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Trade Costs, CO_2, and the Environment†

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This paper quantifies how international trade affects CO_2 emissions and analyzes the welfare consequences of regulating the CO_2 emissions from shipping. To this end, the paper describes a model of trade and the environment, compiles new data on the CO_2 emissions from shipping, and estimates key parameters using panel data regressions. Results show that the benefits of international trade exceed trade's environmental costs due to CO_2 emissions by two orders of magnitude. While proposed regional carbon taxes on the CO_2 emissions from shipping would increase global welfare and increase the implementing region's GDP, they would also harm poor countries. (JEL F18, H23, H87, L92, Q54, Q56)

This paper builds a theoretical and empirical framework that can quantify the environmental costs of international trade due to CO_2 and analyze the welfare consequences of counterfactual policies that would regulate the CO_2 emissions from shipping. To this end, the paper describes a model of trade and the environment, compiles new data on CO_2 emissions from international and intranational shipping, and estimates the model's key parameters via 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_2 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; and 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_2 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 European Union has sought to regulate both passenger and

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goods transportation by air. I also analyze US regulations of CO_2 emissions from all forms of shipping, which were part of the Waxman-Markey Bill of 2009 that passed the US House of Representatives but not the US Senate. Finally, I analyze a global tax on the CO_2 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_2 emissions from international transportation exceeds the CO_2 emissions growth rate from any other sector (International Energy Agency (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 gross domestic product (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 Rodríguez-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 the North American Free Trade Agreement (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 United States, which both have panel data on shipping costs. Hertel et al. (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 of 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 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 population (Goldewijk et al. 2011). For 13 sectors of production, 5 modes of transportation, and 128 countries, these data measure how economic activity affects carbon emissions, representing nearly 1 million carbon emission estimates. Together, these provide a complete accounting of carbon emissions from the global economy. These data show that CO_2 emissions from international and intranational shipping account for about 4 and 5 percent, respectively, of total global CO_2 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_2 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 European Union and United States benefit disproportionately from unilateral regulation; and international trade's benefits are orders of magnitude larger than international trade's environmental costs due to CO_2.

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 2014a). 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 (CGE) models require a huge number of assumptions (Mestelman 1982; Copeland and Taylor 2003; Böhringer, Carbone, and Rutherford 2013; and Davis and Hausman 2016). 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 1 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 I outlines the theory. Section II describes the paper's data. Section III describes measures of the CO_2 emissions from shipping. Section IV reports new estimates of the trade elasticities. Section V measures the full welfare effects of international trade. Section VI applies the model to evaluate EU, US, and global carbon taxes. Section VII describes sensitivity analyses, and Section VIII concludes.

I. 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 et al. 2003) would generate equivalent welfare calculations to this model. The equivalence between these models and Armington models is clear in standard trade settings (Arkolakis, Costinot, and Rodríguez-Clare 2012). That equivalence persists in this framework because the equations determining equilibrium production and consumption, as described in Section IB, 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.

A. *Primitive Assumptions*

ASSUMPTION 1 (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:*

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

$$Q_d^j = \left(\sum_{o=1}^{N} \left(Q_{od}^j\right)^{\frac{\sigma^j - 1}{\sigma^j}}\right)^{\frac{\sigma^j}{\sigma^j - 1}}.$$

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 α_d^j of its expenditure on sector j. Total CO_2 emissions due to country o are E_o, and the parameter μ_d dictates the social cost of CO_2 emissions.[1] CO_2 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:

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

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 $P_d \equiv \Pi_{j=1}^J (p_d^j)^{\alpha_d^j}$. 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_2 emissions affect climate. Assumption (1) approximates those models by using a quadratic damage function to summarize both how CO_2 emissions affect climate and how climate affects utility. For this paper's counterfactuals, this specification provides

[1] 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 et al. (2014). These parameters represent the following thought experiment: if the world marginally increased CO_2 emissions, this would change CO_2 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.

a marginal social cost of carbon emissions, which is nearly constant. For changes in CO_2 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 1 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 μ_d quantifies the magnitude of climate damages such as diminished human health. I rely on the large climate change literature to measure μ_d; it is the only parameter in this paper that cannot be determined within the model. The climate change literature assumes utility functions which are similar but not identical to equation (1). For example, the 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 α_d^j and climate damages μ_d to vary across countries. This assumption does not allow elasticities of substitution σ^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 μ_d to match leading estimates of the global distribution of climate change's costs, as described in Section II.

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

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

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 μ_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 μ_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.

ASSUMPTION 2 (Production Technology and Market Structure): *Firms have Cobb-Douglas production technology and trade costs that take the "iceberg form," where $\tau_{od}^j \geq 1$ units must be shipped for one to arrive:*

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

$$p_{od}^j = c_o^j \tau_{od}^j. \tag{3b}$$

Labor has price w_o and share β_o^j. Intermediate goods have price p_o^j and share $1 - \beta_o^j$. Firms engage in perfect competition and arbitrage price gaps over space, so the product price at destination d equals the production cost c_o^j multiplied by a trade cost τ_{od}^j. This cost function arises if output in each sector is combined into an intermediate good specific to that sector. Production uses the same CES price aggregator as consumption, so p_o^j represents both the consumer price index and the price of intermediate goods shown in (3a). Assumption 3 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.

ASSUMPTION 3 (Transportation Technology): *Trade costs can be decomposed as follows:*

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

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

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

Here t_{od}^j represents the carbon tax per dollar of expenditure, f_{od}^j represents the fuel cost per dollar of expenditure, and δ_{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 δ_{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 et al. (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 κ_{odm} represents the share of o–d trade in dollars transported by mode m. The variable W_{odm} represents the weight-to-value ratio for goods traded between countries o and d by mode m. The variable ξ_m represents the fuel efficiency of transportation mode m, defined in grams of CO_2 emitted per ton-kilometer (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_2, and $t_{odm}^{j,M}$ represents the carbon tax rate for imports. The constants γ_1 and γ_2 convert units of measurement.[2] I treat the global

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

oil supply as perfectly elastic, so shifts in oil demand due to counterfactuals do not affect pretax oil prices. These equations embody two important restrictions: they assume perfect competition in the transport sector and imply that the counterfactual analyses will treat D_{odm}, κ_{odm}, W_{odm}, and ξ_{odm} as fixed.

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 that use other transport modes. For a given country pair and sector, however, mode shares are fixed in counterfactuals. Online Appendix Table A5 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.

ASSUMPTION 4 (Environment): *Trade and production generate CO_2 emissions as follows:*

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

Equation (5) shows how trade contributes to carbon emissions by incorporating CO_2 emissions from both production and transportation. Here, χ_o^j represents the CO_2 emissions per unit of output for sector j in country o, and the constant γ_3 represents tons of CO_2 emitted per dollar of fuel. The ratio X_{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_2 emissions rates from production (χ_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_2 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 end-of-pipe abatement technologies for CO_2 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, no such technologies exist for carbon dioxide.

B. *Competitive Equilibrium*

ASSUMPTION 5 (Market Clearing): *Consumers maximize utility, firms maximize profits, and markets clear.*

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

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

Here λ_{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.[3]

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

Market clearing implies that imports equal exports for each country:

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

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

[3] 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).

C. *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, Eaton, and Kortum 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

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

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.

D. *From Theory to the Data*

In applying this model to counterfactuals, three objects play key roles: the effect of carbon regulations on trade costs ($\hat{\tau}^j_{od}$), trade elasticities (θ^j), and bilateral expenditure shares (λ^j_{od}). The data $\hat{\tau}^j_{od}$ measure how a specific regulation changes trade costs for each sector and country pair. Section II describes data which measure $\hat{\tau}^j_{od}$ as a function of fuel costs per dollar of trade (f_{od}), using equation (4a). The elasticities θ^j represent the causal effect of log bilateral trade costs on log bilateral trade flows for sector j, holding wages and prices in each country fixed. These estimates, shown in Section IV, help analyze the effects of the counterfactuals I study because each counterfactual is equivalent to a change in trade costs. Although I estimate θ^j with data from specific countries and years, under Assumption (1), θ^j describes the effects of trade costs for any country and years. The data λ^j_{od} 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 θ^j. Trade balance defines market equilibrium, which pins down the effect of a policy on wages. The measure of welfare is used to evaluate counterfactuals.

E. *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_2 emissions, then apply an estimate of the "social cost of carbon" to measure environmental benefits (Li, Linn, and Spiller 2013; Holland et al. 2015; and Davis and Hausman 2016). 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, demand elasticities, and assumptions to analyze comparative statics (Babiker 2005; Nijkamp, Wang, and Kremers 2005; and Böhringer, Carbone, and Rutherford 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, Copeland, and Taylor 2001, Copeland and Taylor 2003, and 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_2 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_2 emissions accrue to foreign countries, so the effects of income growth on CO_2 regulations is likely to be smaller than for local pollutants like SO_2 (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, Eaton, and Kortum 2008, Head and Mayer 2014a). The model builds on this literature by accounting for the environmental costs of trade due to CO_2.

II. 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.

A. *CO_2 Emissions from Trade*

Measuring CO_2 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 intranational 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 intranational distances as $0.67\sqrt{area/\pi}$ (Head and Mayer 2014b) 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 (1962)–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 measures 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 (κ^j_{odm}) are the most difficult to obtain since most public datasets do not identify transport modes. To compile these data, I obtained several files which together cover 83 percent of international trade by value and 74 percent of global trade by weight (see the online 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 online 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 this is the only statistical model that fits the requirements of the data. Ordinary least squares (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_2 Emissions from Trade.—Online 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_2 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 (2013) estimate of CO_2 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. (2013) matches published estimates of total CO_2 from all air transportation, but their estimate only represents freight, which accounts for only a third of all air ton-km transportation (IATA 2009).

B. *Shipping Costs for Estimating Trade Elasticities*

I use quarterly reports of transportation costs and trade values for all US imports and Australian imports over the period 1991–2010. Only these countries could provide panel data on transport costs for many sectors and years. The period for which I obtained quarterly data covering both countries is 1991–2010. 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 online Appendix explains how I translate these data into the 13 sectors I analyze.

C. *Counterfactuals: Welfare Effects of International Trade and EU, US, and Global Carbon Taxes*

I use data on bilateral trade, gross output, and CO_2 emissions from production for the year 2007 from GTAP. These data report values for 128 countries and 57 sectors.

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 1 non-tradable sector, which are comparable across all the datasets used in this paper.

The only parameter this paper cannot estimate is μ_d, which is isomorphic to the social marginal cost of CO_2 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_2. The paper does not estimate this parameter because μ_d aggregates information that is beyond the scope of this paper: the damages of climate change (e.g., diminished human health), the atmospheric processes translating CO_2 emissions into climate change, and the trends and discounting of these values over future centuries to obtain their present value.

I choose the values of μ_d so that a one ton increase in CO_2 emissions decreases global GDP by \$29. Specifically, I differentiate equation (2) with respect to $\sum E_o$, then solve for the values of μ_d, which make the marginal global social cost of carbon equal \$29. Online Appendix Table A5 studies alternative numbers for this value. The \$29 figure reflects the most recent estimate of the marginal social cost of CO_2 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: the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND), the Dynamic Integrated Climate-Economy Model (DICE), and the Policy Analysis of the Greenhouse Effect (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_2 reflects a 5 percent 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 percent (Interagency Working Group on the Social Cost of Carbon 2013). For comparison, I also investigate the consequences of assuming that climate damages μ_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 2013, 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 μ_d so that the global impact of marginal increases in CO_2 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, 4–44) (see online Appendix A.6 for details). I also report results assuming that the damages of carbon emissions are proportional across countries.

III. CO_2 Emissions from Trade

This paper compiles data on the CO_2 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.

TABLE 1—TOTAL GREENHOUSE GAS EMISSIONS IN 2007 (*millions of tons of CO_2*)

Source	International (1)	Domestic (2)	Total (3)
Panel A. CO_2 emissions by transport mode and type			
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
Panel B. CO_2 emissions by region			
United States	346	5,993	6,339
European Union	695	4,124	4,819
Other	1,363	16,848	18,211

Notes: All values represent millions of tons of CO_2 in the year 2007. Section II 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.

The CO_2 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_2 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_2 emissions in 2007 of 29.4 gigatons. Other sources report similar global estimates (Marland, Boden, and Andres 2010; IEA 2011). Goods production is responsible for about 90 percent of global CO_2 emissions.

Differences in CO_2 emissions from shipping across countries presage this paper's finding that poor countries lose the most from rising prices of shipping fuels. Shipping fuel emissions depend on the weight-to-value ratio of goods, the distance goods are shipped, and the mode used for transportation, which all vary across the globe (online Appendix Figure A1). 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 United States and European Union. 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 online Appendix Figure A1 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_2 as ships do to move one ton-km (online Appendix Table A1). In part because air shipment is so costly, road trade accounts for most freight—trucks account for 63 percent of all CO_2 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 multiregion input-output matrices provides accounting measures of international CO_2 flows (e.g., Davis and Caldeira 2010), but does not allow prices or wages to change in counterfactuals.

IV. Estimation of Trade Elasticities

A. *Methodology: Trade Elasticities*

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

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

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

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 θ^j. A second challenge 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; Limão and Venables 2001; and 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 δ_{od} and ε_{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 θ.

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 δ_{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 θ^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, and 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 Van 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 θ^j:

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

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

Here $s_{ody}^{j,A}$ represents a measure of shipping costs from quarters two and three, and $s_{ody}^{j,B}$ represents a measure of shipping costs from quarters one and four. The online 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, Berger, and Scott 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 that could contribute to identify s_{ody}^{B} (Feyrer 2009a, b). 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 2 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. Online Appendix Table A3 finds that controlling for tariffs obtains sector-by-sector estimates which have a correlation of 88 percent with the main results. Online Appendix Table A5 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, Duflo, and Mullainathan 2004).

B. *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 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 θ 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 ten for weak instruments (Staiger and Stock 1997).

TABLE 2—TRADE ELASTICITIES, INSTRUMENTAL VARIABLES ESTIMATES

Dependent variable: Regression type	log import shares OLS (1)	log import shares FE (2)	log shipping costs FS (3)	log import shares IV (4)	Observations (5)
Panel A. Economy-wide estimates					
Overall	−20.947	−3.709	0.207	−7.908	4,830
	(2.614)	(1.773)	(0.050)	(4.346)	
Overall: Manufacturing	−24.637	−4.238	0.218	−7.326	4,800
	(1.855)	(1.053)	(0.043)	(4.365)	
Panel B. Sector-specific estimates					
Agriculture, forestry	−4.727	−3.409	0.289	−3.338	3,316
	(1.855)	(1.010)	(0.066)	(3.628)	
Mining	−5.003	−2.125	0.441	−3.450	2,150
	(1.334)	(0.929)	(0.054)	(1.273)	
Food, beverages, tobacco	−15.839	−5.202	0.477	−5.256	3,568
	(1.782)	(1.201)	(0.057)	(2.102)	
Textiles	−19.740	−6.374	0.192	−18.557	3,558
	(1.406)	(0.936)	(0.063)	(5.587)	
Apparel, leather	−18.193	−3.469	0.287	−9.949	3,612
	(1.456)	(1.215)	(0.059)	(3.491)	
Wood	−12.684	−2.568	0.321	−5.901	3,206
	(1.075)	(0.637)	(0.045)	(2.234)	
Paper, printing	−14.439	−1.881	0.196	−5.768	2,778
	(1.375)	(0.592)	(0.038)	(3.001)	
Petroleum, coal, minerals	−13.498	−3.057	0.240	−8.949	2,972
	(1.211)	(0.795)	(0.060)	(4.014)	
Chemicals, rubber, plastics	−16.074	−3.069	0.356	−1.554	3,600
	(1.716)	(1.085)	(0.053)	(3.044)	
Metals	−19.658	−5.517	0.204	−12.941	3,204
	(1.380)	(0.695)	(0.081)	(8.347)	
Machinery, electrical	−28.469	−7.963	0.240	−10.843	3,910
	(2.084)	(0.923)	(0.041)	(2.836)	
Transport equipment	−23.524	−4.505	0.235	−6.868*	2,544
	(2.566)	(1.067)	(0.070)	(3.662)	
Other	−16.644	−4.403	0.156	−12.764	3,626
	(1.133)	(0.615)	(0.052)	(4.565)	
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 United States and Australia. Data have two observations per year: one aggregating quarters two and three, and the other aggregating quarters one and four. 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 one and four of a year on shipping costs measured in quarters two and three 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 appear in parentheses.

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 (online Appendix Table A3). 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 (online Appendix Table A3, column 1). Using other quarters for the regression gives similar results (online Appendix Table A3, column 2). I also reestimate 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 (online Appendix Table A3, 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 (online Appendix Table A3, column 4). Additionally, I investigate including tariffs in shipping costs, and in a separate set of regressions, by controlling for tariffs in the regressions (online Appendix Table A3, 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 (online Appendix Table A3, 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 VII reestimates 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 alternative 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 online Appendix B for additional details.

V. 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 that 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_2. A leading undergraduate trade textbook, for example, laments how China's opening to trade has contributed to climate change but suggests that those environmental costs due to CO_2 are small relative to trade's economic benefits (Krugman, Obstfeld, and Melitz 2012, 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_2.

A. *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, $\hat{I}_d/\hat{P}_d = \prod_{j=1}^{J}\left(\hat{\lambda}_{dd}^j\right)^{\alpha_d^j/\beta_d^j\theta_d^j}$ (Arkolakis et al. 2012).

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

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

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_2. 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, λ_{dd}, combined with the trade elasticity, θ, is sufficient to describe how sending a country to autarky affects its real income. This share λ_{dd} equals one minus the import penetration ratio. This idea is emphasized in Eaton and Kortum (2002) and expanded in Arkolakis, Costinot, and Rodríguez-Clare (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 the equation apply to the more detailed features of this model—the multiplying across sectors j each with exponent α accounts for multiple sectors, and dividing by the sector-specific ratio of intermediate to final goods β 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_2 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 $E'_d = \Sigma_j(\gamma_3 f^j_{dd} + \chi^j_d) X^j_{dd}\hat{X}^j_{dd}/(p^j_{dd}\hat{p}^j_{dd})$. With the wage in country d as numéraire, we have $\hat{X}^j_{dd} = \beta^j_d X_d/X^j_{dd}$. The proportional change in domestic prices due to autarky is $\hat{p}^j_{dd} = (\hat{w}_d)^{\beta^j_d}(\hat{p}^j_d)^{1-\beta^j_d}\hat{\tau}^j_{dd}$. The choice of numéraire and assumption that autarky does not change domestic trade costs imply $\hat{p}^j_{dd} = (\hat{p}^j_d)^{1-\beta^j_d}$. The methodology behind equation (11) implies $\hat{p}^j_{dd} = (\lambda^j_{dd})^{(1-\beta^j_d)/(\beta^j_d\theta^j_d)}$. Substituting $\hat{X}^j_{dd}$ and $\hat{p}^j_{dd}$ into equation (5) gives

$$E'_d = \sum_j (\gamma_3 f^j_{dd} + \chi^j_d)(\beta^j_d X_d)(\lambda^j_{dd})^{-(1-\beta^j_d)/(\beta^j_d\theta^j_d)}. \tag{12}$$

Economic intuition for this measure of CO_2 emissions in autarky is as follows. The emissions data f^j_{dd} and χ^j_d indicate the intensity of carbon emissions from domestic transportation and production, respectively. The remaining terms describe the level of production in autarky. $\beta^j_d X_d$ describes expenditure in the baseline data, and the λ_{dd} term summarizes the effect on output of going to autarky. The role of the term λ^j_{dd} is similar to that in Arkolakis, Costinot, and Rodríguez-Clare (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_2 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, θ^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 θ^j and standard deviation equation 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 1 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

TABLE 3—ANNUAL EFFECTS OF INTERNATIONAL TRADE ON SOCIAL WELFARE (*billions of US dollars*)

	Gains from trade (1)	Enviromental costs of trade (2)	Social welfare (3)	Ratio: (1)/(2) (4)
Panel A. Global				
World	5,455	−33.8	5,485	−161
	[3,450, 27,105]	[−45, −1]	[3,499, 24,680]	[−6,853, −81]
Panel B. By region				
United States	602	−2.5	604	−245
	[393, 3,965]	[−3, 0]	[397, 3,968]	[−12,295, −126]
European Union	2,148	−18.4	2,164	−117
	[1,295, 10,777]	[−24, −1]	[1,317, 10,781]	[−4,425, −56]
Panel C. By GDP per capita				
Richest third	3,724	−24.0	3,746	−155
	[2,414, 18,031]	[−32, −1]	[2,397, 16,240]	[−6,556, −80]
Middle third	1,294	−5.3	1,298	−245
	[756, 7,219]	[−7, 0]	[745, 6,584]	[−9,286, −110]
Poorest third	437	−4.5	441	−96
	[274, 1,855]	[−6, 0]	[279, 1,856]	[−5,592, −47]

Notes: All columns represent US$(2007) in 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 95 percent confidence intervals; see the online Appendix for details. The "Richest," "Middle," and "Poorest" rows distinguish 3 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.

finite-sample approximation than the unadjusted 95 percent confidence region does. Efron (1987) describes the rationale and methodology for the bias-corrected bootstrap; online Appendix C describes this paper's implementation of this methodology in more detail.

B. *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 online Appendix Table A6 lists country-by-county 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_2 emissions by 5 percent (1.7 gigatons of CO_2 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_2 emissions from international shipping, the autarky counterfactual in this section accounts for changes in CO_2 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_2 emissions by a factor of 161 (i.e., by 2 orders of magnitude; see Figure 1). The gains from international trade exceed the environmental costs of trade due to CO_2 in every country. The global gains from international trade, at $5.5 trillion, equal 10 percent of global GDP. The environmental costs of

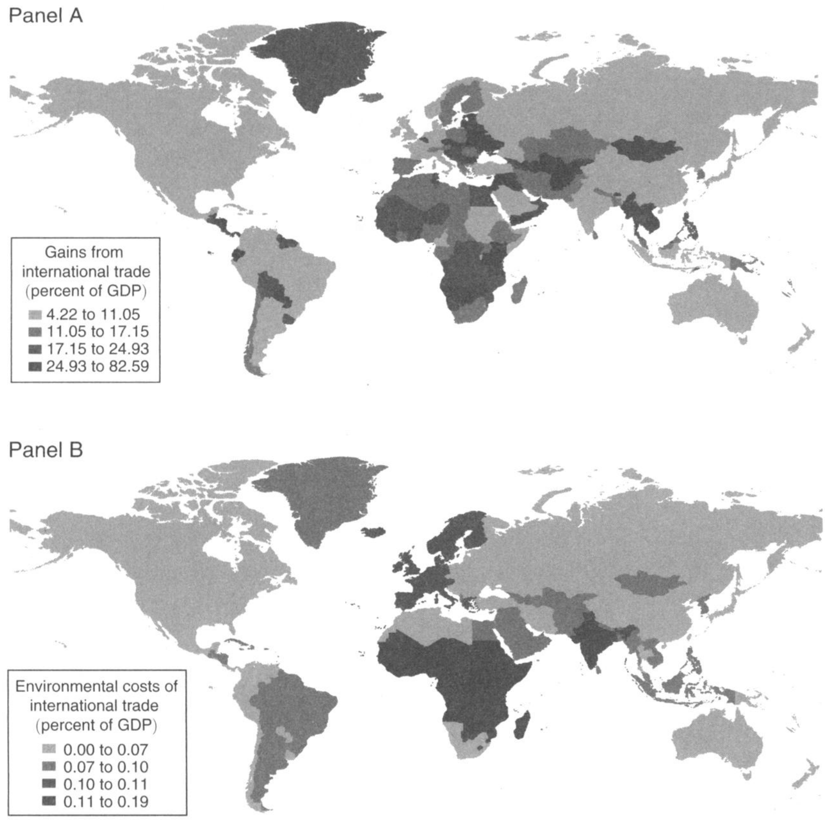

Figure 1. Benefits and Environmental Costs of International Trade by Country (*percent of GDP*)

Notes: The figure plots empirical analogues of equation (7). See main text for details on data sources.

international trade due to CO_2 equal \$34 billion. At a country level, the smallest gains from trade exceed the biggest environmental costs of trade due to CO_2.

Because international shipping accounts for a relatively small share of global CO_2 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_2 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 United States. 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 United States. 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 Trefler (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, Costinot, and Rodríguez-Clare 2012, Ossa 2015), and the confidence region indicates whether one can conclude that welfare calculations from one model differ from another.

VI. 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_2 from this sector is growing at nearly double the rate of the rest of the global economy.

A. *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_2 emissions, distributes CO_2 "allowances" to firms, then lets firms buy and sell those allowances. Each year, a regulated firm must provide the European Union with allowances to cover their regulated CO_2 emissions. In 2011, the ETS regulated CO_2 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 European Union. At the end of each year, each airline would then have to provide the European Union with allowance to cover their regulated CO_2 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_2 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 European Union initially distributed 85 percent of permits for free to airlines, whereas I treat the ETS as a carbon tax.

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

The third counterfactual analyzes the regulation of all domestic and international airborne and maritime shipping. The European Union 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 (ICAO) and the International Maritime Organization (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.

B. *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 $\hat{w}_d$:

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

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 online 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 $\sum_d w_d L_d = \sum_d w_d' L_d$. Online 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 $\left(t_{odm}^{jX}, t_{odm}^{j,M}\right)$ from \$0 to \$29 per ton of CO_2. As discussed in Section II, \$29 reflects a leading estimate of the social cost of CO_2 emissions. Online Appendix A.6 explains how I allocate the global damage to each country—essentially I use estimates 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 other certain 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 European Union 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 θ^j, as described in Section VA.

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 $\widehat{w}_d$. 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).

C. *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 online Appendix Table A6 lists values country-by-country. Each panel of Table 4 lists the effect on welfare for several groups of countries: the world, the European Union and United States, 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_2 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 European Union's gains from trade and the US policy increases the United States' 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 counterfactuals 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

TABLE 4—COUNTERFACTUAL CARBON TAXES ON SHIPPING: EFFECTS ON SOCIAL WELFARE
(*billions of US dollars*)

Group of countries	Gains from trade (1)	Environmental costs of trade (2)	Social welfare: Total (3)	Social welfare: Basis points (4)
Panel A: EU counterfactual				
All (global)	−2.9	−3.8	0.9	0.02
	[−3.4, −2.0]	[−4.5, −2.6]	[0.6, 1.2]	[0.01, 0.02]
United States	−7.5	−0.3	−7.2	−0.48
	[−7.9, −6.9]	[−0.4, −0.2]	[−7.7, −6.7]	[−0.51, −0.44]
European Union	26.6	−2.1	28.7	1.60
	[24.9, 29.6]	[−2.5, −1.4]	[27.0, 31.9]	[1.51, 1.78]
Richest third	11.6	−2.7	14.3	0.34
	[10.3, 13.8]	[−3.2, −1.9]	[12.8, 16.7]	[0.31, 0.40]
Middle third	−9.0	−0.6	−8.4	−0.76
	[−11.8, −7.8]	[−0.7, −0.4]	[−11.1, −7.3]	[−1.00, −0.66]
Poorest third	−5.5	−0.5	−5.0	−1.57
	[−6.2, −5.0]	[−0.6, −0.4]	[−5.8, −4.4]	[−1.82, −1.38]
Panel B: US counterfactual				
All (global)	−2.4	−9.3	6.9	0.12
	[−2.5, −2.2]	[−10.1, −8.5]	[6.1, 7.8]	[0.11, 0.14]
United States	29.4	−0.7	30.1	2.01
	[21.7, 39.3]	[−0.8, −0.7]	[22.5, 40.0]	[1.50, 2.67]
European Union	−6.3	−5.1	−1.2	−0.06
	[−7.6, −4.9]	[−5.6, −4.6]	[−2.8, 0.1]	[−0.16, 0.01]
Richest third	12.7	−6.6	19.3	0.46
	[8.0, 18.2]	[−7.2, −6.0]	[15.2, 24.4]	[0.36, 0.58]
Middle third	−10.0	−1.4	−8.6	−0.77
	[−14.8, −6.3]	[−1.5, −1.3]	[−13.6, −4.8]	[−1.22, −0.43]
Poorest third	−5.1	−1.3	−3.8	−1.20
	[−6.3, −4.0]	[−1.4, −1.2]	[−5.2, −2.6]	[−1.63, −0.82]
Panel C: Global counterfactual				
All (global)	−6.5	−16.7	10.2	0.18
	[−8.0, −4.8]	[−20.0, −13.2]	[8.5, 11.8]	[0.15, 0.21]
United States	2.2	−1.3	3.5	0.23
	[1.1, 3.7]	[−1.5, −1.0]	[2.4, 4.7]	[0.16, 0.31]
European Union	8.8	−9.2	18.0	1.00
	[5.5, 13.8]	[−11.0, −7.3]	[13.2, 23.0]	[0.73, 1.28]
Richest third	10.3	−11.9	22.2	0.53
	[8.5, 14.3]	[−14.2, −9.4]	[19.1, 26.2]	[0.46, 0.63]
Middle third	−10.5	−2.5	−8.0	−0.72
	[−15.3, −7.7]	[−3.0, −2.0]	[−12.7, −5.7]	[−1.14, −0.51]
Poorest third	−6.4	−2.3	−4.1	−1.29
	[−7.3, −5.6]	[−2.8, −1.8]	[−5.4, −3.1]	[−1.71, −0.99]

Notes: The first three columns represent the total effect in billions of US\$(2007) over a decade. The EU counterfactual applies a carbon tax of \$29 per metric ton of CO_2 to all EU imports, exports, and intranational trade by air. The US counterfactual applies a carbon tax of \$29 per metric ton of CO_2 to all US imports, exports, and intranational trade. The global counterfactual applies a carbon tax of \$29 per metric ton of CO_2 to all airborne and maritime imports, exports, and intranational trade. Bracketed numbers represent 95 percent confidence intervals, estimated using the bias-corrected bootstrap of Efron (1987) with B = 200 draws from the θ^j distributions of Table 2, excluding draws of $\theta^j > 0$. The "Richest," "Middle," and "Poorest" rows distinguish 3 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.

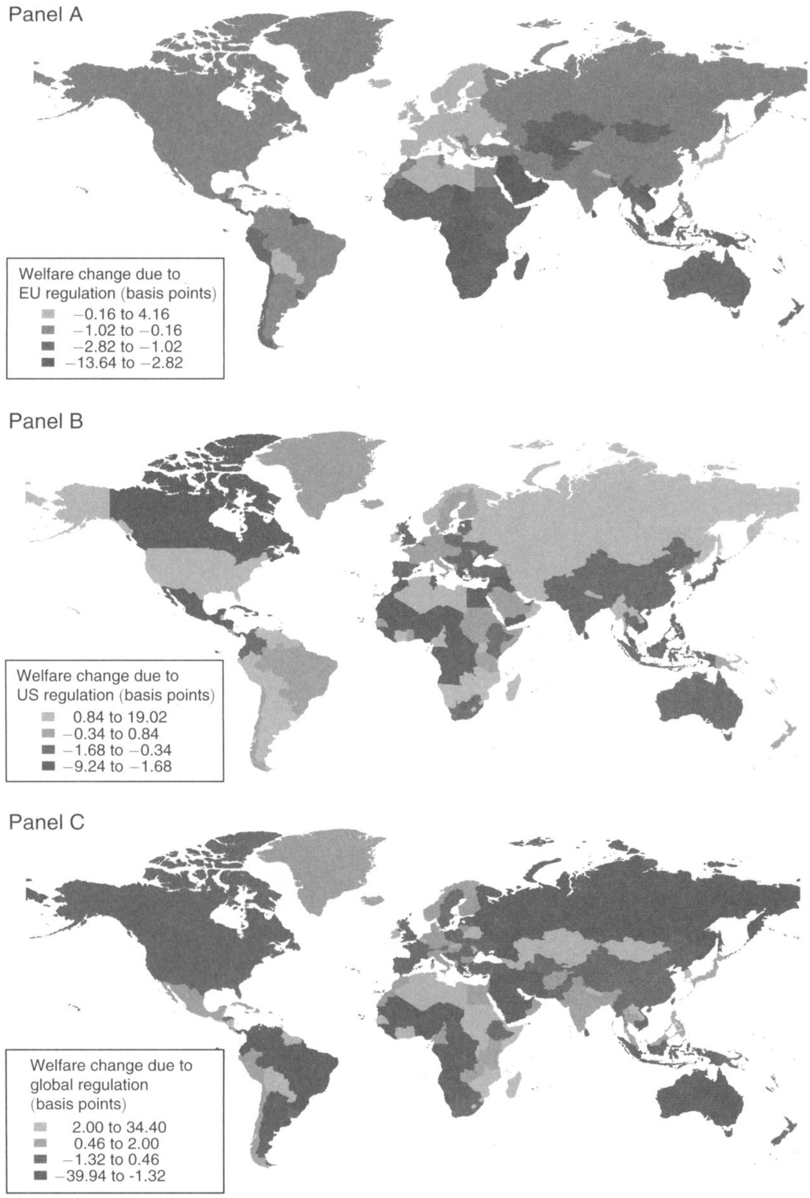

Figure 2. Impact of EU, US, and Global Climate Change Regulations on Social Welfare in Basis Points

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.

result occurs because these regulations act like a unilateral tariff that 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 policies 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_2. 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.

VII. 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 (European Union or United States) experiences a welfare gain while other countries experience a welfare loss. Online Appendix Tables A4 and A5 present results for autarky and for the specific regulations, respectively. For environmental assumptions, I consider the range of social costs of CO_2 from \$11 to \$77 estimated in the Interagency Working Group on the Social Cost of Carbon (2013), the assumption that climate damages μ_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, Judd, and Lontzek 2013). 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 European Union 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 online Appendix Table A3, the sensitivity of model results to allowing endogenous changes in mode shares,[4] 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.[5]

VIII. 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 weds a structural general equilibrium model with reduced-form estimates of key parameters. This approach has similar spirit to the literature on "sufficient statistics for welfare analysis" (Chetty 2009).

[4] Row 15 of online Appendix Table A5 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.

[5] It is worth mentioning some features of the global economy that 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 2016). 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.

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_2 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 trade may create environmental costs due to additional CO_2 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_2 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_2 emissions and divert trade to unregulated routes. These policies also create unequal incidence by increasing welfare in the implementing region and decreasing welfare elsewhere, even before accounting for environmental benefits. Nonetheless, all three of these policies increase global welfare because they decrease the environmental costs of trade more than they decrease the gains from trade. 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).

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