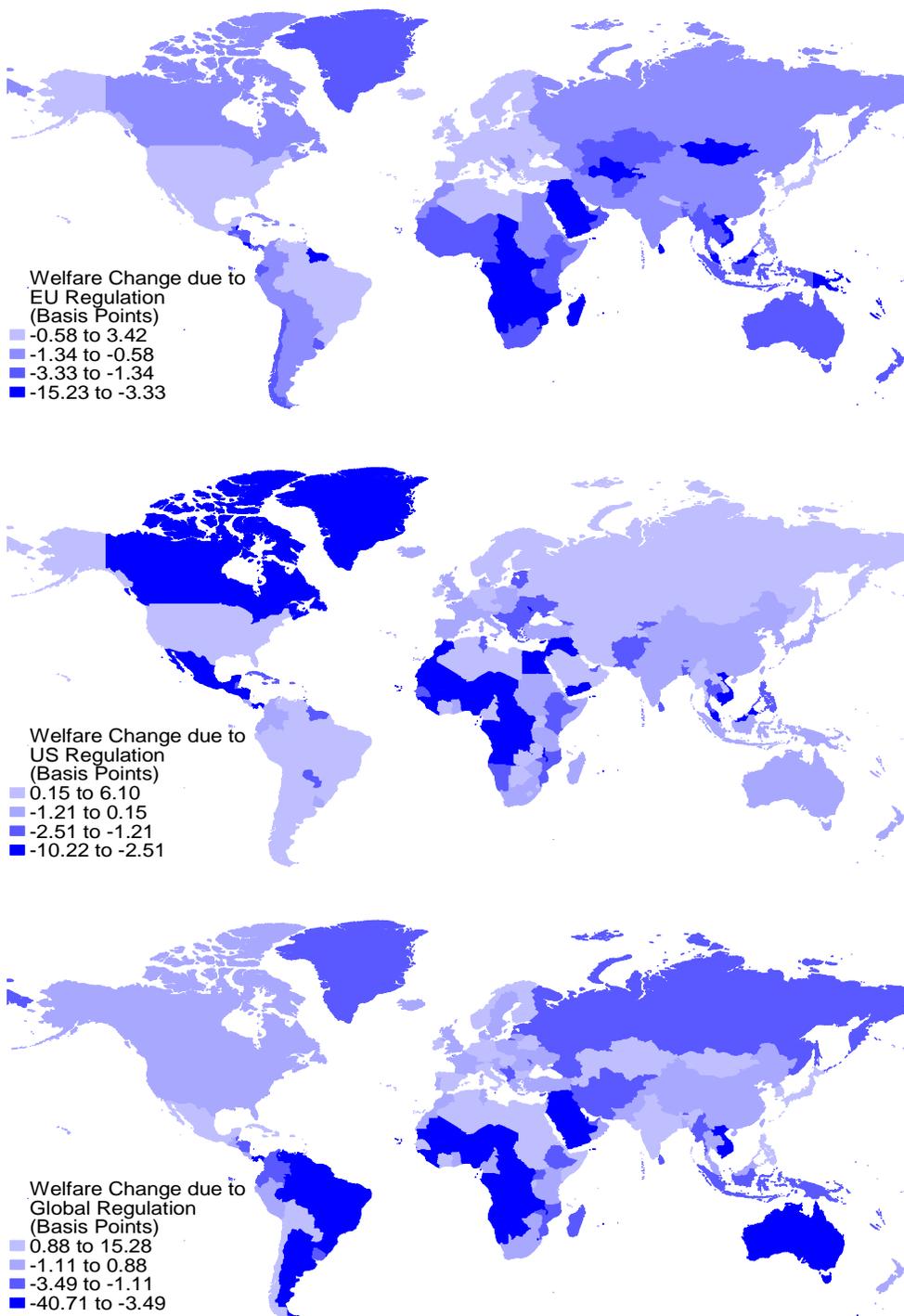


Figure 2: Impact of EU, US, and Global Climate Change Regulations on Social Welfare in Basis Points

Notes: Each regulation imposes a \$29/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 (Millions of Tons of CO<sub>2</sub>)

Source	International (1)	Domestic (2)	Total (3)
<u>Panel A: CO<sub>2</sub> Emissions by Transport Mode and Type</u>			
Shipping: Air	200	40	240
Shipping: Sea	648	132	780
Shipping: Rail	19	25	44
Shipping: Road	383	1,397	1,780
Shipping: Total	1,250	1,594	2,844
Production: Total	1,154	25,370	26,524
Global Total	2,404	26,964	29,368
<u>Panel B: CO<sub>2</sub> Emissions by Region</u>			
US	346	5,993	6,339
EU	695	4,124	4,819
Other	1,363	16,848	18,211

Notes: All values represent millions of tons CO<sub>2</sub> 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

Dependent Variable: Regression Type	Log Import	Log Import	Log Shipping	Log Import	N
	Shares	Shares	Costs	Shares	
	OLS (1)	FE (2)	FS (3)	IV (4)	
Panel A: Economy-Wide Estimates					
Overall	-20.947*** (2.614)	-3.709** (1.773)	0.207*** (0.050)	-7.908* (4.346)	4,830
Overall: Manufacturing	-24.637*** (1.855)	-4.238*** (1.053)	0.218*** (0.043)	-7.326* (4.365)	4,800
Panel B: Sector-Specific Estimates					
Agriculture, Forestry	-4.727** (1.855)	-3.409*** (1.010)	0.289*** (0.066)	-3.338 (3.628)	3,316
Mining	-5.003*** (1.334)	-2.125** (0.929)	0.441*** (0.054)	-3.450*** (1.273)	2,150
Food, Beverages, Tobacco	-15.839*** (1.782)	-5.202*** (1.201)	0.477*** (0.057)	-5.256** (2.102)	3,568
Textiles	-19.740*** (1.406)	-6.374*** (0.936)	0.192*** (0.063)	-18.557*** (5.587)	3,558
Apparel, Leather	-18.193*** (1.456)	-3.469*** (1.215)	0.287*** (0.059)	-9.949*** (3.491)	3,612
Wood	-12.684*** (1.075)	-2.568*** (0.637)	0.321*** (0.045)	-5.901*** (2.234)	3,206
Paper, Printing	-14.439*** (1.375)	-1.881*** (0.592)	0.196*** (0.038)	-5.768* (3.001)	2,778
Petroleum, Coal, Minerals	-13.498*** (1.211)	-3.057*** (0.795)	0.240*** (0.060)	-8.949** (4.014)	2,972
Chemicals, Rubber, Plastics	-16.074*** (1.716)	-3.069*** (1.085)	0.356*** (0.053)	-1.554 (3.044)	3,600
Metals	-19.658*** (1.380)	-5.517*** (0.695)	0.204** (0.081)	-12.941 (8.347)	3,204
Machinery, Electrical	-28.469*** (2.084)	-7.963*** (0.923)	0.240*** (0.041)	-10.843*** (2.836)	3,910
Transport Equipment	-23.524*** (2.566)	-4.505*** (1.067)	0.235*** (0.070)	-6.868* (3.662)	2,544
Other	-16.644*** (1.133)	-4.403*** (0.615)	0.156*** (0.052)	-12.764*** (4.565)	3,626
Mean Across Sectors	-16.038	-4.119	0.280	-8.164	
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 coefficient 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. Column (1) shows the specification of equation (8) from the main text, but with fixed effects omitted. Column (2) shows the specification of equation (8) from the main text, including the fixed effects. Column (3) shows the first-stage regression of shipping costs measured from quarters 1 and 4 of a year on shipping costs measured in quarters 2 and 3 of that year, which corresponds to equation (10) from the main text. Because this is an instrumental variables regression with one endogenous variable and one instrument, the first-stage F-statistic equals the square of the t-statistic. Column (4) shows the instrumental variables regression of log import shares on log shipping costs, where shipping costs are instrumented using the first-stage regression shown in column (3). This corresponds to equation (9) from the main text. 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 (Billion US\$)

	Gains from Trade (1)	Enviromental Costs of Trade (2)	Social Welfare (3)	Ratio: (1)/(2) (4)
<u>Panel A: Global</u>				
World	5455 [3450 , 27105]	-33.8 [-45 , -1]	5485 [3499 , 24680]	-161 [-6853 , -81]
<u>Panel B: By Region</u>				
US	602 [393 , 3965]	-2.5 [-3 , 0]	604 [397 , 3968]	-245 [-12295 , -126]
EU	2148 [1295 , 10777]	-18.4 [-24 , -1]	2164 [1317 , 10781]	-117 [-4425 , -56]
<u>Panel C: By GDP Per Capita</u>				
Richest Third	3724 [2414 , 18031]	-24.0 [-32 , -1]	3746 [2397 , 16240]	-155 [-6556 , -80]
Middle Third	1294 [756 , 7219]	-5.3 [-7 , 0]	1298 [745 , 6584]	-245 [-9286 , -110]
Poorest Third	437 [274 , 1855]	-4.5 [-6 , 0]	441 [279 , 1856]	-96 [-5592 , -47]

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. The "Richest," "Middle," and "Poorest" rows distinguish three groups of 42-43 countries based on 2007 GDP per capita. The GDP per capita ranges defining each group are: above \$14,000; \$2,400 to \$14,000; and below \$2,400.

Table 4: Counterfactual Carbon Taxes on Shipping: Effects on Social Welfare (Billions of US\$)

Group of Countries	Gains from Trade (1)	Environmental Costs of Trade (2)	Social Welfare: Total (3)	Social Welfare: Basis Points (4)
<u>Panel A: EU Counterfactual</u>				
All (Global)	-2.9 [-3.4 , -2.0]	-3.8 [-4.5 , -2.6]	0.9 [0.6 , 1.2]	0.02 [0.01 , 0.02]
US	-7.5 [-7.8 , -6.9]	-0.3 [-0.4 , -0.2]	-7.2 [-7.7 , -6.6]	-0.48 [-0.51 , -0.44]
EU	26.6 [24.9 , 29.6]	-2.1 [-2.5 , -1.4]	28.7 [27.0 , 31.9]	1.60 [1.50 , 1.78]
Richest Third	11.6 [10.3 , 13.8]	-2.7 [-3.2 , -1.9]	14.3 [12.8 , 16.8]	0.34 [0.31 , 0.40]
Middle Third	-9.0 [-11.8 , -7.8]	-0.6 [-0.7 , -0.4]	-8.4 [-11.1 , -7.3]	-0.76 [-1.00 , -0.66]
Poorest Third	-5.5 [-6.2 , -4.9]	-0.5 [-0.6 , -0.4]	-5.0 [-5.8 , -4.4]	-1.57 [-1.82 , -1.38]
<u>Panel B: US Counterfactual</u>				
All (Global)	-2.4 [-2.5 , -2.2]	-9.3 [-10.1 , -8.5]	6.9 [6.1 , 7.8]	0.12 [0.11 , 0.14]
US	29.4 [21.7 , 39.3]	-0.7 [-0.8 , -0.7]	30.1 [22.5 , 40.0]	2.01 [1.50 , 2.67]
EU	-6.3 [-7.6 , -4.9]	-5.1 [-5.6 , -4.6]	-1.2 [-2.8 , 0.1]	-0.06 [-0.16 , 0.01]
Richest Third	12.7 [8.0 , 18.2]	-6.6 [-7.2 , -6.0]	19.3 [15.2 , 24.4]	0.46 [0.36 , 0.58]
Middle Third	-10.0 [-14.8 , -6.3]	-1.4 [-1.5 , -1.3]	-8.6 [-13.6 , -4.8]	-0.77 [-1.22 , -0.43]
Poorest Third	-5.1 [-6.3 , -4.0]	-1.3 [-1.4 , -1.2]	-3.8 [-5.2 , -2.6]	-1.20 [-1.63 , -0.82]
<u>Panel C: Global Counterfactual</u>				
All (Global)	-6.5 [-8.0 , -4.8]	-16.7 [-20.0 , -13.2]	10.2 [8.5 , 11.8]	0.18 [0.15 , 0.21]
US	2.2 [1.1 , 3.7]	-1.3 [-1.5 , -1.0]	3.5 [2.4 , 4.7]	0.23 [0.16 , 0.31]
EU	8.8 [5.5 , 13.8]	-9.2 [-11.0 , -7.3]	18.0 [13.2 , 23.0]	1.00 [0.73 , 1.28]
Richest Third	10.3 [8.5 , 14.3]	-11.9 [-14.2 , -9.4]	22.2 [19.1 , 26.2]	0.53 [0.46 , 0.63]
Middle Third	-10.5 [-15.3 , -7.7]	-2.5 [-3.0 , -2.0]	-8.0 [-12.7 , -5.7]	-0.72 [-1.14 , -0.51]
Poorest Third	-6.4 [-7.3 , -5.6]	-2.3 [-2.8 , -1.8]	-4.1 [-5.4 , -3.1]	-1.29 [-1.71 , -0.99]

Notes: The first three columns represent the total effect in US 2007\$ billions over a decade. The EU counterfactual applies a carbon tax of \$29 per metric ton of CO<sub>2</sub> to all EU imports, exports, and intranational trade by air. The US counterfactual applies a carbon tax of \$29 per metric ton of CO<sub>2</sub> to all US imports, exports, and intranational trade. The global counterfactual applies a carbon tax of \$29 per metric ton of CO<sub>2</sub> 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  $\theta_j$  distributions of Table 2, excluding draws of  $\theta_j > 0$ . The "Richest," "Middle," and "Poorest" rows distinguish three groups of 42-43 countries based on 2007 GDP per capita. The GDP per capita ranges defining each group are: above \$14,000; \$2,400 to \$14,000; and below \$2,400.

# Appendix to Trade Costs, CO<sub>2</sub>, and the Environment

Joseph S. Shapiro

## 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 US 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.

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. 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-sector concordance file described below to link these HS codes to the 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 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 the remaining 17-26 percent of international trade, and for intranational trade, I use 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. For predicting intranational mode shares, I use only contiguous countries, since these reflect the much greater proportion of rail and road shares for nearby transportation.

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

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

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

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

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). Cristea, Hummels, Puzello and Avetisyan (2013) make a similar adjustment.

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

The Australian and US data have similar general structure. In the raw Australian data, there is an observation for each combination of an exporter, 2-digit Harmonized System code, quarter, and year. The Australian data report the value of goods separately at their port of origin and port of destination. I define the shipping cost as the difference between these values. In the raw US data, there is an observation for each combination of an exporter, 10-digit Harmonized System code, month, and year. The US data report the charges for insurance and shipping for each observation. I define the US shipping cost as these charges divided by the value of the goods at their US port of entry. The value at their US port of entry (i.e., the CIF value) equals the reported value of the goods plus the reported charges for insurance and shipping.

I use a few rules to compile the Australian and US data. 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.

For both the US and Australian data, the shipping cost  $s$  used in regressions equals the total shipping cost reported for an exporter-quarter-sector, divided by the total value of shipments for this trade flow. This measure is equivalent to a trade-flow weighted average across the various months, industries, and countries that comprise an exporter-quarter-sector.

Defining the 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 sectors I analyze. For the 2002 revision, I use a dataset created by Thomas Hutcherson as part of the Global Trade and Analysis Project (GTAP) which links each 6-digit HS code to the 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. By 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.

The Australian data are only available at the 2-digit HS code level. To link these data to the 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 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 winsorize 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 winsorize country-by-sector value-added (GDP) data at 1.5 and 98.5 percent of gross output. Similarly, I winsorize Cobb-Douglas expenditure shares at one percent and scale expenditure shares for other sectors so they sum to one for each country. These each affect a handful of observations with outlying values. 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. Some results distinguish three groups of countries by GDP per capita, which equals national GDP divided by national population, as reported in the GTAP data.

### A.4 Other Data for CO<sub>2</sub> Emissions from Trade

The data sources recording the 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-value ratios used to fill in missing data (see the Appendix).

Fuel efficiency ( $\xi_{odm}$ , measured in gCO<sub>2</sub>/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<sub>2</sub>/ton-km (IATA 2009). 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<sub>2</sub> emissions would imply. For simplicity, I follow most policymakers in measuring airplanes’ climate change impact according to their CO<sub>2</sub> emissions. For maritime trade, the CO<sub>2</sub> 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<sub>2</sub>/ton-km.<sup>1</sup> 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 trans-

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<sup>1</sup>For air, IATA reports a global air fuel economy of 39.0 liters/ton-km. I convert this to gCO<sub>2</sub> using the US Energy Information Agency’s reference rate of 9.57 kg CO<sub>2</sub> per gallon of jet fuel. For sea, IEA (2011) reports that international marine transportation emitted 624.5 MtCO<sub>2</sub>. Freight accounts for 90 percent of civilian ship CO<sub>2</sub> emissions (IMO 2009, p. 160) and the IEA international maritime data generally exclude military ship emissions (Reece 2004). Dividing CO<sub>2</sub> emissions of 562.05 MtCO<sub>2</sub> by the 50.6 trillion ton-km of international freight reported to be traded by ship gives the 11.11 rate.

portation literature, each representing a specific region. This approach leads to fuel economy estimates of 23.0 gCO<sub>2</sub>/ton-km for rail and 119.0 gCO<sub>2</sub>/ton-km for road (Appendix Table 1). I impose a fuel consumption rate ( $\xi$ ) of zero for the “other” transportation mode.

I use estimates of the CO<sub>2</sub> emissions from production compiled by GTAP. GTAP uses the “Tier 1” method of the Intergovernmental Panel on Climate Change (IPCC 1997) to compile these data.<sup>2</sup> For each sector and country in the year 2007, these data report the tons of CO<sub>2</sub> emitted by producing the good. I use the GTAP data because it provides extensive country and sector detail. Among ways of estimating CO<sub>2</sub> emissions, 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 for each country.

## A.5 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 Regional Integrated Climate-Economy (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).

## A.6 Climate Damages

The social cost of carbon value \$29 for the year 2007 linearly extrapolates the Interagency estimates of \$32 for the year 2010 and \$37 for the year 2015. Cai, Judd and Lontzek (2012) report several possible values of the social cost of carbon. I take the value \$200 from their Figure 8 because it reflects a risk aversion parameter consistent with the literature they cite

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<sup>2</sup>The IPCC describes three methods (“Tiers”) of calculating greenhouse gas emissions from economic activity. The Tier 1 method assigns a greenhouse gas emissions coefficient to each physical unit of fossil fuel, then multiplies this coefficient by the physical units of each fossil fuel used directly to produce output in a given sector of a country. The Tier 2 method uses country-specific emission factors and other data. The Tier 3 method uses sector- or country-specific models. This study uses Tier 1 data because they are what is comparable and available for all countries and sectors with industry classification and time period that matches the rest of this paper.

(i.e., ten or smaller), it allows for tipping points, and it conservatively reflects the maximum possible value of the uncertain damage parameter among values they consider.

I use estimates from the RICE model (Nordhaus and Boyer 2000) to calculate each region’s climate damages as follows. Nordhaus and Boyer’s calculate the damage due to a 2.5°C warming for each of 13 regions, expressed as a portion of GDP, as follows: US 0.45%, China 0.22%, Japan 0.50%, OECD Europe 2.83%, Russia -0.65%, India 4.93%, Other High Income -0.39%, High Income OPEC 1.95%, Eastern Europe 0.71%, Middle Income 2.44%, Lower-middle Income 1.81%, Africa 3.91%, and Low Income 2.64%. These values clearly abstract from calamitous possibilities in some countries—some island nations, for example, may lose significant shares of their land mass due to global sea level rise and flooding. This is, however, the most comprehensive set of estimates available. Denoting this damage for a region as  $d_r$ , I measure a country’s proportion of global climate damages as  $\frac{d_r G_r}{\sum_r d_r G_r}$ . So for a global marginal social cost of carbon of \$19.96, I choose  $\mu_d$  so that in the baseline, a one-ton increase in carbon emissions decreases indirect utility for countries in region  $r$  by  $19.96 \frac{d_r G_r}{\sum_r d_r G_r}$ .

The functional form in assumption A1 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.

## B How Reasonable are these Trade Elasticities?

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

I implement this test using data 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 2). All three types of goods have strong instruments, with first stage F-statistics between 26 and 90. 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, those goods have an intermediate elasticity of -5.81. Statistically, all three elasticities

are significantly different from zero, though the three estimates have overlapping confidence regions. 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.

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. 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 -18.56, whereas Caliendo and Parro (2015) find elasticities of -51 to -69. My most differentiated sector has an elasticity of -1.55, which is more negative than Caliendo and Parro’s -0.37.

## C Comparison to Estimates by International Organizations

This paper describes detailed measures of CO<sub>2</sub> 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<sub>2</sub> emissions but which can therefore use simpler data and methods.

The totals implied by these data are close to totals of these published sources. 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<sub>2</sub> emissions in the EU cap-and-trade system. I estimate total air freight CO<sub>2</sub> emissions involving the EU of 75.3 MtCO<sub>2</sub>, while the European Commission (2011) implies a value of 78.9 MtCO<sub>2</sub>. 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<sub>2</sub>, and total sea tons shipped are 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.

Several assumptions are required to compare my estimates of air and sea CO<sub>2</sub> 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 to 2006, flights to and from the EU emitted an annual mean of 221.4 MtCO<sub>2</sub>. Applying the 0.336 freight/transportation ratio described above implies annual EU air freight emissions of 74.61 MtCO<sub>2</sub>. Applying the 5.7 percent 2005-2007 growth in international air transportation CO<sub>2</sub> emissions (IEA 2011) implies an EU-reported total of 78.86 MtCO<sub>2</sub>.

The IEA calculates its international air estimate as follows. The IEA reports that international air transportation emitted 431 MtCO<sub>2</sub> in the year 2007. Assuming again that 33.6 percent of this represents freight, we have an IEA estimate for air freight of 145 MtCO<sub>2</sub>.

The ICAO total air estimate is calculated as follows. The ICAO (2009) estimates that domestic and international aviation emitted a total of 632 MtCO<sub>2</sub> in the year 2006. I inflate this by the 2006-2007 5 percent 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<sub>2</sub> for international plus domestic air freight.

## D 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  $13 \times 1$  vector  $\theta$  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  $b$ th 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- $\alpha$ th percentile of the  $B$  estimates  $\zeta(1), \dots, \zeta(200)$ . 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- $\alpha$ th percentile of a standard normal CDF. The bias correction coefficient

$z_0$  is calculated from the share of bootstrap estimates  $\zeta(1), \dots, \zeta(200)$  which are less than the full-sample estimate  $\zeta$ :

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

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.

## E Welfare Effects of Climate Change Regulation

I use the following algorithm to assess welfare under counterfactual policies:

1. Choose an initial candidate vector of wage changes  $\hat{w}_d$  for all countries.
2. Given the candidate wage vector  $\hat{w}_d$  at an iteration of the algorithm, estimate the vector of price changes  $\hat{p}_d^j$  by iterating over the equation  $\hat{p}_d^j = (\hat{w}_d)^{\beta_d^j} (\hat{p}_d^j)^{1-\beta_d^j}$ . This step reflects the contraction map algorithm of Alvarez and Lucas (2007).
3. Given these candidate values of  $\hat{w}_d$  and  $\hat{p}_d^j$ , new trade and production  $X_{od}^{j'}$  are given by equation (E.1). As shown below the trade and production decisions  $X_{od}^{j'}$  can be calculated as a function of the parameters  $\theta^j$ , the data  $(\lambda_{od}^j, T_o^j, \beta_o^j, \alpha_o^j)$ , the chosen carbon taxes  $t_{od}^j$ , and the recovered wage and price changes  $\hat{w}_d$  and  $\hat{p}_d^j$ .
4. Check whether the resulting values  $(X_{od}^{j'}, t_{od}^{j'}, T_d')$  satisfy the equilibrium market clearing condition (6b). If not, adjust the candidate values of  $\hat{w}_d$  and return to step 2.
5. Once the equilibrium values of  $\hat{w}_d$  are found in step 4, substitute the new values of  $X_{od}^{j'}/p_{od}^{j'}$  into equation (5) to determine new carbon dioxide emissions  $E_d'$  from each country.
6. Using the equations described in section 2.2, substitute values of  $\hat{I}_d, \hat{P}_d, E_o,$  and  $E_o'$  into equation (7) to measure the change in social welfare for each country.

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

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

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:

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

$$\hat{p}_d^j = \left[ \sum_{o=1}^N \lambda_{od}^j (\hat{c}_o^j \hat{\tau}_{od}^j)^{\theta^j} \right]^{1/\theta^j} \quad (\text{E.2})$$

$$\hat{\lambda}_{od}^j = \left( \frac{\hat{c}_o^j \hat{\tau}_{od}^j}{\hat{p}_d^j} \right)^{\theta^j} \quad (\text{E.3})$$

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. As in the main text,  $x'$  represents the value of the variable  $x$  after a regulation is imposed, and no vectors or matrices in this section are transposed. 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:

$$A = \text{diag} \left( (1 - \beta_d^j) \sum_{o=1}^N \frac{\lambda_{od}^{j'}}{1 + t_{od}^j} \left[ 1 + t_{od}^j (1 - G_{od}) \right] \right)$$

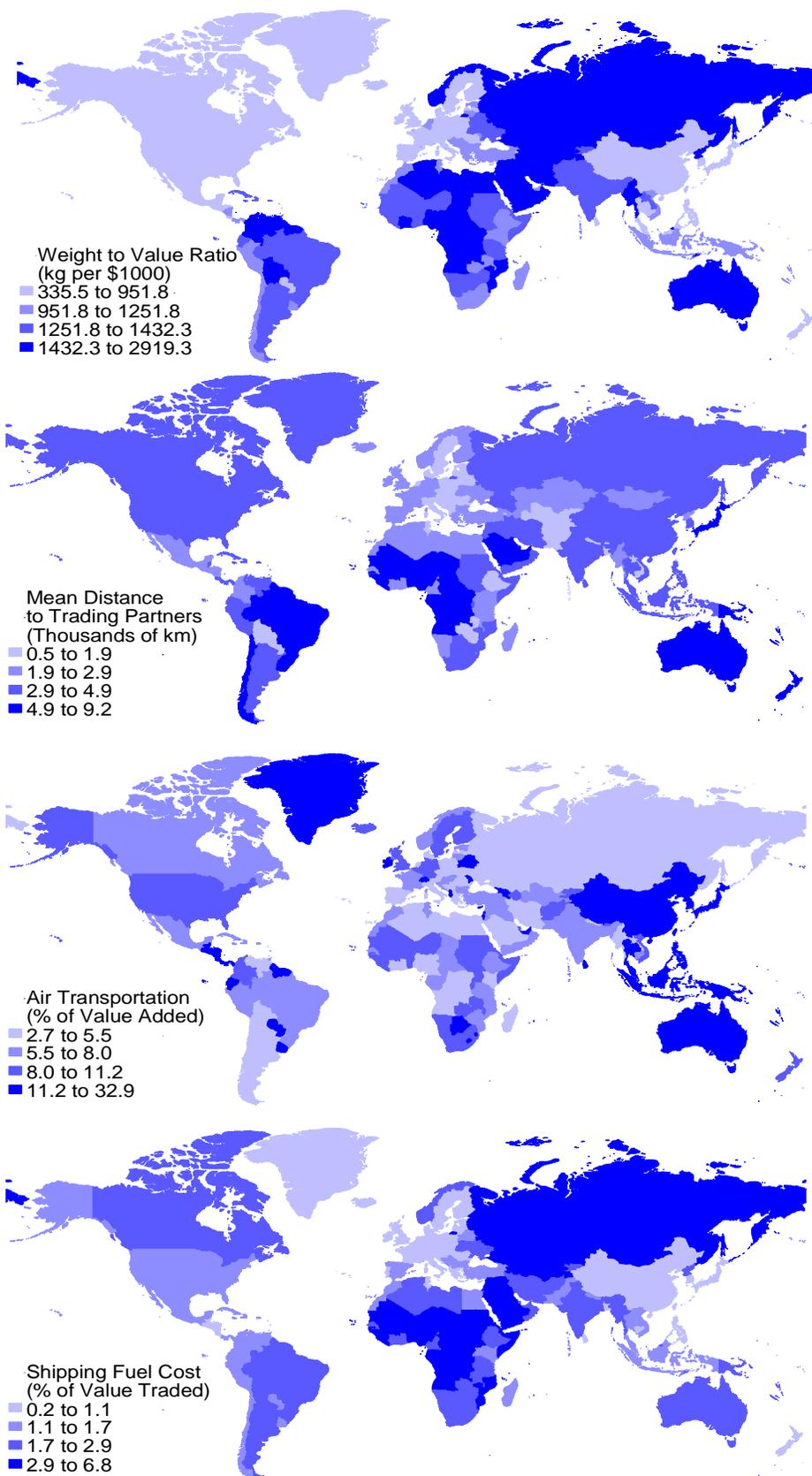
$$= \begin{bmatrix} (1 - \beta_1^1) \sum_o \frac{\lambda_{o1}^{1'}}{1 + t_{o1}^1} & & & 0 \\ & (1 - \beta_1^2) \sum_o \frac{\lambda_{o1}^{2'}}{1 + t_{o1}^2} & & \\ & & \ddots & \\ 0 & & & (1 - \beta_N^J) \sum_o \frac{\lambda_{oN}^{J'}}{1 + t_{oN}^J} \end{bmatrix}$$



## References

- ADB, “Reducing Carbon Emissions from Transport Projects,” Technical Report, ADB 2010.
- Alvarez, Fernando and Robert E. Lucas, “General equilibrium analysis of the Eaton-Kortum model of international trade,” *Journal of Monetary Economics*, 2007, 54, 1726–1768.
- Anderson, James E. and Eric van Wincoop, “Trade Costs,” *Journal of Economic Literature*, 2004, 42(3), 691–751.
- Cai, Yongyang, Kenneth L. Judd, and Thomas S. Lontzek, “The Social Cost of Stochastic and Irreversible Climate Change,” 2012. NBER Working Paper 18704.
- Caliendo, Lorenzo and Fernando J. Parro, “Estimates of the Trade and Welfare Effects of NAFTA,” *Review of Economic Studies*, 2015, 82(1), 1–44.
- Cefic, “Guidelines for Measuring and Managing CO<sub>2</sub> Emission from Freight Transport Operations,” Technical Report, Cefic 2011.
- Cristea, Anca D., David Hummels, Laura Puzello, and Misak G. Avetisyan, “Trade and the Greenhouse Gas Emissions from Internatoinal Freight Transport,” *Journal of Environmental Economics and Management*, 2013, 65(1), 153–173.
- Defra, “2009 Guidelines to Defra / DECC’s GHG Conversion Factors for Company Reporting,” Technical Report, Defra 2009.
- Efron, Bradley, “Better Bootstrap Confidence Intervals,” *Journal of the American Statistical Association*, 1987, 82(397), 171–185.
- European Commission, “Allocation of aviation allowances in an EEA-wide Emissions Trading System,” 2011.
- Giannouli, Myrsini, Zissis Samaras, Mario Keller, Peter deHaan, Manfred Kallivoda, Spencer Sorenson, and Aliko Georgakaki, “Development of a database system for the calculation of indicators of environmental pressure caused by transport,” *Science of the Total Environment*, 2006, 357, 247–270.
- IATA, “World Air Transport Statistics,” Technical Report, IATA 2009.
- ICAO, “Global Aviation CO<sub>2</sub> Emissions Projections to 2050,” Technical Report, ICAO 2009.
- IEA, “CO<sub>2</sub> Emissions from Fuel Combustion,” Technical Report, IEA 2011.
- IMO, “Second IMO GHG Study 2009,” Technical Report, IMO 2009.
- IPCC, “IPCC Guidelines for National Greenhouse Gas Inventories,” Technical Report, IPCC 1997.

- McDonald, Scott and Karen Thierfelder**, “Deriving a Global Social Accounting Matrix from GTAP Versions 5 and 6 Data,” Technical Report, GTAP Technical Paper 22 2004.
- Nordhaus, William D. and Joseph Boyer**, *Warming the World: Economic Models of Global Warming*, MIT Press, 2000.
- NTM**, “Basic freight calculator.” Available at <http://www.ntmcalc.org/index.html>. Accessed August 5, 2012.
- ORR**, “National Rail Trends 2007-2008 Yearbook,” Technical Report, ORR 2009.
- Psaraftis, Harilaos N. and Christos A. Kontovas**, “CO2 Emission Statistics for the World Commercial Fleet,” *WMU Journal of Maritime Affairs*, 2009, *8(1)*, 1–25.
- Rauch, James E.**, “Networks Versus Markets in International Trade,” *Journal of International Economics*, 1999, *48(1)*, 7–35.
- Reece, Mieke**, “Reporting of International Aviation and Marine Bunkers in the Joint IEA/IECE/Eurostat Questionnaires,” 2004. Presentation, Workshop on Emissions of Greenhouse Gases from Aviation and Navigation, Copenhagen, May 2004.
- UNCTAD**, “Review of Maritime Transport,” Technical Report, UNCTAD 2009.
- UNECA**, “Assessing Regional Integration in Africa IV: Enhancing Intra-African Trade,” Technical Report, UNECA 2010.



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 Table 1: Review of Fuel Economy Estimates, by Transportation Mode (gCO<sub>2</sub>/Ton-km)

Mode	Value (gCO <sub>2</sub> /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 <sub>2</sub> 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, by Rauch (1999)  
 Classification

	Log Shipping Costs (FS) (1)	Log Import Shares (IV) (2)	N (3)
Differentiated	0.26*** (0.05)	-5.75** (2.66)	4,750
Reference Priced	0.38*** (0.04)	-5.81** (2.40)	4,104
Homogenous	0.36*** (0.07)	-9.18*** (2.86)	3,374

Notes: See notes to Table 2.

Appendix Table 3: Trade Elasticities, Instrumental-Variables Estimates, Sensitivity Analysis

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Agriculture, Forestry	-3.431 (2.182)	-4.777*** (1.806)	-2.461 (2.850)	-3.264 (3.139)	-3.015 (2.072)	-0.031 (3.163)	-9.602* (5.519)	-2.086** (0.992)
Mining	-3.212* (1.723)	-2.405 (1.513)	-1.153 (1.808)	-3.263* (1.952)	-2.943* (1.648)	-3.338** (1.685)	-2.96 (2.087)	-1.940*** (0.616)
Food, Beverages, Tobacco	-7.180** (3.323)	-6.709 (4.124)	-8.771** (3.545)	-8.141* (4.388)	-6.719** (3.070)	-5.202 (4.362)	-5.309*** (1.776)	-4.765*** (0.888)
Textiles	-24.102*** (7.549)	-13.987*** (4.610)	-27.589*** (10.128)	-24.441** (9.897)	-21.505*** (6.472)	-34.455*** (11.989)	-17.437*** (4.963)	-7.041*** (0.885)
Apparel, Leather	-6.328** (2.618)	-9.757*** (2.984)	-7.754** (3.012)	-7.915** (3.644)	-5.988** (2.425)	-14.039*** (3.876)	-9.533*** (3.231)	-4.335*** (0.903)
Wood	-6.067*** (2.137)	-7.259* (4.074)	-8.077** (3.185)	-5.383* (2.911)	-5.712*** (2.003)	-6.981*** (2.371)	-7.661*** (2.504)	-1.898*** (0.575)
Paper, Printing	-4.792 (3.398)	-3.838 (4.614)	-4.703 (5.864)	-5.234 (4.554)	-4.572 (3.084)	-4.129 (3.341)	-4.572 (4.233)	-1.194*** (0.442)
Petroleum, Coal, Minerals	-8.612*** (3.171)	-12.256*** (4.087)	-6.064* (3.291)	-9.994* (5.659)	-7.855** (3.019)	-10.583*** (3.444)	-6.480** (3.106)	-3.512*** (0.769)
Chemicals, Rubber, Plastics	-5.514** (2.454)	-2.444 (2.523)	-3.666 (3.088)	-5.471* (2.933)	-3.930** (1.946)	-5.774* (3.029)	-2.573 (3.615)	-4.090*** (0.920)
Metals	-13.849** (6.135)	-21.824** (10.597)	-13.356** (6.772)	-16.721** (8.224)	-12.135** (5.253)	-16.876*** (6.450)	-12.846 (12.314)	-5.354*** (0.735)
Machinery, Electrical	-11.042*** (2.978)	-4.516 (5.525)	-20.173** (7.772)	-11.785*** (3.815)	-8.797*** (2.200)	-12.346*** (3.246)	-10.597*** (3.648)	-7.325*** (0.701)
Transport Equipment	-6.429 (5.508)	-10.355 (6.433)	-12.045* (7.118)	-7.656 (8.651)	-5.336 (4.626)	-6.720 (6.138)	-3.56 (2.915)	-4.551*** (0.913)
Other	-6.692* (3.769)	-8.215 (8.546)	-16.818** (7.373)	-7.350 (4.855)	-6.916* (3.623)	-8.254** (4.102)	-16.712** (6.922)	-3.301*** (0.547)
Mean Across Sectors	-8.250	-8.334	-10.202	-8.971	-7.340	-9.902	-8.449	-3.953
Correlation with Table 2, Col. 4	0.85	0.70	0.89	0.87	0.88	0.88	0.88	0.65
Quarters 1,4 instrument quarters	Yes	No	No	No	No	No	No	No
Quarters 1,2 instrument quarters	No	Yes	No	No	No	No	No	No
GLS weights	No	No	Yes	No	No	No	No	No
log(x+0.00001)	No	No	No	Yes	No	No	No	No
Include tariffs in shipping cost	No	No	No	No	Yes	No	No	No
Control separately for tariffs	No	No	No	No	No	Yes	No	No
Full year FE estimates	No	No	No	No	No	No	Yes	No
Cross sectional estimates	No	No	No	No	No	No	No	Yes

Notes: The 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 4. An observation represents a good-exporter-importer-year. Cross-sectional estimates include origin FE, destination FE, and year FE only. All standard errors clustered by importer-exporter pair. \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.10$ .

Appendix Table 4. Sensitivity to Model Assumptions, Full Welfare Effects of International Trade (Billions of US\$)

Model	Gains from Trade	Environmental Costs of Trade	Change in Welfare	Change in Welfare (Percentage Points)		
				Richest	Middle	Poorest
	(1)	(2)	(3)	(4)	(5)	(6)
1. Main results	5,359	-59	5,389	9	11	14
2. Social Cost of CO <sub>2</sub> =\$11/ton	5,359	-22	5,371	9	11	14
3. Social Cost of CO <sub>2</sub> =\$77/ton	5,359	-156	5,439	9	11	14
4. Proportional Climate Damages	5,359	-59	5,390	9	11	14
5. Social Cost of CO <sub>2</sub> =\$200/ton, Proportional Climate Damages	5,359	-404	5,567	9	11	15
6. Trade Elasticity = -4.14	4,483	-59	4,517	8	8	12
7. Trade Elasticity = -8.28	2,305	-62	2,353	4	4	6
8. Trade Elasticities: AT 3, Column 1	3,121	-60	3,165	6	5	8
9. Trade Elasticities: AT 3, Column 2	4,290	-60	4,329	7	8	11
10. Trade Elasticities: AT 3, Column 3	4,893	-58	4,929	9	8	11
11. Trade Elasticities: AT 3, Column 4	2,963	-60	3,008	5	5	7
12. Trade Elasticities: AT 3, Column 5	3,614	-60	3,655	6	6	9
13. Trade Elasticities: AT 3, Column 6	13,168	-51	13,189	22	26	31
14. All Domestic Mode Shares from CFS	5,359	-105	5,430	9	11	14

Notes: See paper text for additional details on each row. Columns (1) through (3) are in US\$ billions. "AT 3" refers to Appendix Table 3. Columns (4)-(6) separate countries into three groups of 42-43 countries based on 2007 GDP per capita. The GDP per capita ranges defining each group are: above \$14,000; \$2,400 to \$14,000; and below \$2,400.

Appendix Table 5. Sensitivity to Model Assumptions, Carbon Taxes (Billions of US\$)

Model	Gains from Trade (1)	Environmental Costs of Trade (2)	Change in Welfare					
			Global (3)	EU (4)	US (5)	Basis Points		
						Richest (6)	Middle (7)	Poorest (8)
<u>Panel A: EU Carbon Tax for Air Shipping</u>								
1. Main Results	-2.90	-3.80	0.90	28.70	-7.20	0.34	-0.76	-1.57
2. SCC=\$11	-0.11	-0.31	0.20	4.54	-1.04	0.06	-0.13	-0.25
3. SCC=\$77	-2.90	-10.08	7.18	32.15	-6.72	0.45	-0.67	-1.29
4. Proportional Climate Damages	-2.90	-4.12	1.22	27.93	-6.40	0.35	-0.73	-1.66
5. SCC=\$200, Proportional Damages	-12.05	-51.00	38.95	75.92	-5.54	1.44	-0.98	-3.26
6. Trade Elasticity = -4.14	-2.15	-2.83	0.68	31.97	-7.66	0.39	-0.92	-1.70
7. Trade Elasticity = -8.28	-3.07	-3.94	0.87	28.71	-7.48	0.34	-0.78	-1.53
8. Trade Elasticities: AT 3, Column 1	-2.92	-3.77	0.85	28.03	-7.38	0.32	-0.71	-1.51
9. Trade Elasticities: AT 3, Column 2	-3.09	-4.04	0.95	30.51	-7.47	0.36	-0.83	-1.55
10. Trade Elasticities: AT 3, Column 3	-2.84	-3.59	0.75	25.52	-7.29	0.29	-0.59	-1.47
11. Trade Elasticities: AT 3, Column 4	-3.06	-3.97	0.90	27.76	-7.36	0.32	-0.70	-1.48
12. Trade Elasticities: AT 3, Column 5	-2.76	-3.58	0.83	29.07	-7.40	0.34	-0.76	-1.56
13. Trade Elasticities: AT 3, Column 6	-2.97	-3.89	0.93	27.85	-7.30	0.32	-0.68	-1.53
14. All Domestic Mode Shares from CFS	-0.60	-1.85	1.25	11.98	-2.69	0.16	-0.30	-0.60
15. Endogenous Mode Share Shifts	-2.90	-3.41	0.51	28.48	-7.24	0.33	-0.76	-1.58
16. Detailed Inter-Industry Links	-0.45	-0.86	0.40	4.38	-0.88	0.06	-0.11	-0.23
<u>Panel B: US Carbon Tax for All Shipping</u>								
1. Main Results	-2.38	-9.33	6.95	-1.17	30.15	0.46	-0.77	-1.20
2. SCC=\$11	-0.36	-1.39	1.03	-1.70	12.12	0.16	-0.33	-0.56
3. SCC=\$77	-14.96	-60.73	45.77	17.88	69.08	1.58	-1.42	-1.39
4. Proportional Climate Damages	-2.38	-10.12	7.74	-3.06	32.13	0.48	-0.72	-1.43
5. SCC=\$200, Proportional Damages	-80.91	-377.53	296.56	86.46	198.98	6.84	1.65	-2.57
6. Trade Elasticity = -4.14	-2.35	-9.06	6.70	-1.01	29.23	0.45	-0.76	-1.18
7. Trade Elasticity = -8.28	-2.70	-10.24	7.54	0.04	20.05	0.34	-0.36	-0.80
8. Trade Elasticities: AT 3, Column 1	-2.40	-9.38	6.98	-0.73	28.86	0.45	-0.73	-1.17
9. Trade Elasticities: AT 3, Column 2	-2.37	-9.63	7.26	0.46	22.25	0.37	-0.43	-1.11
10. Trade Elasticities: AT 3, Column 3	-2.30	-9.08	6.78	-2.07	36.01	0.54	-1.03	-1.36
11. Trade Elasticities: AT 3, Column 4	-2.42	-9.48	7.07	-0.56	28.31	0.44	-0.71	-1.15
12. Trade Elasticities: AT 3, Column 5	-2.36	-9.20	6.84	-0.73	29.26	0.46	-0.75	-1.23
13. Trade Elasticities: AT 3, Column 6	-2.40	-9.06	6.66	-0.82	32.13	0.50	-0.87	-1.43
14. All Domestic Mode Shares from CFS	-5.25	-23.02	17.77	2.97	13.34	0.35	0.17	0.47
15. Endogenous Mode Share Shifts	-2.38	-9.33	6.95	-1.17	30.15	0.46	-0.77	-1.20
16. Detailed Inter-Industry Links	-12.77	-3.37	-9.40	-0.37	0.47	-0.10	-0.37	-0.41
<u>Panel C: Global Carbon Tax for Air &amp; Sea Shipping</u>								
1. Main Results	-6.53	-16.71	10.18	18.00	3.47	0.53	-0.72	-1.29
2. SCC=\$11	-1.05	-2.60	1.55	5.25	1.08	0.16	-0.31	-0.61
3. SCC=\$77	-36.77	-100.76	63.98	72.57	12.64	2.02	-1.43	-1.51
4. Proportional Climate Damages	-6.53	-18.13	11.60	14.61	7.02	0.57	-0.62	-1.69
5. SCC=\$200, Proportional Damages	-168.85	-567.36	398.34	204.45	158.79	9.65	1.54	-7.07
6. Trade Elasticity = -4.14	-5.81	-14.55	8.74	17.90	1.96	0.56	-0.85	-1.65
7. Trade Elasticity = -8.28	-9.04	-21.01	11.97	19.54	1.17	0.54	-0.61	-1.24
8. Trade Elasticities: AT 3, Column 1	-6.51	-16.55	10.04	17.17	3.08	0.50	-0.64	-1.18
9. Trade Elasticities: AT 3, Column 2	-6.64	-17.14	10.50	20.17	2.54	0.56	-0.88	-1.02
10. Trade Elasticities: AT 3, Column 3	-5.14	-14.12	8.98	12.72	3.52	0.40	-0.42	-1.01
11. Trade Elasticities: AT 3, Column 4	-6.78	-17.20	10.42	17.38	2.99	0.50	-0.64	-1.09
12. Trade Elasticities: AT 3, Column 5	-6.11	-15.73	9.62	17.60	3.26	0.52	-0.73	-1.28
13. Trade Elasticities: AT 3, Column 6	-6.55	-16.85	10.30	17.34	4.03	0.50	-0.61	-1.23
14. All Domestic Mode Shares from CFS	-6.61	-14.86	8.24	18.44	5.30	0.55	-0.96	-1.30
15. Endogenous Mode Share Shifts	-6.53	-17.83	11.30	18.61	3.55	0.55	-0.70	-1.24
16. Detailed Inter-Industry Links	-37.60	-7.68	-29.93	0.96	-2.82	-0.35	-1.00	-1.35

Notes: Numbers represent total effects over a decade. Columns (1) through (5) represent billions of 2007 US\$. "AT 3" refers to Appendix Table 3. Columns (6)-(8) separate countries into three groups of 42-43 countries based on 2007 GDP per capita. The GDP per capita ranges defining each group are: above \$14,000; \$2,400 to \$14,000; and below \$2,400.

Appendix Table 6. Country-by-Country Estimates

	Gains from International Trade (\$Bn)	Environmental Costs of International Trade (\$Bn)	Welfare Change in Basis Points due to . . .		
			EU Regulation		Global
			Regulation	US Regulation	Regulation
	(1)	(2)	(3)	(4)	(5)
Albania	1.80	-0.01	-0.62	-1.87	-1.98
Argentina	24.84	-0.25	-0.77	1.08	-6.18
Armenia	1.67	-0.01	-0.59	-1.18	-0.29
Australia	68.36	0.00	-1.39	-0.43	-4.86
Austria	63.67	-0.41	1.36	0.17	0.40
Azerbaijan	10.12	-0.03	-2.08	6.12	6.53
Bahrain	3.17	-0.01	-1.35	1.81	1.02
Bangladesh	10.51	-0.07	-1.57	-1.34	0.62
Belarus	16.32	-0.01	0.73	0.41	4.81
Belgium	299.15	-0.51	2.99	-0.85	2.55
Bolivia	3.32	-0.01	-0.96	0.42	2.72
Botswana	4.73	-0.02	-11.98	0.96	-9.17
Brazil	56.99	-1.27	-0.24	0.25	-3.49
Bulgaria	13.67	-0.01	1.26	-1.94	0.90
Cambodia	2.81	-0.01	-2.79	-5.37	-8.37
Cameroon	1.73	-0.03	-1.91	0.81	-1.05
Canada	141.12	0.00	-0.66	-2.52	0.37
Caribbean	23.70	-0.25	-0.71	-1.25	1.40
Chile	19.59	-0.12	-1.94	0.66	1.22
China	320.93	-0.29	-0.89	-1.07	-0.22
Colombia	18.76	-0.14	-0.74	-0.71	-1.62
Costa Rica	6.30	-0.02	-4.30	-0.93	-0.50
Cote D Ivoire	2.79	-0.03	-2.41	3.61	4.29
Croatia	13.23	-0.02	-0.25	-1.84	-0.50
Cyprus	3.83	-0.02	0.00	-3.03	-2.57
Czech Republic	45.86	-0.05	2.66	0.03	1.25
Denmark	33.83	-0.35	0.98	0.00	0.86
Ecuador	16.21	-0.03	-2.27	-0.90	-2.85
Egypt	25.49	-0.13	-0.97	-3.87	1.49
El Salvador	16.92	-0.01	-0.95	-5.06	0.67
Estonia	8.46	-0.01	0.39	-1.78	-1.99
Ethiopia	2.34	-0.03	-1.60	-1.54	-1.82
Finland	34.00	-0.27	1.68	0.34	1.17
France	239.11	-2.93	1.17	-0.04	0.61
Georgia	3.29	-0.01	-0.98	-2.19	-1.17
Germany	342.36	-3.70	2.57	0.49	1.60
Ghana	5.08	-0.04	-1.94	-0.95	0.88
Greece	40.58	-0.35	-0.06	-1.84	-1.08
Guatemala	7.62	-0.04	-1.39	-3.76	-0.48
Honduras	3.55	-0.01	-2.03	-9.40	-3.05
Hong Kong	69.41	0.00	-2.67	-2.94	-2.04
Hungary	31.60	-0.04	2.72	-0.37	1.24
India	93.03	-2.32	-0.62	-0.24	1.67
Indonesia	33.93	-0.44	-2.24	-0.24	-2.25
Iran	32.20	-0.20	-0.66	1.22	-3.11
Ireland	22.28	-0.29	3.40	1.99	3.27
Israel	28.17	0.00	-0.73	-2.60	0.44
Italy	213.92	-2.37	1.34	0.04	1.21
Japan	351.48	-0.85	0.00	-0.77	1.51
Kazakhstan	16.88	-0.07	-1.83	1.37	1.82
Kenya	8.45	-0.04	-2.95	-1.26	0.53
Korea	134.53	-1.00	-0.35	-1.03	3.07
Kuwait	13.63	-0.09	-6.78	1.40	-33.79
Kyrgyzstan	2.10	0.00	-1.03	-2.50	-1.81
Laos	2.07	0.00	-9.16	0.25	-3.49

Appendix Table 6. Country-by-Country Estimates

	Gains from International Trade (\$Bn)	Environmental Costs of International Trade (\$Bn)	Welfare Change in Basis Points due to . . .		
			EU Regulation	US	Global
				Regulation	Regulation
(1)	(2)	(3)	(4)	(5)	
Latvia	6.50	-0.01	-0.13	-1.96	-2.02
Lithuania	11.42	-0.01	0.50	-1.40	0.10
Luxembourg	12.30	-0.06	1.29	-0.14	-0.08
Madagascar	0.94	-0.01	-5.93	-0.89	-3.02
Malawi	1.04	-0.01	-9.44	-3.28	-9.33
Malaysia	25.27	-0.17	-3.40	-3.29	0.51
Malta	3.48	-0.01	0.73	-4.65	-3.26
Mauritius	1.19	-0.01	-15.23	-2.53	-6.23
Mexico	109.18	-0.72	-0.39	-4.79	1.08
Mongolia	1.17	0.00	-5.38	1.60	15.28
Morocco	11.39	-0.05	-1.06	-4.01	0.59
Mozambique	1.99	-0.01	-7.01	-2.32	-3.37
Namibia	2.32	-0.01	-9.65	-1.22	-7.19
Nepal	1.40	-0.01	-0.49	-1.02	-1.02
Netherlands	54.45	-0.87	1.78	0.93	2.16
New Zealand	12.67	0.00	-1.70	-0.02	-0.99
Nicaragua	2.58	-0.01	-2.43	-6.27	-1.60
Nigeria	20.08	-0.25	-1.65	-2.56	-13.45
Norway	30.84	-0.43	1.30	1.57	1.60
Oman	8.80	-0.03	-3.14	1.33	-0.02
Pakistan	19.34	-0.15	-0.73	-1.21	0.27
Panama	4.27	-0.01	-1.68	-10.27	-5.31
Paraguay	6.29	-0.01	-0.89	-1.90	0.97
Peru	9.16	-0.08	-1.29	1.20	0.57
Philippines	28.04	-0.15	-0.76	-1.86	1.72
Poland	70.52	-0.12	0.73	-0.59	0.40
Portugal	36.44	-0.26	1.00	-0.76	0.60
Qatar	5.16	-0.06	-1.65	1.05	-3.68
Rest of Central Africa	4.61	-0.06	-5.75	-2.55	-22.15
Rest of Central America	0.41	0.00	-4.37	-1.95	-3.22
Rest of East Asia	2.49	-0.03	-1.15	-0.81	-1.08
Rest of Eastern Africa	5.63	-0.09	-1.07	0.15	1.87
Rest of Eastern Europe	2.68	0.00	-1.06	-3.51	-2.27
Rest of EFTA	3.51	-0.03	1.35	-1.16	-0.36
Rest of Europe	17.07	0.00	-0.77	-1.91	-1.32
Rest of Fmr. Soviet Union	12.95	-0.04	-3.51	4.31	-1.08
Rest of North Africa	32.66	-0.15	0.73	3.26	2.66
Rest of North America	1.38	-0.01	-1.70	-2.55	-2.67
Rest of Oceania	5.00	-0.02	-4.04	-0.07	-1.71
Rest of SACU	0.23	-0.01	-10.14	0.27	-5.95
Rest of South America	1.43	-0.01	-8.40	-1.82	-6.01
Rest of South Asia	3.20	-0.01	-2.50	-2.24	-1.37
Rest of South Central Africa	12.29	-0.10	-4.08	-7.66	-40.70
Rest of Southeast Asia	7.35	-0.03	-2.89	0.52	-2.53
Rest of Western Africa	8.09	-0.06	-1.88	-5.68	-5.24
Rest of Western Asia	43.87	-0.14	-3.33	-3.45	-5.76
Romania	28.16	-0.05	0.31	-1.34	-0.40
Russian Federation	90.23	0.00	-1.00	1.06	-1.56
Saudi Arabia	36.04	-0.29	-4.04	0.26	-22.74
Senegal	1.99	-0.02	-2.58	-1.36	1.67
Singapore	53.52	0.00	-2.24	-1.51	10.38
Slovakia	22.70	-0.02	1.96	-0.39	1.56
Slovenia	12.56	-0.01	0.98	-0.60	-0.20
South Africa	33.12	-0.20	-3.10	-0.26	0.46
Spain	170.40	-1.60	1.14	-0.64	0.96

Appendix Table 6. Country-by-Country Estimates

	Gains from International Trade (\$Bn)	Environmental Costs of International Trade (\$Bn)	Welfare Change in Basis Points due to . . .		
			EU Regulation	US Regulation	Global Regulation
	(1)	(2)	(3)	(4)	(5)
Sri Lanka	4.71	-0.03	-3.64	-2.28	-2.59
Sweden	56.54	-0.51	1.91	0.32	0.84
Switzerland	61.17	-0.48	0.44	0.04	0.42
Taiwan	77.24	-0.38	-2.09	-2.17	4.50
Tanzania	4.84	-0.03	-2.91	-0.64	-0.71
Thailand	48.04	-0.17	-2.15	-1.31	0.69
Tunisia	7.57	-0.02	-0.48	-2.39	0.87
Turkey	74.20	-0.47	-0.27	-1.00	0.59
Uganda	1.69	-0.02	-5.88	0.45	-1.49
Ukraine	59.30	-0.04	-0.14	-1.59	-0.08
United Arab Emirates	39.15	-0.16	-3.16	-1.21	-1.23
United Kingdom	235.92	-3.11	1.54	-0.37	0.57
USA	601.67	-2.46	-0.48	2.01	0.23
Uruguay	5.25	-0.02	-1.64	-0.06	-2.22
Venezuela	17.66	-0.16	-0.40	4.45	-5.42
Viet Nam	32.60	-0.07	-7.03	-3.25	-8.90
Zambia	2.10	-0.02	-8.49	1.99	-3.93
Zimbabwe	1.97	-0.01	-4.97	-0.92	-0.39