Kyoto and Carbon Leakage: An Empirical Analysis of the Carbon Content of Bilateral Trade*

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Abstract

Has the Kyoto Protocol induced carbon leakage? We conduct the first empirical ex-post evaluation of the Protocol. We derive a theoretical gravity equation for the CO_2 content of trade, which accounts for intermediate inputs, both domestic and imported. The structure of our new panel database of the carbon content of sectoral bilateral trade flows allows controlling for the endogenous selection of countries into the Kyoto Protocol. Binding commitments under Kyoto have increased committed countries' embodied carbon imports from non-committed countries by around 8% and the emission intensity of their imports by about 3%. Hence, Kyoto has indeed led to leakage.

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Keywords: carbon leakage, CO_2 content of trade, gravity equation, Kyoto Protocol.

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1 Introduction

Global warming caused by anthropogenic CO_2 emissions is a major public concern around the world. Because countries' greenhouse gas emissions have global effects, decentralized national regulation is inefficient. The Kyoto Protocol, an international agreement which sets binding emission targets for 37 industrialized countries and the European Union (EU), has met major criticism from its beginnings in 1997 onwards. Its *principle of common but differentiated responsibilities* excepts emerging and developing countries *en bloc* and sets widely different targets even for the 37 committed nations.[1] Countries like China or India face no binding constraints. The U.S. did not ratify the Protocol because it did not include the "meaningful" participation of all developing as well as industrialized countries, arguing that ratification would unfairly put the U.S. at a competitive disadvantage.

Related to this policy concern, economists have long pointed out the possibility of *carbon leakage*: regulation in some countries could change relative goods prices and hence shift production of CO_2-intensive goods to places that are exempt from such regulation (see, e.g. Copeland and Taylor, 2005).[2] This sort of regulatory arbitrage is particularly important if trade costs are low and falling. Carbon leakage may offset domestic emission savings achieved through stricter climate policy. It can even lead to a global increase in emissions if non-committed countries operate out-dated carbon-intensive technologies and energy sources.

The potential competitiveness loss and carbon leakage have sparked a debate in the U.S. and Europe about border tax adjustment (BTA) measures against countries that do not take actions to prevent climate change within the current multilateral agreement. Proposed American legislation[3] contains such a provision and the French president Nicolas

[1]The commitments range from a *reduction* of emissions with respect to the base year 1990 of 21% by Germany and Denmark to an *increase* in emissions of 15% by Spain.

[2]Note that stricter regulation can also depress the world price of energy and thus increase the energy demand in non-regulating countries (supply-side leakage). In our study we focus on the demand side channel of carbon leakage.

[3]E.g., the Clean Energy and Security Act (also called Waxman-Markey Bill).

Sarkozy has made similar proposals for the EU. Carbon-related BTAs always have the air of green protectionism and could be costly if non-committed countries resort to retaliation. So, it is important to assess the empirical relevance of trade-induced carbon leakage.

A vast computable general equilibrium (CGE) literature tries to assess *ex ante* the amount of carbon leakage resulting from the Kyoto Protocol. Carbon leakage is typically measured as the emission increase in non-Kyoto countries relative to the emission reduction in Kyoto countries. The results of the CGE simulations differ depending on parametrization and modeling assumptions. They range from moderate leakage rates of 5-40% (for example Felder and Rutherford, 1993; Bernstein et al., 1999; Burniaux and Martins, 2000) to up to 130% (Babiker, 2005). A recent important contribution by Elliott et al. (2010) finds substantial carbon leakage ranging from 15 to 25% depending on the tax rate. *Ex post* empirical evidence on carbon leakage, on the other hand, is scant. In essence, carbon leakage is a special case of the pollution haven effect, i.e. the trade effect of environmental regulation.[4] The general insight of the pollution haven literature is that environmental regulation indeed affects trade flows and the location choice of firms.

To our knowledge, the only study that investigates carbon policy is World Bank (2008). The authors employ a gravity framework to test for the effects of carbon taxes on bilateral trade in goods. They conclude there is no evidence for carbon leakage. However, there are potential problems. First, estimates might be biased due to non-random selection of countries into the Protocol. E.g., a country's green preferences could be related to both its carbon policy and its trade flows. Second, different sectors might be differently prone to carbon leakage as they differ with respect to the carbon intensity of production. Analyzing bilateral trade flows might suffer from a sectoral aggregation bias. Third, a focus on *trade flows* (rather than on the carbon content) does not allow to infer on the reallocation of emissions across countries since emission intensities vary across sectors and countries. Last, investigating trade flows could underestimate carbon leakage because it

[4] There is quite a body of literature looking on pollution haven effects. See, e.g. Ederington and Minier (2003); Ederington et al. (2005); Levinson and Taylor (2008); and the survey article by Brunnermeier and Levinson (2004).

disregards adjustments on the intermediate stages of production. When firms move production to another country, this might have very different effects on emissions relocation depending on whether (energy-intensive) intermediates are sourced domestically or imported. Levinson (2009) makes this point in a study of the U.S. emission savings due to trade.

In this study, we propose a novel way to test for carbon leakage. We suggest to investigate the *carbon content of trade* to understand whether and by what extent commitments made under the Kyoto Protocol affect carbon leakage. The carbon content of trade measures all upstream CO_2 emissions associated with a trade flow along the production chain. Hence, climate policy induced changes in the carbon content of trade reflect the full (direct and upstream) extent of carbon leakage due to relocation of production. Computation of the carbon embodied in trade requires knowledge of the input-output and sectoral emission structure of all investigated countries. Several studies estimate the carbon content of trade for a cross section of countries (see e.g. Ahmad and Wyckoff, 2003; Peters and Hertwich, 2008; Nakano et al., 2009). Only very recently, Peters et al. (2011) have provided an estimation for 113 regions for the years 1990-2008 based on the Global Trade Analysis Project (GTAP). GTAP only provides emission coefficients and input-output data for its base years (1997, 2000 and 2004). The estimates for the years in between are interpolations. None of the studies works with bilateral data and employs econometric techniques. Therefore, we construct our own database with the bilateral carbon content of trade for 40 countries, 12 industries, and the years 1995-2007. Our database mainly builds on OECD and UN data and, contrary to the study by Peters et al. (2011), has yearly data on emission coefficients.

We motivate our empirical approach by a gravity model for CO_2. The carbon content of trade is determined by a gravity-type equation that features climate policy. We show that in a two-country case (e.g. a Kyoto and non-Kyoto block) a unilateral carbon tax in a country leads to increased imports of carbon from the country without such taxes. Put differently, the trade partner increases its emissions in reaction to the country's tighter climate policy. We conduct an econometric ex-post evaluation of the leakage effects triggered by the Kyoto Protocol. The maintained assumption in our analysis is that committed countries have indeed stricter climate policies. Note that this assumption is hard to put to a rigorous empirical test because of the plethora of different policies adopted by countries. Yet, anecdotal evidence hints at policy action after ratification.[5] Estimating our carbon content gravity model raises several econometric issues. Most importantly, selection into the Kyoto Protocol is most likely not random. Here the structure of our data helps. While the observational units in our analysis are country-pairs (dyads), selection into a multilateral agreement such as Kyoto is done by single countries (monads) based on that country's position relative to all trading partners.[6] So, the extensive use of country × year dummies effectively accounts for *all* reasons why a country may commit at a certain point in time to pollution targets under the Kyoto Protocol.

Our within estimations imply that sectoral carbon imports of a committed country from an uncommitted exporter are about 8% higher than if the country had no commitments. The carbon intensity of those imports is about 3% higher. The empirical evidence also hints at technological clean-up in Kyoto countries. Sector by sector, we find robust evidence for carbon leakage for at least five out of twelve sectors. The affected sectors include such likely candidates as basic metals, other non-metallic mineral products or paper and pulp. Wood and wood products or textiles, on the other hand, seem unaffected by leakage. The findings are robust, in particular to using a model in long first-differences. They highlight the importance of subjecting all countries of the world to binding emission targets. The results also imply that countries' domestic emissions are poor measures of their overall impact on climate change.

The paper is organized as follows: Section 2 lays out the gravity model for CO_2. Section 3 describes our data. Section 4 discusses our empirical strategy and section 5 presents the results and robustness checks. Section 6 concludes.

[5]See data displayed on www.lowcarboneconomy.com/Low_Carbon_World/Data/View/12.

[6]See Copeland and Taylor (2005) for a theoretical argument on the optimal choice of carbon policies.

2 Gravity for CO_2

This section develops a simple partial equilibrium model of indirect bilateral trade in CO_2 emissions. The objective is to propose a simple theoretical framework which (i) delivers a gravity equation for the carbon content of bilateral trade, and (ii) provides guidance in the theory-consistent accounting for embodied CO_2 emissions. To meet these aims, the model must allow for domestic and imported goods to be used as intermediate inputs and for technology differences across sectors and countries. The model can also be used to carry out simple comparative statics and a decomposition of carbon policy effects into scale, technique and composition effects.[7]

2.1 Consumers

There are K countries, indexed $i, j, k = 1, ..., K$, which are structurally similar, but may differ with respect to climate policy or country size. Each country consumes a manufacturing good M_i and a homogeneous good H_i. The manufacturing good is a Cobb-Douglas composite of goods M_i^s from S sectors, indexed $s = 1, \ldots, S$. μ^s denotes the expenditure share of sector s in manufacturing, with $\sum \mu^s = 1$. The differentiated varieties within each sector s are home-made as well as imported. N_j^s denotes the number of symmetric varieties produced in country j. Agents have CES preferences over quantities of varieties q_{ij}^s. Overall utility is given by:

$$U_i = (H_i)^{1-\omega}(M_i)^{\omega}, \quad \text{with } M_i = \prod_{s=1}^{S} (M_i^s)^{\mu^s}, \; M_i^s = \sum_{j=1}^{K} N_j^s (q_{ij}^s)^{\frac{\sigma^s - 1}{\sigma^s}}, \tag{1}$$

where $\sigma^s > 1$ is the sectoral elasticity of substitution.[8]

[7] The distinction of scale, technique and composition effects of changes in trade flows goes back to seminal work by Grossman and Krueger (1993) on the environmental effects of NAFTA.

[8] We could additively separably include an externality due to the emissions arising from manufacturing. Since we focus on the positive and not the normative aspects of the relationship between exogenous climate policies and firm location, the negative externality would play no role in the subsequent analysis and is left our for simplicity.

The price index dual to M_i is denoted by $\Pi_i = \prod_{s=1}^{S} (P_i^s)^{\mu^s}$, where the sectoral price index is $P_i^s = \left(\sum_{j=1}^{K} N_j^s (p_{ij}^s)^{1-\sigma^s} \right)^{1/(1-\sigma^s)}$. Prices of sector-$s$ varieties delivered from country j to i have the c.i.f. price $p_{ij}^s = \tau_{ij}^s p_j^s$, where $\tau_{ij}^s \geq 1$ is the usual iceberg trade cost factor and p_j^s is the mill (ex-factory) price of a differentiated variety in country j.

2.2 Firms

Output of the homogeneous good sector is freely tradable and acts as numeraire. It is produced under perfect competition from labor with a constant marginal productivity of one. The homogeneous good can be consumed. It can also be used as an input, namely fuel. Using the homogeneous good as the numeraire and assuming that it is produced in every country, wage rates are equalized to unity so that $w_i = 1$.[9]

The S differentiated goods sectors feature monopolistic competition and increasing returns to scale. Each sector is populated by an endogenously determined mass of symmetric firms, which each produces a distinct variety. The minimum unit cost function of a firm is $c_i^s [\Pi_i, b_i, w_i]$, where the function $c_i^s [\cdot]$ has the usual properties.[10] It reports the cost-minimizing combination of three inputs – the manufacturing good, fossil fuel, and labor, whose prices are given by Π_i, b_i, and w_i respectively. $b_i = t_i$ differs across countries because of (ad valorem) carbon taxes $t_i \geq 1$, which are wasteful.[11] Alternatively, one could think of t_i as regulation to control CO_2 intensity that uses up resources. Total costs of a generic firm consist of a variable and fixed part and are given by

$$C_i^s = c_i^s [\Pi_i, t_i, 1] \, y_i^s + f^s, \tag{2}$$

[9]The use of a numeraire sector has a long tradition, see Behrens et al. (2009) for a recent related example and some discussion. Since the present paper is interested in the empirical relationship between trade in goods and climate policies, it appears natural to take the prices of fuel, and (essentially) labor as exogenous. The econometric strategy will be able to accommodate differences in fuel prices over time and countries.

[10]It is homogeneous of degree 1, as well as increasing and strictly convex in all arguments.

[11]We assume that tax income is not rebated, e.g. in a lump-sum fashion, so that income of the representative consumer is exogenous and depends on country size only. This simplifies comparative statics results. The assumption is not unusual in a multi-country setting with taxes, see e.g. Ossa (2011).

where y_i^s is the output level of the firm and f^s denotes its fixed labor requirement.

Profits of a generic firm in country i are given by $(p_i^s - c_i^s[\cdot])y_i^s - f^s$. Profit maximization yields the optimal price $p_i^s = c_i^s\sigma^s/(\sigma^s - 1)$. Substituting this into profits and recognizing that free entry forces profits to zero, the size of the firm in equilibrium is given by $\bar{y}_i^s = (\sigma^s - 1)f^s/c_i^s$.

2.3 International trade flows

In what follows, importer countries will be denoted by the index m, and exporters by x. To avoid notational clutter, the sectoral index is suppressed whenever possible. Maximizing (1) subject to the appropriate budget constraint, country m consumer demand for varieties produced in country x is

$$d_{mx} = N_x \frac{\mu\omega L_m}{P_m}\left(\frac{p_{mx}}{P_m}\right)^{-\sigma}, \tag{3}$$

where L_m is country m's income which is equal to its labor force,[12] $\mu\omega L_m/P_m$ denotes real expenditure allocated to the sector and p_{mx}/P_m is the price of varieties from country x relative to the average of all consumed varieties in m.

Differentiated goods are also required as inputs for production. Since firms demand the same composite manufacturing good as consumers, they have the same demand structure. With the additional assumption that $c_i[\Pi_i, t_i, 1] = \Pi_i^\alpha t_i^\beta$ is Cobb-Douglas, where $\alpha, \beta \in (0,1)$ are the cost share of intermediates and fuel respectively, the following theoretical gravity equation for goods can be stated:

Result 1. *The quantity of country m's total sectoral imports Q_{mx} from country x is given by*

$$Q_{mx} = Z \cdot (1 + g_m) \cdot L_m \cdot (P_m)^{\sigma-1} \cdot N_x \cdot (c_x[\cdot])^{-\sigma} \cdot (\tau_{mx})^{-\sigma}, \tag{4}$$

where $Z \equiv \mu\omega(\frac{\sigma-1}{\sigma})^\sigma$ is a constant, $g_m > 0$ is a multiplier for intermediate trade, $L_m(P_m)^{\sigma-1}$ describes country m's ***market capacity*** *in a sector, and $N_x(c_x[\cdot])^{-\sigma}$ is*

[12] This includes income generated in the extraction of fossil fuel.

country x's ***supply capacity***.

Proof. See Appendix.

Note that (4) differs from the usual gravity equation (discussed, e.g., in Redding and Venables (2004, p. 57 f.), from where we borrow the terms market and supply capacity) in two ways: first, Q_{mx} is not the value but the quantity of bilateral trade (so that the exponent on trade costs is $-\sigma$ and not $1-\sigma$); second, the trade multiplier g_m accounts for trade in intermediate goods. g_m increases in the cost share of the final good. Moreover, g_m also reflects comparative advantage in dirty versus clean goods production. When a country has a comparative advantage in the homogeneous clean good (e.g. due to a stricter climate policy) the country produces and exports relatively more of the homogeneous good and differentiated goods trade is dampened. Climate policies will affect Q_{mx} through their effects on market and supply capacities of the trading partners.

The model is closed with S goods market clearing conditions in each country i :

$$\bar{y}_i \quad = \quad \frac{(\sigma-1)f}{c_i} = \sum_{m=1}^{K}(1+g_m)\frac{\mu\omega L_m}{P_m}(\frac{p_{mi}}{P_m})^{-\sigma}\tau_{mi}, \qquad i=1,\ldots,K. \tag{5}$$

Condition (5) states that the supply of a variety has to equal its demand inclusive of trade costs from all importing countries.

2.4 The carbon content of bilateral trade

In the present paper, the objective is to empirically analyze whether carbon policies have affected the location of emissions through international trade of goods. Sectors are linked via input-output (I-O) linkages. Empirically, emissions by upstream sectors often dwarf direct ones and relevant upstream sectors produce carbon-intensive inputs that are scarcely traded internationally (e.g., electricity). Hence, we need to understand the carbon content of trade, i.e., the quantity of CO_2 that is embodied in a country's trade flows.

It is useful to distinguish between two accounting methods. The first accounts only for upstream emissions of domestic suppliers; we refer to this concept as *single-region I-O* (SRIO) method. The second method additionally accounts for foreign upstream emissions caused by imports of intermediates; in line with the literature, we refer to this as *multi-region I-O* (MRIO) method. The SRIO approach uses the exporter's I-O table $\mathbf{B}_x$ (with dimensionality $S \times S$) and computes the matrix of input requirements according to the Leontief inverse $\mathbf{A}_x = (\mathbf{I} - \mathbf{B}_x)^{-1}$. As shown by Trefler and Zhu (2010) in the context of a more standard factor content of trade study, the MRIO approach differs from the SRIO approach simply by using a multi-regional input-output table $\mathbf{B}$, i.e., a $KS \times KS$ matrix whose elements are bilateral I-O matrices, denoted $\mathbf{B}_{ji}$, which record country $j's$ usage of intermediate goods supplied from country i. Computationally, the SRIO and MRIO methods differ only with respect to the dimensionality of the inputs requirement matrix.

Result 2. *The CO_2 content of imports of m from x is given by*

$$E^s_{mx} = \eta^s_x Q^s_{mx}, \tag{6}$$

where

$$\eta^s_x \equiv \begin{cases} \mathbf{e}^s_x \mathbf{A}^s_x & \text{for SRIO} \\ \mathbf{e}^s \tilde{\mathbf{A}}^s_x & \text{for MRIO} \end{cases}.$$

The row vector $\mathbf{e}^s_x$ collects only the exporters' sectoral emission coefficients while $\mathbf{e}^s$ is the collection of all those vectors world-wide. The column vector $\mathbf{A}^s_x$ reports the exporter's sectoral input coefficients (column s in the domestic Leontief-inverse), while $\tilde{\mathbf{A}}^s_x$ is the vector of world-wide input requirements of sector s in country x (column $S(x-1)+s$ in the multi-region Leontief inverse).

Proof. See Appendix.

Substituting equation (4) into (6), one obtains a *gravity equation for CO_2*. Climate policy affects the carbon content of trade through emission intensities η_x, η_m, market and supply capacities and the intermediates multiplier.

The MRIO method is required when one is interested in a country's total carbon footprint. However, for the purpose of the present empirical analysis, the SRIO approach is preferable. The reason is that changes in the SRIO CO_2 content of trade mirror changes in the *trade partner's* CO_2 emissions only. So, the SRIO model allows inference on the amount of emissions (direct and upstream) relocated to a trade partner when country i

strengthens its climate policy — i.e. carbon leakage. The major drawback of the MRIO method is that effects in the trade partner cannot easily be disentangled from effects in third countries. The SRIO method, on the other hand, ignores the fact that country i's stricter climate policy may affect from where the trade partner and other countries purchase their inputs – which in turn affects the location of emissions, too. For these reasons, we report results based on both the MRIO and the SRIO approaches.

2.5 Climate policy and the CO_2 content of bilateral trade

Before we turn towards the empirical analysis of gravity equation (6), we characterize the comparative statics of carbon policies in a simple special case of the model. As is customary in the theoretical literature (Antweiler et al., 2001), we can decompose the sectoral effect of environmental policy in the presence of international trade into two terms: a *technique effect* that relates to the substitution away from energy towards other factors of production, and a *scale effect* which is driven by the change in the cost of production relative to other countries and therefore to the volume of sectoral imports.[13] In principle, the importer's technique and scale effect are both affected by own carbon taxes as well as by the ones of foreign countries. Neglecting third country effects, and using $\hat{x} = dx/x$, linearizing $E_{mx} = \eta_x Q_{mx}$ yields

$$\hat{E}_{mx} = \underbrace{\kappa_{\eta,m}\hat{t}_m + \kappa_{\eta,x}\hat{t}_x}_{\text{technique effects}} + \underbrace{\kappa_{Q,m}\hat{t}_m + \kappa_{Q,x}\hat{t}_x}_{\text{scale effects}}, \tag{7}$$

where $\kappa_{\xi,j}$ denotes the elasticity of a variable ξ with respect to j's carbon tax, with $\xi \in \{\eta, Q\}, j \in \{m, x\}$.

In a model featuring I-O linkages, it is not feasible to find a closed form solution for the elasticities in equation (7) because one would have to solve for the number of varieties N_i in (5). However, the special case of *no intermediates trade* (i.e. the cost share α of the intermediate is zero) lends itself to analytical expressions for the scale and technique effects. A firm's unit cost function then only depends on its own country's

[13] On the aggregate bilateral trade level, there is a composition effect in addition which is driven by the change in the mix of traded goods.

climate policy and is given by $c_x[\cdot] = t_x^{\beta}$. Applying Shephard's Lemma, the emission intensity is $\eta_x = e_x = \beta(t_x)^{\beta-1}$. Solving for N_x[14] and using N_x and c_x in equation (4), the bilateral trade volume is

$$Q_{mx} = (\frac{\sigma-1}{\sigma})^{\sigma+1}\mu\omega L_m(\tau_{mx})^{-\sigma}(t_x)^{-\beta}(\sum_j \phi_{mj}\frac{F_j}{F_x})^{-1}, \tag{8}$$

where $\phi_{ij} \equiv (\tau_{ij})^{1-\sigma}$ and F_j denotes a trade-cost weighted measure of j's market potential. It is given by $F_j \equiv \sum_k \frac{\varphi_{jk}L_k}{\varphi_k}$. φ_{jk} is an entry of the inverse trade cost matrix and $\varphi_k \equiv \sum_{i=1}^{K} \varphi_{ki}(t_i)^{\beta(\sigma-1)}$ is a cost-weighted measure of country k's inverse centrality (proximity to trade partners). Note that the trade volume directly depends on the exporter's carbon tax t_x with an exponent of $-\beta$. Climate policy of all countries enters through the last term. It is a measure of the exporter's (size-, distance- and cost-weighted) centrality relative to all countries. A change in a country's climate policy affects its costs and therefore its proximity to other countries.

Result 3. *The technique and scale elasticities of carbon taxes in the importer and the exporter countries are given by*

$$\begin{aligned}
\kappa_{\eta,m} &= 0; \\
\kappa_{Q,m} &= \frac{\beta(\sigma-1)F_m - \sum_j \phi_{mj}F_j\kappa_{\lambda,m}}{\sum_j \phi_{mj}F_j} \\
\kappa_{\eta,x} &= -(1-\beta) < 0; \\
\kappa_{Q,x} &= -\sigma\beta - \frac{\sum_j \phi_{mj}F_j\kappa_{\lambda,x}}{\sum_j \phi_{mj}F_j},
\end{aligned}$$

where $\lambda \equiv \lambda_j/\lambda_x$ is the ratio of some country j's share in varieties relative to the exporter's share in world varieties, and $\kappa_{\lambda,i}$ is the elasticity of λ with respect to i's carbon tax, $i \in \{m, x\}$.

Proof. See Appendix.

If the importer country m imposes a carbon tax while the exporter country x remains inactive (i.e., $i = m$; $\hat{t}_m > 0$, $\hat{t}_x = 0$), there is no technique effect, since in our special

[14] Details are provided in Appendix A.3.

case country m's tax does not have any price effect in country x, so $\kappa_{\eta,m} = 0$.[15] The sign of the scale effect $\kappa_{Q,m}$ depends on the effect of increased costs in m, and on x's relative proximity, which in turn depends on all bilateral trade costs. While generally ambiguous, in the two-country case country x increases the share of varieties it produces (i.e. its competitiveness in manufacturing) so that imports Q_{mx} increase and, hence, $\kappa_{Q,m} > 0$.[16]

If the exporter country x imposes a carbon tax while the importer m remains inactive (i.e., $i = x$, $\hat{t}_x > 0$, $\hat{t}_m = 0$), country m's carbon imports are decreased by the technique effect, since country x lowers its carbon intensity with an elasticity of $\kappa_{\eta,x} = -(1-\beta) < 0$. The sign of the scale effect $\kappa_{Q,x}$ is, again, ambiguous. The direct effect of $\hat{t}_x > 0$ is to lower the trade volume with an elasticity of $-\sigma\beta$. In a two-country world, $\kappa_{Q,x} < 0$ as country x loses competitiveness so that the volume of its sales falls unambiguously.

Summarizing, we expect the carbon content of imports to rise if the importer is committed under the Kyoto Protocol and to fall if the exporter is committed. The higher the elasticity of substitution σ and the higher the carbon intensity of a sector β, the stronger is the reaction of the carbon content of trade to climate policy. However, those predictions are derived under strong assumptions. It will be left to the empirical exercise to determine the sign and magnitude of scale, technique and the overall effect of the Kyoto Protocol.

3 Data

3.1 Data sources

In this section, we use Result 2 to construct a novel dataset of the CO_2 content of bilateral trade flows for the period 1995 to 2007. Three types of data are required: input-output tables, sectoral CO_2 emission coefficients, and bilateral trade data.

[15]This would be different if the world-wide price of carbon fuels were endogenous. Note, however, that the reduced world fuel price would only strengthen the effects. So we can disregard it without loss of generality.

[16]Detailed expressions for the elasticities are provided in Appendix A.3

Input-output tables. I-O tables allow accounting for upstream emissions of CO_2. The OECD provides harmonized I-O tables for a total of 40 countries (its members plus other countries including Brazil, Russia, India and China). A key feature and a novelty of that data is the presence of a time dimension for the major share of countries. I-O tables are observed around the years 1995, 2000, and 2005; for 37 out of 40 countries, we have at least two tables per country.[17] The OECD input-output tables contain 48 industries (2 digit ISIC). Unfortunately, we have to aggregate the I-O data to 15 industries to match the available emissions data.[18] When taking other countries' upstream CO_2 emissions into account (in the MRIO model), we would need to know from which country each sector sources its imported inputs. In other words, we need *bilateral* I-O tables. Such data are not available. However, we observe θ_{ij}^{s}, the share of imports from country j in country $i's$ total absorption of sector s inputs. Following Trefler and Zhu (2010), we assume that this share applies equally in all sectors in country i that make use of input s. For example, if the U.S. imports 20% of its steel absorption from China and a sector uses steel as intermediate input, then we assume 20% of this steel was sourced in China. Consequently, the bilateral input-output table of country i with country j is

$$\boldsymbol{B_{ji}} = \boldsymbol{\theta_{ij}} \cdot \boldsymbol{B_j}, \tag{9}$$

where $\mathbf{B_j}$ is the reported I-O table of country j and $\boldsymbol{\theta_{ij}}$ is a column vector containing the shares θ_{ij}^{s}.

Trade data. We obtain bilateral trade data (f.o.b.) from the UN Commodity Trade (COMTRADE) database.[19] We use a concordance table provided by Eurostat to translate the data from the SITC commodity classification into ISIC. Prior to 1999, bilateral trade

[17] We used the I-O tables from 1995 for the years 1995-97, those from 2000 for 1998-2002, and those from 2005 for 2003-2007.

[18] Table B-I in the appendix shows the sectoral breakdown. There is an obvious trade-off between country coverage and the level of sectoral disaggregation. Our focus on international trade links forces us to include as many countries as possible, possibly at the risk of some aggregation bias.

[19] We do not have information on bilateral service trade.

data for Belgium and Luxembourg are reported jointly. Therefore trade, output and emissions data of both countries are aggregated.

Sectoral CO_2 emission coefficients. We use information on the level of sectoral CO_2 emissions from fuel combustion reported by IEA.[20] In order to obtain emission coefficients, we need to divide sectoral emission levels by some measure of sectoral output. Whenever possible, output data come from the OECD's Structural Analysis Database (STAN). When data is missing, we use the Industrial Statistics Database (INDSTAT4) of the UNIDO and the UN System of National Accounts. For some countries and years, however, sectoral output data are missing altogether so that our data set is unbalanced. This is no major problem for our econometric analysis. A detailed data description is relegated to the Data Appendix.

Other covariates. GDP per capita (in constant 2000 US $) stems from the World Development Indicators (WDI) 2010 database. Bilateral distance measures and dummies for contiguity and common language are taken from the CEPII distances database. Information on joint FTA membership comes from the WTO. The EU and WTO dummy are constructed from the homepage of the EU and WTO, respectively. Information on the Kyoto status of countries is obtained from the UNFCCC homepage.

3.2 Descriptive statistics

We start by looking at trends in country pair's carbon content of trade. To visualize the data, we divide the sample into a pre-treatment period (1997-2000) and a post-treatment period (2004-07). All "Kyoto countries" (i.e., countries with binding Kyoto commitments) except Russia have ratified the Protocol between 2001-03,[21] and we choose the pre- and

[20]Other sources of carbon dioxide emissions such as fugitive emissions, industrial processes or waste are disregarded. However, CO_2 emissions from fuel combustion make up 80% of total CO_2 emissions.

[21]Russia, which ratified in 2004, is treated as Kyoto country. Since Australia ratified in late 2007, it is treated as non-Kyoto country.

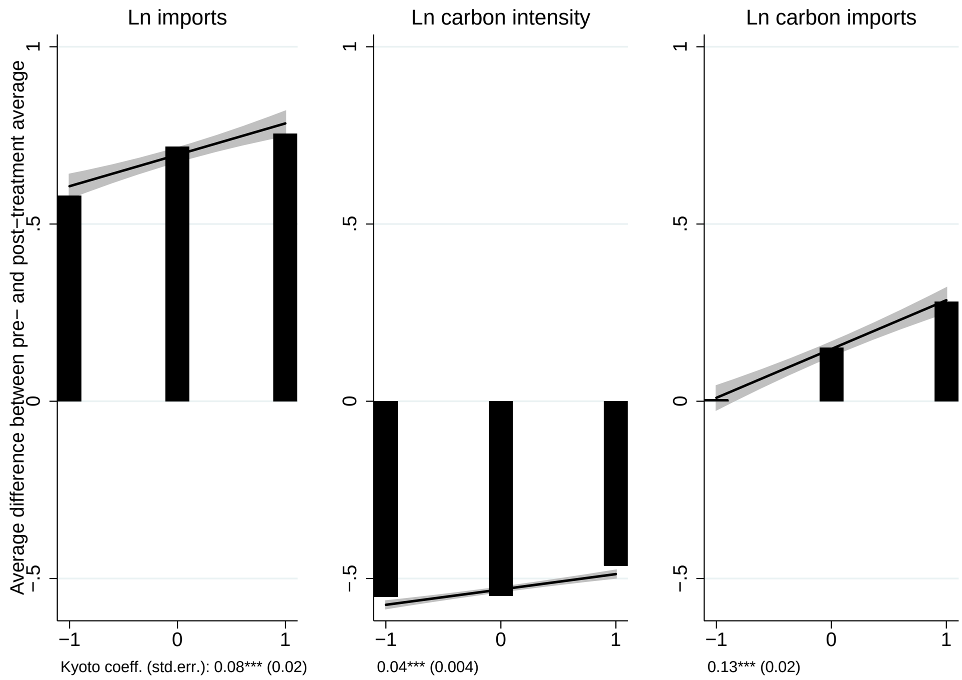
post-treatment periods to be symmetric around this treatment window. The black bars in Figure 1 shows the difference between *average sectoral bilateral* imports, carbon intensity of bilateral imports and the CO_2 content of imports (measured using the SRIO method) for an average country pair in three different groups: country pairs where only the exporter is a Kyoto country but not the importer (-1), country pairs where both or no country is a Kyoto country (0), and pairs where only the importer has a Kyoto commitment but not the exporter (1).

The left panel in Figure 1 show bilateral imports. It is evident that trade has increased significantly in all groups. With an average of 57%, imports of non-Kyoto countries from Kyoto trade partners have risen the least. For pairs with no or two Kyoto countries, imports have increased most: by about 75%. The black line shows the linear fit and the shaded area the 95% confidence interval of a first-differenced regression of $\ln Q_{ij,t}$ on $Kyoto_{i,t} - Kyoto_{j,t}$ where t refers to the pre- or post-treatment periods. The resulting coefficient is 0.08. It is statistically significant at the 1% level. So, Kyoto importers have a higher increase in import volumes from non-committed countries.

The results on the carbon intensity of bilateral imports in the middle panel are striking. Carbon intensity of imports has dropped dramatically, reflecting fuel-saving technological progress and/or a shift towards greener varieties. For instance, it has fallen by half for the group with two or no Kyoto countries. But country pairs with a differential Kyoto commitment of 1 (importer but not exporter committed) have seen the smallest decrease in the carbon intensity of their imports. The regression yields a coefficient of differential Kyoto commitment of 0.04, statistically significant at the 1% level.

Finally, the right panel in Figure 1 repeats the same exercise for the carbon content of imports. It shows that, for a pair with only a committed importer, the carbon content of imports grew by about 28%, on average. For country pairs, where either both countries or neither of them have Kyoto commitments, the carbon content of trade has risen, on average, by 15% and for country pairs with only a Kyoto exporter by roughly 1%. The first-differenced regression of $\ln EM_{ij,t}$ on $(Kyoto_{i,t} - Kyoto_{j,t})$ gives a coefficient of 0.13 (statistically significant at the 1% level). This suggests that a Kyoto country increases its carbon content of imports after treatment by more than a similar non-Kyoto country.

Figure 1: Differential Kyoto commitment and imports, carbon intensity and carbon content of trade



Note: The bars show the average difference between pre-treatment (1997-2000) and post-treatment (2004-07) averages for country pairs where only the exporter has a commitment under Kyoto (-1), both countries or none of the two have Kyoto commitments (0), or only the importer has Kyoto commitments (1). The black line shows a linear fit and the shaded area the 95% confidence interval of a regression of the respective average sectoral bilateral variable on differential Kyoto commitment.

The results displayed in Figure 1 are suggestive and turn out to qualitatively confirm evidence based on more elaborate econometrics. They are, however plagued by a number of potentially important problems. First, as discussed above, both the value and CO_2 content of imports are driven by confounding factors that are not taken account of in the figure. Second, Kyoto commitments may be endogenous. The next section addresses these issues. Third, Figure 1 does not deflate import values. Using the importer's GDP deflator leaves the direction of the effects unchanged. Results are less robust when working with the exporter's GDP deflator. The right choice of the deflator is a contentious issue in the gravity literature. Fortunately, in the following analysis, the extensive use of country-and-time fixed effects makes deflation redundant (see Baldwin and Taglioni, 2007, for a similar argument).

Next, we turn to *sectoral bilateral* data. The summary statistics of Table 1 show that carbon intensities of imports differ significantly across sectors: they are particularly high in sectors 2 (electricity), 3 (metals) or 5 (other minerals) and particularly low in sectors 6 (transport equipment) and 11 (textiles and leather). The intensities also differ across different blocs of countries: on average, imports from non-committed exporters are about two times as carbon-intensive as those from committed countries. Interestingly, regardless from where imports are sourced, the carbon intensity of committed importers is on average about 25% lower than that of non-committed importers.

4 Empirical strategy

In the following, we empirically estimate gravity equations of the types derived in equation (4) and (6). Taking logarithms on (6), one obtains a gravity equation for emissions embodied in bilateral imports that bears strong formal similarity to the standard gravity equation for bilateral trade in goods.

The empirical implementation of our gravity equations encounters a number of econometric problems. The three most important are (i) measurement error in the interesting independent variable (Kyoto status), (ii) selection into the Kyoto Protocol, and (iii) unobserved determinants of bilateral trade volumes.

4.1 Measuring the Kyoto effect

We do not have comprehensive and comparable information about countries' specific climate policies and how those relate to the ratification of the Kyoto Protocol. The same problem occurs in the related literature on the trade flow effects of international agreements. There, researchers simply define a binary variable that takes value 1 if the two members of a country pair are both members in the same free trade agreement (FTA) (Baier and Bergstrand, 2007), or the WTO (Rose, 2004), or if they are in a currency union (Baldwin and Taglioni, 2007), and so forth. Studies evaluating the treatment effects of international environmental agreements such as the Montreal, Helsinki or Oslo Protocols take a similar stance and code a binary variable, see e.g. Ringquist and Kostadinova (2005). Following the literature, we take the year of ratification of any binding commitments within the Kyoto Protocol as the decisive indicator for a country's stance of climate policy. In our regressions we use

$$Kyoto_{i,t} = \begin{cases} 1 & \text{if country } i \text{ has a binding emission cap and } t \geq \text{year of ratification} \\ 0 & \text{else} \end{cases},$$

where t indexes years. For instance, $Kyoto_{i,t} = 0$ for a country i that has not ratified the Protocol yet or has no binding emission targets under the Protocol.

Due to the principle of '*common but differentiated responsibility*', developing countries have an *en bloc* exemption from CO_2 emission reduction obligations. However, there is substantial heterogeneity within the group of countries that have commitments. First, the poorest country in our sample with a binding commitment under the Protocol is Romania (#99 in 227 countries ranked according to their 2009 GDP per capita in PPP terms); some of the world's richest countries have no commitments (U.S.), but also South Korea or Israel. Some EU member states such as Malta or Cyprus have no binding obligations. Second, timing of ratification differs across countries. We have 40 countries in our sample, 12 have no commitments over the entire period 1995-2007. The ratification of commitments by national parliaments started in 2001 (Czech Republic and Romania). Most countries have ratified in the years 2002 and 2003; Russia has ratified the Protocol in 2004 and Australia has ratified in 2007.

It is clear that a Kyoto dummy is only a very inaccurate measure for the intensity of a country's treatment under the Protocol. The resulting measurement error is likely to be substantial. We can therefore expect that our estimates are biased toward zero. In a robustness check we use a long differences-in-differences estimator on pre- and post-treatment averages. By defining a broad treatment window (2001-2003), this measurement error should be less severe.[22]

[22]See e.g. Aakvik and Tjøtta (2011) for a similar argument on the timing of treatment effects under the Helsinki and Oslo Protocols which govern sulfur emissions.

4.2 Selection into the Kyoto Protocol

There are many reasons to believe that selection into Kyoto membership is not random. First, it may depend on countries' preferences, their available abatement technologies and their endowment structure. For example, a country that has a comparative advantage in carbon-intensive goods (i.e., is a net exporter of those goods) may be unwilling to join the Protocol, because it is set to profit most by a falling world market price of fossil fuel if it remains outside. Or a country where carbon-free opportunities to produce energy are abundant may find it easy to commit to a target while at the same time it already exports low-carbon goods.[23] Or, former communist countries, that have had very carbon-intensive technologies in the early 1990s, may find it easy to join the Protocol because they were anyway on the way of adopting new, more carbon-efficient technologies. Second, a country may be concerned about its international competitiveness. If it expects important trade partners not to adopt emission targets it may refuse to do so as well. This has long been and continues to be the position of the U.S.

Hence, we have to deal with the possible endogeneity of Kyoto commitments to avoid spurious correlations. It is important to note that the decision to ratify the Protocol relates to *a country's position relative to the whole world*: if it unilaterally decides to cap its emissions, its cost competitiveness relative to *all* trading partners changes. It will join if the share of imports that come from countries that are likely to adopt caps as well is large enough and refuse to join in the opposite case.

Fortunately, the structure of our data offers some ways to control for the relevant determinants of ratifying binding obligations. Since we observe *country pairs* for a series of years in every sector, we can control for country characteristics at each year by including dummies for each country-and-year combination. Since we have 13 years and 40 countries, this amounts to including a maximum of 520 dummy variables, each representing a country's situation at a given year. As long as a country's decision to join the Protocol is

[23] A country that has rich endowments of fossil fuels may refuse to join the Protocol because it wants to keep the price of fossil fuels high; at the same time it is likely to have a comparative advantage in carbon-intensive goods so that it has high carbon exports.

multilateral (does not depend on individual trade partners but on their aggregate), inclusion of these country-and-year effects controls for all conceivable determinants of Kyoto commitments. As the dependent variable in our gravity equation is *bilateral*, we still have variance left to identify the effect of *differential* Kyoto commitment.

The major drawback of this strategy is that we can only identify the effect of two countries' differences in Kyoto status rather than each country's Kyoto status separately. However, relative to an instrumental variable approach, its key advantage is its generality. It is difficult to find a convincing instrumental variable; the validity of the exclusion restriction can only be assumed. A second advantage of our strategy lies in the fact that it makes estimation of our gravity equation particularly easy: we do not have to use proxies for the importer's demand capacity and the exporter's supply capacity. When we are interested in estimating the effects of the importer's and the exporter's Kyoto commitments separately, we can only include simple country effects as the time variance at the country level identifies the interesting coefficients.

4.3 Controlling for unobserved heterogeneity

Another challenge in gravity modeling is how to deal with country-pair specific unobserved heterogeneity, due, for instance, to imperfect observability of trade costs. In our context, also differences in endowments, climatic conditions or preferences for the environment in a country pair might affect trade flows as well as the decision to select into the Kyoto Protocol. For these reasons, we use fixed-effects estimation (i.e., include country-pair effects into the regression) or time-differentiate equation (6).[24] Both strategies have the advantage of controlling for all historical (e.g., the bilateral trade position at the beginning of the sample) and geographical determinants that may have lead to self-selection of countries into climate policy as well as FTAs. This strategy effectively controls for *all* time-invariant determinants of bilateral trade in CO_2, including determinants that are country-specific and not country-pair specific. However, it fails to control for unobserved

[24]This is proposed by Baier and Bergstrand (2007) to estimate treatment effects of joint FTA membership that suffers from the same problem.

changes in those characteristics (e.g., if a change in consumer preferences leads at the same time to less carbon imports and to stricter climate control policies).[25] Therefore, the additional inclusion of country-year dummies may be important.

In the context of our exercise, the fixed-effects (FE) model is probably preferable to first-differencing (FD). The reason is that our measurement of climate policy through Kyoto status is prone to measurement error. This resulting bias is known to be particularly problematic in first-differenced models (see Griliches and Hausman, 1986). Moreover, due to the unbalanced nature of the panel, time-differencing implies a substantial loss in degrees of freedom. Finally, it is well known that FE estimation is preferable when error terms are serially uncorrelated while FD is better when they follow a random walk. So, for most regressions, we report both, the FE estimates and the FD estimates but tend to prefer the former over the latter.

4.4 Regressions estimated

These considerations lead us to write (6) in estimable form as

$$\begin{aligned} \ln Y_{mxt} &= \kappa_{Y,m} Kyoto_{mt} + \kappa_{Y,x} Kyoto_{xt} + \beta_m \ln GDP_{mt} + \beta_x \ln GDP_{xt} \\ &\quad + \boldsymbol{\gamma}' \mathbf{POL}_{mxt} + \boldsymbol{\mu}' \mathbf{MR}_{mxt} + \boldsymbol{\nu}_{mx} + u_{mxt}, \end{aligned} \tag{10}$$

or, alternatively, as

$$\begin{aligned} \ln Y_{mxt} &= \kappa_Y \left(Kyoto_{mt} - Kyoto_{xt} \right) + \tilde{\boldsymbol{\gamma}}' \mathbf{POL}_{mxt} \\ &\quad + \boldsymbol{\upsilon}_m \times \boldsymbol{\upsilon}_t + \boldsymbol{\upsilon}_x \times \boldsymbol{\upsilon}_t + \boldsymbol{\upsilon}_{mx} + \tilde{u}_{mxt}, \end{aligned} \tag{11}$$

where $Y_{mxt} \in \{Q_{mxt}, \eta_{mxt}, E_{mxt}\}$ and sectoral indexes are again suppressed.[26] The $\kappa_{Y,i}$ parameters differ from those in (7) in that they are not elasticities due to the binary nature of the treatment variable. $\mathbf{POL}_{mxt}$ is a vector of trade policy variables in dummy form (common WTO, FTA and EU membership). $\mathbf{MR}_{mxt}$ is the vector of bilateral multilateral

[25] Country-and-time effects would pick this effect up if it would be proportional for all trade partners.

[26] It is understood that covariate's coefficients are estimated separately for each dependent variable. To keep notation simple, the respective $Y-$index is supressed.

resistance terms, computed according to Baier and Bergstrand (2009) and accounting for all elements of $\mathbf{POL}_{mxt}$ and for the usual time-invariant bilateral trade determinants such as bilateral distance, common language, contiguity, and colonial ties.[27] $\boldsymbol{\nu}_{mx}$ and $\boldsymbol{v}_{mx}$ are country-pair specific intercepts, and the vectors $\boldsymbol{v}_m, \boldsymbol{v}_x, \boldsymbol{v}_t$ collect country m, country x, and year dummies. The error terms u_{mxt} and $\tilde{u}_{mxt}$ are assumed to have the usual properties. We eliminate the country-pair effects either by applying the within-transformation operation or by first-differencing. Note that country pair effects $\boldsymbol{\nu}_{mx}$ nest simple country effects $\boldsymbol{\nu}_m$ and $\boldsymbol{\nu}_x$. We argue above that inclusion of the terms $\boldsymbol{v}_m \times \boldsymbol{v}_t$ and $\boldsymbol{v}_x \times \boldsymbol{v}_t$ allows to account for all determinants of Kyoto commitments; since equation (10) cannot contain those terms as otherwise $\kappa_{Y,m}$ and $\kappa_{Y,x}$ could not separately be identified, there is a risk of obtaining biased estimates as long as time-invariant country effects do not suffice to account for the possible endogeneity of Kyoto commitments.

We run equations (10) and (11) separately for each of our 12 sectors and 3 dependent variables. We also pool across sectors and run a single regression, treating country-pair $\times$ sector as the cross-sectional dimension.

5 Results

5.1 Pooled regressions: benchmark

Table 2 provides the results of regressions of types (10) and (11). For a first analysis, we pool our sectoral data. Odd-numbered models (A1, A3, B1, B3, C1, C3) effectively control only for all time-invariant country characteristics that may influence a country's choice to commit to binding obligations under Kyoto, but allow to identify the effects of importer and exporter commitments separately. Even-numbered columns (A2, A4, B2, B4, C2, C4) include a full set of interactions between country and year effects, so that only

[27] In the context of the standard gravity model, Baier and Bergstrand (2009, p. 80) show that the multilateral resistance terms take the form $MR^V_{mx} = \sum_{k=1}^K \vartheta_k V_{mk} + \sum_{i=1}^K \vartheta_i V_{ix} - \sum_{i=1}^K \sum_{k=1}^K \vartheta_k \vartheta_i V_{ki}$ where $V \in \{\ln DIST, COLONY, COMLANG, CONTIG, FTA, WTO, EU\}$ and ϑ_k is country k's share in world GDP.

variables that vary across country-pairs *and* time (such as differential Kyoto commitment, or the stance of bilateral trade policy) can be identified. These regressions account for all conceivable reasons for which a country may wish to adopt binding Kyoto commitments.

Columns (A1) to (A4) use the log of imports (in U.S. dollar), Q, as the dependent variable; regressions (B1) to (B4) use the log of the CO_2 intensity of imports, η, and regressions (C1) to (C4) the log of carbon imports, E (computed using the SRIO method). By equation (7), $\kappa_{E,m} = \kappa_{\eta,m} + \kappa_{Q,m}$, $\kappa_{E,x} = \kappa_{\eta,x} + \kappa_{Q,x}$ and $\kappa_E = \kappa_\eta + \kappa_Q$, where the $\kappa-$coefficients measure the percent change of the variable $Y = \{E, \eta, Q\}$ when an importer m or an exporter x accepts Kyoto commitments. We refer to coefficients $\kappa_{Q,m}, \kappa_{Q,x}$ and κ_Q as *scale effects* and to coefficients $\kappa_{\eta,m}, \kappa_{\eta,x}$ and κ_η as *technique effects*.

As a general feature, FE models produce larger estimates than FD models, regardless whether country-and-year effects are included or not. This is not surprising, see our discussion on measurement error in section (4.3). We interpret the FD results as lower bounds of the true effect.

In the FE models (A1), (B1) and (C1), the effect of *importer commitment* (Kyoto_m) on total carbon imports is the sum of the scale effect $\kappa_{Q,m}$, estimated at 0.02 but statistically insignificant (column (A1)) and the technique effect $\kappa_{\eta,m}$, estimated to be -0.00 (statistically insignificant, column (B1)). The sum is 0.02 (statistically insignificant, column (C1)). So, importer commitment does not lead to changes in either quantity or carbon intensity of imports from a non-committed country. The positive coefficient of 0.02 on the carbon content of trade would be consistent with *carbon leakage*. However, the effect is not measured with sufficient statistical precision.

The total effect of *exporter commitment* (Kyoto_x) on carbon imports is the sum of the scale effect (-0.10, statistically significant at the 1% level), plus the technique effect (-0.08, statistically significant at the 1% level). Exporter commitment leads to a technique effect as the carbon intensity of imports from a committed exporter falls (either because the exporter shifts into less carbon-intensive sectors or uses less carbon-intensive techniques, or both): This is a *cleaning-up* effect. Additionally, export sales of committed exporters go down. This suggests a reduction of Kyoto countries' competitiveness. The negative scale effect is in line with a *leakage* effect if the reduction in export sales is not met by an equal reduction in consumption.

Next, we run regression (11). The inclusion of country-and-year effects controls for endogenous selection into Kyoto commitments but makes separate identification of the exporter and importer Kyoto effects ($\kappa_{Q,m}$ and $\kappa_{Q,x}$) impossible. Instead, we identify the effect of *differential* Kyoto commitment. If the estimates $\hat{\kappa}_{Q,m}$ and $\hat{\kappa}_{Q,x}$ in regression (A1) were unaffected by an endogeneity bias, then the estimate $\hat{\kappa}_Q$ should be close to $\left(\hat{\kappa}_{Q,m} - \hat{\kappa}_{Q,x}\right)/2$, i.e., 0.06. The estimate of κ_Q reported in (A2) is 0.05, so that the bias resulting from not including country-and-year effects seems minor.[28] Similar observations can be made in columns (B2) and (B3), too. On average, differential Kyoto commitment (either the importer is committed and the exporter is not, or the reverse), increases bilateral CO_2 imports by 8%, about half of which is due to a scale effect and the remainder due to a technique effect. This is again consistent with carbon leakage, the positive Kyoto effect implies that, compared to the counterfactual, additional emissions occur in non-Kyoto countries and are then "imported" by Kyoto countries.

When looking at the results from FD estimation, the cleaning-up effect is supported while a scale effect of Kyoto commitment is not supported. The total effect is about a quarter as large as with FE estimation (now the estimated effect on carbon imports is 2%). In sum, there is strong evidence that Kyoto policies have had non-negligible effects on the quantity, carbon intensity and total carbon content of bilateral import flows.

5.2 Pooled regressions: robustness checks

Table 3 presents some sensitivity analysis to Table 2. The regressions in Panels A and B use pooled sectoral data and the same econometric models as those in Table 2. In contrast, they vary the way the CO_2 content of bilateral imports is measured and use alternative samples. Panel C reports results for aggregated data. To save space, the table only shows results from FE regressions, reports only effects on carbon intensity and carbon content

[28]The country-and-year effects present in (A2), however, are jointly strongly significant (the F-statistic is 101.21).

of imports[29] and suppresses all coefficients other than those on the Kyoto variables.[30]

Alternative measures of CO_2 imports. Columns (A1) to (A4) in Panel A use the MRIO measure of the carbon content of bilateral imports rather than the SRIO one. Comparing the results to the corresponding columns (B1),(B2) and (C1),(C2) in Table 2, using the MRIO method to compute the carbon content of trade yields almost identical results. So, results do not appear to be sensitive to whether upstream emissions in third countries are taken into account or not.

Columns (A5) to (A6) in Panel A use input-output tables and emission coefficients from the year 2000 for the SRIO computation of the CO_2 content of trade, making no use of the updates for following or past years. Thereby, energy-saving technical progress remains unaccounted for. Comparing results with those obtained in Table 2, the effects on the importer's commitment on carbon intensity and carbon imports remain unchanged. However, the effect on the exporter's commitment on the carbon intensity now is zero. This is an interesting observation. It implies that the reduced CO_2 content of committed countries (as observed in our benchmark regressions in Table 2) is primarily driven by technical change and not by a change in the composition of exports toward less carbon-intensive sectors. Differential commitment increases CO_2 imports by 5%; this is only about 60% of the effect obtained when technical change is allowed for. Alternatively, if only the input-output table is fixed in the year 2000 this does not affect the estimated coefficient, see columns (A7) and (A8) for the MRIO case. So changes in the economies' supply structure play no role for Kyoto's effect on embodied carbon.

Alternative samples. Does the massive increase in Chinese exports following its accession to the WTO in 2001 drive the findings in Table 2? Or are the results driven by former communist countries from Eastern Europe, which have quite substantially reduced their CO_2 emissions due to the rapid modernization of their industries in the aftermath

[29]The effect on bilateral trade volume is the difference between the coefficient on total CO_2 imports and the one on CO_2 intensity.

[30]Details are found in Tables C-I to C-III of Appendix C.

of 1989-1992? Columns (B1) to (B4) of Panel B report regression output for a reduced sample from which China and transition countries have been dropped.[31] The overall picture remains intact: Differential Kyoto commitment leads to an increase in the volume of carbon imports by about 3% (column B4). In this specific sample, however, differential commitment lowers the carbon intensity of imports by about 2% (column B2). The scale effect (not shown), which is the difference between the coefficient on overall imports and intensity ($0.03 - (-0.02) = 0.05$, not shown), is strongly positive, too. The fact that intensity falls may be a sign that China and transition countries have increased their export sales in labor-intensive and thus relatively carbon-free sectors.

Bertrand et al. (2004) argue that estimated treatment effects could be spurious if both the treatment variable and the dependent variable have a common trend. This might be an issue in our framework: Since no Kyoto country has so far withdrawn from the Kyoto Protocol, once the Kyoto dummy switches to one it does not change thereafter. Bertrand et al. propose a long differences-in-differences estimator, i.e. estimating the treatment effect with pre- and post-treatment averages, to cure the problem. Most Kyoto countries ratified the Protocol between 2001 and 2003, so we choose this as our treatment window. The pre-treatment period is 1997-2000 and the post-treatment period is 2004-2007, see also Figure 1.[32] Columns (B5) to (B8) in Panel B show results for the long differences-in-differences estimator on the pooled sectoral data. Column (B5) again reports cleaned-up exports from committed exporters, but now we also find an increase in the carbon intensity of imports for committed importers. Contrary, there is no evidence that a committed importer increases its embodied carbon imports; whereas Kyoto exporters export less embodied carbon. Turning to the results with country-and-time effects, column (B6) and (B8) support our earlier results. Kyoto commitment of the importer but not the exporter is associated with 4% more carbon-intensive imports and 10% higher carbon imports, both statistically significant at the 1% level. So the earlier results do not stem from spurious correlation.

[31] Excluding only China or only the transition countries does not lead to different results.

[32] Russia ratified in 2004 and is treated as a Kyoto country, Australia ratified in late 2007 and is put in the control group.

Aggregated data. Finally, columns (C1) to (C8) in Panel C report results for data aggregated over sectors. Compared to columns (B1) to (C4) in Table 2, the sign patterns of the Kyoto coefficients are unchanged. However, estimated coefficients are considerably larger. This may be due to the presence of aggregation bias.

5.3 Differential commitment sector by sector

In the next step, we run regression (11) sector-by-sector.[33] Table 4 reports the results for FE and long differences-in-differences estimation. Differential commitment has strong effects on total carbon imports in 8 out of 12 sectors (electricity, basic metals, chemicals, other non-metallic minerals, transport equipment, machinery, paper and pulp and non-specified industries).[34] The measured coefficient $\hat{\kappa}_E$ ranges between 8 and 24%. It is highest in carbon-intensive industries (such as basic metals or paper and pulp) and/or industries in which the degree of product differentiation is low.

The reasons for increased carbon imports vary across sectors. Only one sector (paper and pulp) features positive and significant scale *and* technique effects. Leakage in the basic metals, non-metallic mineral products, transport equipment and machinery sector is solely due to Kyoto countries significant increases in imports. On the contrary, in the agricultural, electricity, chemicals, textiles and leather and non-specified industries sector the carbon intensity of committed countries' imports rises and gives thus rise to more carbon imports. In conclusion, some sectors seem to be more prone to carbon leakage than others. And only some sectors' competitiveness is affected through Kyoto commitment.

[33]To save space the regression results without country-and-time effects are not reported. Inclusion of country-and-time dummies does not fundamentally change the picture. Full regression output is found in Tables C-IV to C-IX in the Appendix

[34]One sector (textiles and leather) displays a negative and significant coefficient.

6 Conclusions

We have developed a gravity model for carbon embodied in trade. Stricter domestic climate policies reduce domestic emissions but may raise them elsewhere as consumers switch suppliers. This phenomenon – carbon leakage – is equivalent to more emissions embodied in imports and less emissions embodied in exports. Therefore we suggest to test for carbon leakage with a gravity-type equation for CO_2 embodied in trade within a novel data set of bilateral sectoral carbon flows embodied in trade flows. When implementing this test for carbon leakage one has to acknowledge that commitment in the Kyoto Protocol might not be random. The structure of our data allows us to use country-and-time effects to control for self-selection into treatment. Furthermore, it also allows us to control for country-pair specific unobserved heterogeneity in carbon imports and exports.

We show that carbon leakage is empirically relevant. Our within estimations imply that sectoral carbon imports of a committed country from an uncommitted exporter are about 8% higher than if the country had no commitments. The carbon intensity of those imports is about 3% higher. The empirical evidence also hints at technological cleaning-up in Kyoto countries. Sector-by-sector regressions show that some sectors are more prone to carbon leakage than others.

Note that the finding of increased carbon imports of committed importers from non-Kyoto countries is a necessary and sufficient condition for the existence of carbon leakage. Nevertheless, we cannot compare our estimates with the carbon leakage measures obtained in CGE studies. To this end, we would need an estimate of the average Kyoto country's emission savings due to its climate policy. Due to the problem of self-selection into treatment, this causal relationship is not easily uncovered in an econometric setup. The inclusion of country-and-time effects is no feasible option for this problem since this makes identification of the coefficient of interest impossible. A convincing instrumental variable approach for membership in the Kyoto Protocol would be needed. This is beyond the scope of the present paper.[35]

[35] Aichele and Felbermayr (forthcoming) provide first results using instrumental variables estimates on country-level data.

Nevertheless, our results suggest that the issue of carbon leakage is a serious challenge to international climate saving programs. Since a multilateral agreement that commits all countries to binding emission targets does not exist and looks increasingly unlikely, the first-best policy to combat climate change, namely a world-wide cap on emissions, is not feasible. Policymakers in the European Union and the U.S. have called for border tax adjustments to tackle the problem. Establishing the empirical relevance of carbon leakage as a result of unilateral climate policy, our analysis lends support to these policy positions. Since such taxes pose important informational problems and may be conceived as protectionist, more research into their design is needed.

Before closing, we want to stress that our empirical strategy was geared toward identifying the average effect of unilateral climate policy. Our empirical results cannot straightforwardly be used for the simulation of global CO_2 emissions as a response to climate policy scenarios, e.g., the potential commitment to an emission cap by the U.S., or the counterfactual situation of no global climate policy at all. To that end, one would need to use the estimated elasticities in a structural general equilibrium model. We view this as a challenging but worthwhile avenue for further research.

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Table 1: Summary statistics of the dependent variables

Sector	Variable	Exporter commitment YES Mean	Exporter commitment YES Std.dev	Exporter commitment NO Mean	Exporter commitment NO Std.dev	Importer commitment YES Mean	Importer commitment YES Std.dev	Importer commitment NO Mean	Importer commitment NO Std.dev
1	Imports	57.5	235.9	50.2	209.0	71.4	262.5	43.8	193.4
	CO_2 intensity imports	0.5	0.4	0.7	0.5	0.5	0.4	0.6	0.5
	CO_2 content imports	22.0	98.1	29.4	133.2	31.6	132.8	25.1	118.8
2	Imports	42.3	240.5	51.5	228.2	53.2	257.0	46.4	220.1
	CO_2 intensity imports	3.0	2.9	5.7	7.0	3.8	3.7	5.3	6.9
	CO_2 content imports	107.3	696.5	247.8	1044.1	207.2	1116.4	200.5	861.7
3	Imports	207.0	690.2	136.9	501.5	215.8	655.3	134.3	525.3
	CO_2 intensity imports	1.4	1.5	2.8	3.0	1.8	1.8	2.7	3.0
	CO_2 content imports	211.8	757.9	334.2	1475.4	289.3	1014.0	297.4	1396.6
4	Imports	511.1	1606.0	252.5	911.4	480.4	1578.0	269.6	949.6
	CO_2 intensity imports	0.9	1.1	1.6	1.9	1.0	1.0	1.5	1.9
	CO_2 content imports	192.1	559.9	250.8	960.8	250.0	889.0	224.8	841.3
5	Imports	57.3	173.1	39.1	158.1	57.0	174.4	39.5	157.7
	CO_2 intensity imports	1.3	0.9	2.6	2.9	1.7	1.7	2.4	2.8
	CO_2 content imports	55.1	160.8	77.6	380.1	70.5	244.9	70.4	357.1
6	Imports	332.7	1299.6	235.0	1473.3	334.1	1497.5	236.4	1382.4
	CO_2 intensity imports	0.3	0.3	0.7	1.0	0.4	0.5	0.6	0.9
	CO_2 content imports	67.4	287.5	95.7	609.8	99.5	564.1	80.7	509.7
7	Imports	843.7	2497.1	649.5	2951.9	819.7	2378.3	662.8	2989.0
	CO_2 intensity imports	0.3	0.4	0.8	1.1	0.5	0.6	0.7	1.1
	CO_2 content imports	166.4	555.6	383.4	2967.7	329.8	1878.7	309.0	2700.3
8	Imports	181.6	575.9	120.5	431.7	195.5	598.0	114.6	418.0
	CO_2 intensity imports	0.4	0.3	0.7	0.7	0.5	0.4	0.7	0.7
	CO_2 content imports	53.4	160.3	66.5	281.1	71.0	258.7	58.6	245.8
9	Imports	104.2	346.4	77.8	369.2	107.0	367.6	77.0	359.5
	CO_2 intensity imports	0.4	0.3	0.8	1.1	0.5	0.6	0.8	1.0
	CO_2 content imports	34.1	144.0	40.9	216.4	38.8	154.3	38.7	212.3
10	Imports	26.8	164.6	21.4	115.8	28.8	85.7	20.5	150.9
	CO_2 intensity imports	0.4	0.4	0.7	0.8	0.5	0.5	0.7	0.8
	CO_2 content imports	9.7	71.8	16.9	126.8	15.2	85.6	14.2	122.3
11	Imports	125.6	376.4	146.6	695.6	170.2	595.6	126.7	620.3
	CO_2 intensity imports	0.3	0.2	0.6	0.7	0.4	0.4	0.6	0.7
	CO_2 content imports	29.7	91.6	130.4	938.5	99.7	667.7	98.1	823.9
12	Imports	326.9	971.3	247.8	1103.3	339.6	1025.1	243.5	1079.5
	CO_2 intensity imports	0.4	0.4	1.5	1.7	0.9	1.2	1.3	1.6
	CO_2 content imports	104.0	475.4	245.4	1708.3	182.9	802.8	208.8	1643.8

Note: The table displays summary statistics of dependent variables sector-by-sector. Imports are in Mio US-$, CO_2 intensity of imports in kg CO_2 per US-$ and CO_2 content of imports in kt CO_2.

Table 2: Regressions on pooled data

	(A1)	(A2)	(A3)	(A4)	(B1)	(B2)	(B3)	(B4)	(C1)	(C2)	(C3)	(C4)
Dep. variable:	Ln imports, Q_{mx}				Ln CO_2 intensity of imports, η_x				Ln CO_2 imports, E_{mx}			
Method:	FE	FE	FD	FD	FE	FE	FD	FD	FE	FE	FD	FD
Kyoto_m	0.02		0.03***		-0.00		-0.00		0.02		0.03***	
	(0.01)		(0.01)		(0.00)		(0.00)		(0.02)		(0.01)	
Kyoto_x	-0.10***		0.03***		-0.08***		-0.03***		-0.18***		0.00	
	(0.02)		(0.01)		(0.00)		(0.00)		(0.02)		(0.01)	
Kyoto_m-Kyoto_x		0.05***		0.01		0.03***		0.02***		0.08***		0.02**
		(0.01)		(0.01)		(0.00)		(0.00)		(0.01)		(0.01)
ln GDP_m	1.86***		2.94***		0.05***		-0.02*		1.91***		2.91***	
	(0.06)		(0.07)		(0.02)		(0.01)		(0.06)		(0.08)	
ln GDP_x	1.08***		0.75***		-1.09***		-1.06***		-0.01		-0.31***	
	(0.06)		(0.07)		(0.02)		(0.02)		(0.07)		(0.08)	
Joint FTA membership	-0.00	-0.01	0.00	-0.00	0.01	0.02**	0.00	0.00	0.00	0.01	0.00	0.00
	(0.04)	(0.03)	(0.03)	(0.03)	(0.01)	(0.01)	(0.00)	(0.00)	(0.04)	(0.04)	(0.03)	(0.03)
Joint WTO membership	-0.07	-0.14	-0.07	-0.10	0.02	-0.00	-0.01	0.00	-0.05	-0.14	-0.08	-0.09
	(0.16)	(0.16)	(0.14)	(0.17)	(0.03)	(0.04)	(0.02)	(0.02)	(0.17)	(0.17)	(0.15)	(0.17)
Joint EU membership	-0.09***	-0.09***	-0.02	-0.02	-0.00	-0.00	-0.00	-0.00	-0.09***	-0.09***	-0.02	-0.02
	(0.03)	(0.03)	(0.02)	(0.02)	(0.01)	(0.01)	(0.00)	(0.00)	(0.03)	(0.03)	(0.02)	(0.02)
MR terms[a]	YES		YES		YES		YES		YES		YES	
Country × year effects		YES		YES		YES		YES		YES		YES
Year effects	YES		YES		YES		YES		YES		YES	
Country-pair sector effects	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Observations	223,499	223,499	202,420	202,420	223,499	223,499	202,420	202,420	223,499	223,499	202,420	202,420
adj. R^2	0.18	0.21	0.02	0.02	0.63	0.71	0.24	0.42	0.05	0.07	0.01	0.02
RMSE	0.84	0.83	0.86	0.85	0.20	0.18	0.15	0.13	0.86	0.85	0.87	0.86

Note: Fixed-effects (FE) and first-differenced (FD) panel regressions on pooled sectoral data. Standard errors (in brackets) are corrected for clustering within country-pair and sector; ***,** and * denote statistical significance at the 1%, 5% and 10% level, respectively.

[a] All relevant multilateral resistance control variables included (i.e., FTA, WTO, EU, distance, contiguity, common language); see Baier and Bergstrand (2009).

Table 3: Regressions on Pooled Data, Robustness Checks

Panel A: Alternative measures of CO_2 imports

	(A1)	(A2)	(A3)	(A4)	(A5)	(A6)	(A7)	(A8)
Measure:	MRIO				Technique fixed		MRIO I-O fixed	
Dependent variable:	Ln CO_2 intensity		Ln CO_2 imports		Ln CO_2 imports		Ln CO_2 imports	
Method:	FE[a]	FE[b]	FE[a]	FE[b]	FE[a]	FE[b]	FE[a]	FE[b]
Kyoto_m	-0.00		0.02		0.02		0.02	
	(0.00)		(0.02)		(0.01)		(0.01)	
Kyoto_x	-0.07***		-0.16***		-0.10***		-0.16***	
	(0.00)		(0.02)		(0.02)		(0.02)	
Kyoto_m-Kyoto_x		0.02***		0.07***		0.05***		0.07***
		(0.00)		(0.01)		(0.01)		(0.01)
Observations	223,460	223,460	223,460	223,460	223,384	223,384	223,499	223,499
adj. R^2	0.65	0.71	0.07	0.08	0.18	0.21	0.05	0.06

Panel B: Alternative samples and estimators

	(B1)	(B2)	(B3)	(B4)	(B5)	(B6)	(B7)	(B8)
Sample:	w/o China & transition countries[c]				Pre- and post treatment averages			
Dependent variable:	Ln CO_2 intensity		Ln CO_2 imports		Ln CO_2 intensity		Ln CO_2 imports	
Method:	FE[a]	FE[b]	FE[a]	FE[b]	FE[a]	FE[b]	FE[a]	FE[b]
Kyoto_m	-0.00		-0.00		0.03***		-0.04	
	(0.01)		(0.02)		(0.01)		(0.04)	
Kyoto_x	0.02***		-0.12***		-0.08***		-0.29***	
	(0.01)		(0.02)		(0.01)		(0.04)	
Kyoto_m-Kyoto_x		-0.02***		0.03**		0.04***		0.10***
		(0.00)		(0.01)		(0.01)		(0.02)
Observations	136,392	136,392	136,392	136,392	36,269	36,269	36,269	36,269
adj. R^2	0.53	0.65	0.03	0.06	0.72	0.77	0.07	0.11

Panel C: Aggregate data

	(C1)	(C2)	(C3)	(C4)	(C5)	(C6)	(C7)	(C8)
Dependent variable:	Ln CO_2 intensity				Ln CO_2 imports			
Method:	FE[a]	FE[b]	FD[a]	FD[b]	FE[a]	FE[b]	FD[a]	FD[b]
$Kyoto_m$	0.02		0.00		0.20***		0.05***	
	(0.02)		(0.01)		(0.03)		(0.02)	
$Kyoto_x$	-0.20***		-0.06***		-0.16***		-0.02	
	(0.02)		(0.01)		(0.04)		(0.02)	
$Kyoto_m$-$Kyoto_x$		0.07***		0.03***		0.13***		0.04**
		(0.01)		(0.01)		(0.02)		(0.02)
Observations	15,422	15,422	13,864	13,864	15,422	15,422	13,864	13,864
R^2 (within)	0.56	0.61	0.16	0.28	0.20	0.26	0.06	0.12

Note: Standard errors (in brackets) corrected for clustering within country-pair; ***,** and * denote statistical significance at the 1%, 5% and 10% level, respectively. [a] Regressions include controls for country characteristics (importer GDP and exporter GDP) and all relevant multilateral resistance control variables (i.e., FTA, WTO, EU, distance, contiguity, common language; see Baier and Bergstrand (2009); not shown). [b] Regressions include full set of country × year effects. [c] Transition countries are CZE, EST, HUN, POL, ROU, RUS, SVN, SVK.

Table 4: Sector-by-sector regressions: differential commitment

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable:	Ln imports		Ln CO_2 intensity		Ln CO_2 imports	
Method:	FE	long FE	FE	long FE	FE	long FE
(1) Agriculture, forestry, fishing	-0.04	-0.02	0.02***	0.06***	-0.02	0.05
	(0.04)	(0.08)	(0.01)	(0.01)	(0.04)	(0.08)
(2) Electricity, energy, mining and quarrying	0.08	0.14	0.05***	0.10***	0.13**	0.24**
	(0.06)	(0.12)	(0.01)	(0.02)	(0.06)	(0.12)
(3) Basic metals	0.20***	0.21**	-0.00	0.01	0.20***	0.21**
	(0.04)	(0.08)	(0.01)	(0.01)	(0.04)	(0.08)
(4) Chemicals and petrochemicals	0.02	0.02	0.06***	0.07***	0.08***	0.09*
	(0.03)	(0.05)	(0.01)	(0.02)	(0.03)	(0.06)
(5) Other non-metallic mineral products	0.14***	0.17***	-0.00	0.00	0.14***	0.18**
	(0.03)	(0.07)	(0.01)	(0.02)	(0.03)	(0.07)
(6) Transport equipment	0.15***	0.18**	0.01	0.01	0.16***	0.21**
	(0.04)	(0.08)	(0.01)	(0.02)	(0.04)	(0.09)
(7) Machinery	0.13***	0.10**	0.01	0.00	0.15***	0.11**
	(0.02)	(0.05)	(0.01)	(0.02)	(0.03)	(0.05)
(8) Food products, bever-, ages, tobacco	0.01	0.06	0.01**	0.03**	0.02	0.10
	(0.03)	(0.08)	(0.01)	(0.01)	(0.04)	(0.08)
(9) Paper, paper products, pulp and printing	0.15***	0.16**	0.02***	0.04***	0.17***	0.19***
	(0.04)	(0.07)	(0.01)	(0.01)	(0.04)	(0.07)
(10) Wood and wood products	-0.11**	-0.15	0.02**	0.05***	-0.08*	-0.09
	(0.05)	(0.09)	(0.01)	(0.02)	(0.05)	(0.09)
(11) Textile and leather	-0.12***	-0.19***	0.02***	0.03*	-0.09***	-0.15**
	(0.03)	(0.06)	(0.01)	(0.02)	(0.03)	(0.06)
(12) Non-specified industries	-0.01	-0.02	0.09***	0.11***	0.09***	0.10**
	(0.02)	(0.04)	(0.01)	(0.02)	(0.03)	(0.05)

Note: Each cell is the result of a separate regression. The explanatory variable listed is differential Kyoto commitment and takes values (-1,0,1). The method of estimation is either fixed effects (within, FE) or long differences-in-differences estimation on pre- and post-treatment averages (long FE). Each regression includes trade policy controls (joint WTO, FTA, and EU membership) and a full set of country×year effects. Heteroskedacticity-robust standard errors (in brackets) are adjusted for within country-pair clustering. ***, ** and * denote statistical significance at the 1%, 5% and the 10% levels, respectively.

A Proofs

A.1 Result 1. Intermediate demand by firms

Each sector ℓ demands the output of every sector as an input via the final output good. Assuming that the cost function (2) is Cobb-Douglas with $c_m^\ell[.] = \Pi_m^{\alpha^\ell} t_m^{\beta^\ell} w_m^{(1-\alpha^\ell-\beta^\ell)}$, substituting the expression for Π_m, recognizing that $w_m = 1$ by choice of numeraire, and applying *Shephard's Lemma*, one obtains the unit input requirement for sector-s varieties from country x for the use of intermediate inputs in sector ℓ in country m,

$$\frac{\partial c_m^\ell [\cdot]}{\partial p_{mx}^s} = \alpha^\ell \mu^s c_m^\ell [\cdot] \frac{N_x^s (p_{mx}^s)^{-\sigma^s}}{(P_m^s)^{1-\sigma^s}}. \tag{A-1}$$

Sector-s intermediate goods trade between countries m and x, ι_{mx}^s, is the respective unit input requirement times total output of all demanding sectors $\ell = 1, \ldots, S$. Hence,

$$\begin{aligned}
\iota_{mx}^s &= \sum_{\ell=1}^{S} \frac{\partial c_m^\ell [\cdot]}{\partial p_{mx}^s} N_m^\ell y_m^\ell \\
&= \mu^s N_x^s (p_{mx}^s)^{-\sigma_s} (P_m^s)^{\sigma_s - 1} \sum_{\ell=1}^{S} \alpha^\ell (\sigma^\ell - 1) N_m^\ell f^\ell \\
&= \mu^s \omega L_m N_x^s (p_{mx}^s)^{-\sigma_s} (P_m^s)^{\sigma_s - 1} \sum_{\ell=1}^{S} \frac{\alpha^\ell}{\omega} (\sigma^\ell - 1) \frac{L_{m,HQ}^\ell}{L_m} \\
&= g_m N_x^s \frac{\mu^s \omega L_m}{P_m^s} (\frac{p_{mx}^s}{P_m^s})^{-\sigma^s}, \qquad \text{(A-2)}
\end{aligned}$$

where the second line follows from using equation (A-1), recognizing that $y_m^\ell = \frac{(\sigma^\ell - 1) f^\ell}{c_m^\ell}$. The third line follows from multiplying by $\frac{\omega L_m}{\omega L_m}$ and noting that $N_m^\ell f^\ell = L_{m,HQ}^\ell$ is the total amount of headquarter services used in a sector. For the fourth line we factor out the term

$$g_m \equiv \sum_{\ell=1}^{S} \frac{\alpha^\ell}{\omega} (\sigma^\ell - 1) \frac{L_{m,HQ}^\ell}{L_m}, \tag{A-3}$$

with the remaining term in the equation being isomorphic to the expression for trade in final goods. Note first that $g_m > 0$ if intermediate input linkages exist (i.e., if $\alpha^\ell \neq 0$). Clearly, the amount of intermediates trade rises with the intermediates input requirement α. Intermediates trade is higher, when the share of headquarter services in the labor force in the importer m is high. I.e. if a country has a comparative disadvantage in the homogeneous goods sector and focuses more on the manufacturing varieties (e.g. due to a lax climate policy) it will have a higher trade volume.

A.2 Result 2. The carbon content of trade

The inter-industry demand for sector ℓ varieties in sector s is found by applying Shephard's lemma to sector-s's unit cost function, $\frac{\partial c_i^s[\cdot]}{\partial p_i^\ell}$. Those direct inter-industry demands for all ℓ and s combinations can be summarized in an $S \times S$ input-output table:

$$\boldsymbol{B_i} = \begin{pmatrix} \frac{\partial c_i^1}{\partial p_i^1} & \cdots & \frac{\partial c_i^S}{\partial p_i^1} \\ \vdots & \ddots & \vdots \\ \frac{\partial c_i^1}{\partial p_i^S} & \cdots & \frac{\partial c_i^S}{\partial p_i^S} \end{pmatrix}.$$

The Leontief inverse of this I-O table, $\boldsymbol{A_i} = (\boldsymbol{I} - \boldsymbol{B_i})^{-1}$, gives the total input requirement of all sector pairs along the domestic production chain. That is, the sth column of $\boldsymbol{A_i}$ is the total demand of sector s for the different varieties available. In order to translate this into the corresponding emissions of a good, premultiply with the vector of direct emission intensities of all varieties. The domestic carbon content of a sector-s variety is thus the vector product of the national carbon emission vector and the vector of unit input requirements of that sector, $\eta_i^s = \boldsymbol{e_i A_i^s}$.

The same logic applies for the MRIO accounting method. However, in the MRIO framework the I-O table captures the input-output relations between all sector pairs in all country pairs, see Trefler and Zhu (2010). That is, the I-O table is now a $KS \times KS$ matrix with

$$\boldsymbol{B} = \begin{pmatrix} \boldsymbol{B_{11}} & \boldsymbol{B_{12}} & \cdots & \boldsymbol{B_{1K}} \\ \boldsymbol{B_{21}} & \boldsymbol{B_{22}} & \cdots & \boldsymbol{B_{2K}} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{B_{K1}} & \boldsymbol{B_{K2}} & \cdots & \boldsymbol{B_{KK}} \end{pmatrix},$$

where $\boldsymbol{B_{ji}}$ is the matrix of intermediate usage of country i sourced by country j. $\boldsymbol{B_{ji}}$ is again found by Shephard's Lemma,

$$\boldsymbol{B_{ji}} = \begin{pmatrix} \frac{\partial c_i^1}{\partial p_{ij}^1} & \cdots & \frac{\partial c_i^S}{\partial p_{ij}^1} \\ \vdots & \ddots & \vdots \\ \frac{\partial c_i^1}{\partial p_{ij}^S} & \cdots & \frac{\partial c_i^S}{\partial p_{ij}^S} \end{pmatrix}.$$

Going through the same steps as for the SRIO method, the total carbon content of a sector-s variety of country i is $\tilde{\eta}_i^s = \boldsymbol{e}\tilde{\boldsymbol{A}}_{\boldsymbol{i}}^{\boldsymbol{s}}$, where $\boldsymbol{e} = (e_1 \dots e_K)$ is the world-wide emission vector and $\tilde{\boldsymbol{A}}_{\boldsymbol{i}}^{\boldsymbol{s}}$ is the vector of world-wide input requirements of sector-s in country i – i.e. column $(S(i-1)+s)$ of the world-wide Leontief inverse $\boldsymbol{A} = (\boldsymbol{I} - \boldsymbol{B})^{-1}$.

A.3 Result 3. Special case: No intermediates trade

This section draws on results presented in Behrens et al. (2009). Let's assume that a firm's cost share of intermediates is zero. Then, the Cobb-Douglas unit cost functions and market clearing conditions are (using that $w_i = 0$ by choice of numeraire).

$$c_i\left[t_i\right] = (t_i)^{\beta} \qquad \forall\, i = 1, \dots, K,$$

$$\frac{\sigma f}{\mu\omega t_i^{\beta(1-\sigma)}} = \sum_{m=1}^{K} \frac{\phi_{mi} L_m}{\sum_{k=1}^{K} \phi_{mk} N_k (t_k)^{\beta(1-\sigma)}} \qquad \forall\, i = 1, \dots, K, \tag{A-4}$$

where $\phi_{ij} \equiv \tau_{ij}^{1-\sigma}$. We assume symmetric transportation costs without loss of generality. Define the matrices respectively vectors

$$\mathbf{t} \equiv \text{diag}\begin{pmatrix} t_1 \\ \vdots \\ t_K \end{pmatrix}, \ \boldsymbol{\Phi} \equiv \begin{pmatrix} 1 & \cdots & \phi_{1K} \\ \vdots & \ddots & \vdots \\ \phi_{1K} & \cdots & 1 \end{pmatrix}, \ \mathbf{L} \equiv \begin{pmatrix} L_1 \\ \vdots \\ L_K \end{pmatrix}, \ \mathbf{N} \equiv \begin{pmatrix} N_1 \\ \vdots \\ N_K \end{pmatrix},$$

the scalar $r \equiv \frac{\mu\omega}{\sigma f}$, and let $\mathbf{1}$ be a vector of ones. Then, we can rewrite the free entry-and-exit condition in matrix notation as

$$r\mathbf{t}^{\beta(1-\sigma)}\boldsymbol{\Phi}\text{diag}(\boldsymbol{\Phi}\mathbf{t}^{\beta(1-\sigma)}\mathbf{N})^{-1}\mathbf{L} = \mathbf{1}.$$

Behrens et al. (2009) show how to solve this for $\mathbf{N}$ with simple matrix algebra:

$$\begin{aligned} \mathbf{L} &= \frac{1}{r}\text{diag}(\boldsymbol{\Phi}\mathbf{t}^{\beta(1-\sigma)}\mathbf{N})\boldsymbol{\Phi}^{-1}\mathbf{t}^{\beta(\sigma-1)}\mathbf{1} \\ \Leftrightarrow \mathbf{L} &= \frac{1}{r}\text{diag}(\boldsymbol{\Phi}^{-1}\mathbf{t}^{\beta(\sigma-1)}\mathbf{1})\boldsymbol{\Phi}\mathbf{t}^{\beta(1-\sigma)}\mathbf{N} \\ \Leftrightarrow \mathbf{N}^* &= r\mathbf{t}^{\beta(\sigma-1)}\boldsymbol{\Phi}^{-1}\text{diag}(\boldsymbol{\Phi}^{-1}\mathbf{t}^{\beta(\sigma-1)}\mathbf{1})^{-1}\mathbf{L}. \end{aligned}$$

Assuming an interior solution, the number of varieties is given by

$$N_i^* = \frac{\mu\omega}{\sigma f}(t_i)^{\beta(\sigma-1)} \sum_{j=1}^{K} \frac{\varphi_{ij} L_j}{\sum_{k=1}^{K} \varphi_{jk} (t_k)^{\beta(\sigma-1)}} = \frac{\mu\omega}{\sigma f}(t_i)^{\beta(\sigma-1)} \sum_{j=1}^{K} \frac{\varphi_{ij} L_j}{\varphi_j}, \tag{A-5}$$

where φ_{ij} is an entry of $\mathbf{\Phi}^{-1}$. $\varphi_j \equiv \sum_{k=1}^{K} \varphi_{jk}(t_k)^{\beta(\sigma-1)}$ is a cost-weighted measure of a country j's inverse centrality (proximity to trade partners). The φ_{ij}'s and L_j's are exogenous variables. So the number of varieties a country produces depends on its carbon tax and the size of all trading partners weighted with a relative measure of their proximity – and thus on the carbon tax of all other countries as well.

As in Behrens et al. (2009), it is useful to express the number of varieties in shares. Multiplying (A-4) by N_i and summing over all countries, we can show that the number of varieties available worldwide is fixed[1] and depends on world size, fixed costs and taste and technology parameters:

$$\begin{aligned}
\sum_i \frac{\sigma f}{\mu\omega} N_i &= \sum_i N_i \sum_{m=1}^{K} \frac{\phi_{mi} L_m t_i^{\beta(1-\sigma)}}{\sum_{k=1}^{K} \phi_{mk} N_k (t_k)^{\beta(1-\sigma)}} \\
\frac{\sigma f}{\mu\omega} \sum_i N_i &= \sum_{m=1}^{K} L_m \frac{\sum_i N_i \phi_{mi} t_i^{\beta(1-\sigma)}}{\sum_{k=1}^{K} \phi_{mk} N_k (t_k)^{\beta(1-\sigma)}} \\
\frac{\sigma f}{\mu\omega} \bar{N} &= \sum_{m=1}^{K} L_m = L \\
\bar{N} &= \frac{\mu\omega L}{\sigma f}.
\end{aligned}$$

Since $\bar{N}$ is exogenously given, changes in the cost structure across countries (like changes in climate policy) will shift the shares in varieties across the globe. Let $\lambda_i \equiv \frac{N_i}{\bar{N}}$ be country i's share in world varieties and $\theta_i \equiv \frac{L_i}{L}$ the country's share in world income. From (A-5) λ_i is given by

$$\lambda_i \equiv \frac{N_i}{\bar{N}} = \frac{\mu\omega}{\sigma f \frac{\mu\omega L}{\sigma f}}(t_i)^{\beta(\sigma-1)} \sum_{j=1}^{K} \frac{\varphi_{ij} L_j}{\varphi_j} = (t_i)^{\beta(\sigma-1)} \sum_{j=1}^{K} \frac{\varphi_{ij}\theta_j}{\varphi_j}. \tag{A-6}$$

[1]Note that this result stems from assuming that fixed costs are expressed as headquarter services and not in an input bundle. This implies that firm size is not fix and depends on marginal costs, i.e. climate policy. Otherwise, the number of varieties available worldwide would depend on marginal costs.

Scale effects Rearranging (A-6) such that $F_j \equiv \sum_{j=1}^{K} \frac{\varphi_{ij}\theta_j}{\varphi_j} = \lambda_i (t_i)^{\beta(1-\sigma)}$ and plugging into equation (4), we get an alternative useful expression for bilateral import volumes:

$$Q_{mx} = (\frac{\sigma-1}{\sigma})^{\sigma+1} \mu\omega L_m (\tau_{mx})^{-\sigma} (t_x)^{-\sigma\beta} (\sum_j \phi_{mj} (t_j)^{\beta(1-\sigma)} \frac{\lambda_j}{\lambda_x})^{-1}.$$

Differentiating with respect to the exporter's climate policy yields:

$$\begin{aligned}
\frac{\partial Q_{mx}}{\partial t_x} &= -\sigma\beta(\frac{\sigma-1}{\sigma})^{\sigma+1} \mu\omega L_m (\tau_{mx})^{-\sigma} (t_x)^{-\sigma\beta-1} (\sum_j \phi_{mj} (t_j)^{\beta(1-\sigma)} \frac{\lambda_j}{\lambda_x})^{-1} \\
&\quad -(\frac{\sigma-1}{\sigma})^{\sigma+1} \mu\omega L_m (\tau_{mx})^{-\sigma} (t_x)^{-\sigma\beta} \frac{\sum_j \phi_{mj} (t_j)^{\beta(1-\sigma)} \frac{\partial(\frac{\lambda_j}{\lambda_x})}{\partial t_x}}{(\sum_j \phi_{mj} (t_j)^{\beta(1-\sigma)} \frac{\lambda_j}{\lambda_x})^2}. \\
\Leftrightarrow \frac{\partial Q_{mx}}{\partial t_x} \frac{t_x}{Q_{mx}} &= -\sigma\beta - \frac{\sum_j \phi_{mj} (t_j)^{\beta(1-\sigma)} \frac{\partial(\frac{\lambda_j}{\lambda_x})}{\partial t_x} t_x \frac{\lambda_j/\lambda_x}{\lambda_j/\lambda_x}}{\sum_j \phi_{mj} (t_j)^{\beta(1-\sigma)} \frac{\lambda_j}{\lambda_x}} \\
&= -\sigma\beta - \frac{\sum_j \phi_{mj} (t_j)^{\beta(1-\sigma)} \lambda_j \kappa_{\lambda,x}}{\sum_j \phi_{mj} (t_j)^{\beta(1-\sigma)} \lambda_j} = -\sigma\beta - \frac{\sum_j \phi_{mj} F_j \kappa_{\lambda,x}}{\sum_j \phi_{mj} F_j},
\end{aligned}$$

where the last line again makes use of equation (A-6) and $\kappa_{\lambda,x} \equiv \frac{\partial \lambda_j/\lambda_x}{\partial t_x} \frac{t_x}{\lambda_j/\lambda_x}$. If the exporter increases its carbon tax, the import volume directly reacts with an elasticity of $-\sigma\beta$. The second term reflects how varieties are shifted across the globe in response to x's higher carbon tax. This indirect effect depends on trade costs between some country j and the importer, j's share in varieties, and how this share changes relative to the exporter's share in varieties.

The importer's scale effect can be calculated accordingly as:

$$\begin{aligned}
\frac{\partial Q_{mx}}{\partial t_m} &= -Q_{mx} \frac{\beta(1-\sigma)(t_m)^{\beta(1-\sigma)-1} \frac{\lambda_m}{\lambda_x} + \sum_j \phi_{mj} (t_m)^{\beta(1-\sigma)} \frac{\partial(\frac{\lambda_j}{\lambda_x})}{\partial t_m}}{\sum_j \phi_{mj} (t_j)^{\beta(1-\sigma)} \frac{\lambda_j}{\lambda_x}}. \\
\Leftrightarrow \frac{\partial Q_{mx}}{\partial t_m} \frac{t_m}{Q_{mx}} &= \frac{\beta(\sigma-1)(t_m)^{\beta(1-\sigma)} \lambda_m - t_m \lambda_x \sum_j \phi_{mj} (t_j)^{\beta(1-\sigma)} \frac{\partial(\frac{\lambda_j}{\lambda_x})}{\partial t_m}}{\sum_j \phi_{mj} (t_j)^{\beta(1-\sigma)} \lambda_j} \\
&= \frac{\beta(\sigma-1) F_m - \sum_j \phi_{mj} F_j \kappa_{\lambda,m}}{\sum_j \phi_{mj} F_j},
\end{aligned}$$

So, the importer's scale effect is driven by the varieties (price index) channel only.

Special case: Two country world Let's assume we are in a two country world. The trade cost matrix is $\Phi = \begin{pmatrix} 1 & \phi \\ \phi & 1 \end{pmatrix}$ and its inverse is $\Phi^{-1} = \frac{1}{1-\phi^2} \begin{pmatrix} 1 & -\phi \\ -\phi & 1 \end{pmatrix}$. We investigate the trade flow Q_{12}, i.e. country 1 is the importer, country 2 the exporter. The exporter's scale effect is given by:

$$\kappa_{Q,2} = -\sigma\beta - \frac{\kappa_{\lambda,2} F_1}{F_1 + \phi F_2}.$$

For an interior solution, all F_i's have to be positive; otherwise the respective N_i's are non-positive. Thus, the sign of the second term depends on how the worldwide number of varieties shifts between country 1 and 2. Since all terms in

$$\frac{\partial \lambda_1}{\partial t_2} = \frac{\phi\beta(\sigma-1)(t_1 t_2)^{\beta(\sigma-1)}}{t_2}\left(\frac{\theta_1}{(\varphi_1)^2} + \frac{\theta_2}{(\varphi_2)^2}\right) > 0$$

are positive, country 1's share in varieties rises when country 2 strengthens its climate policy. Having only two countries, this implies that country 2's share in varieties falls. I.e. $\kappa_{\lambda,2} \equiv \frac{\partial(\lambda_1/\lambda_2)}{\partial t_2}\frac{t_2}{\lambda_1/\lambda_2}$ is positive. Thus the exporter's scale effect $\kappa_{Q,2} < 0$. If the exporter imposes a stricter climate policy, the import volume falls.

In the two country case, the importer's scale effect is

$$\kappa_{Q,1} = \frac{\beta(\sigma-1)F_1 - \kappa_{\lambda,1} F_1}{F_1 + \phi F_2}.$$

We have already shown, that the own share of varieties falls with a stricter climate policy. So $\kappa_{\lambda,1} \equiv \frac{\partial(\lambda_1/\lambda_2)}{\partial t_1}\frac{t_1}{\lambda_1/\lambda_2}$ is negative. Thus, the importer's scale effect $\kappa_{Q,1} > 0$. If the importer imposes a stricter climate policy, the import volume rises.

B Data Appendix

Input-output tables

The OECD collects input-output tables for its members and various other countries. Input-output (I-O) tables are observed around the years 1995, 2000 and 2005. We apply the 1995 I-O table for the years 1995-98, the 2000 table for 1999-2002 and the 2005 table for 2003-07. For 37 out of the 40 countries we have at least two I-O tables; Table B-II gives an overview of availability for each country. For cases where no input-output table was available for the years under investigation we chose the I-O table of the nearest year possible. This implies the assumption that the economic structure (and specifically the relative prices) has not changed between these two points in time. The OECD I-O tables contain 48 industries, mostly on the two digit level of the International Standard Industrial Classification of All Economic Activities (ISIC) Revision 3. We aggregated these I-O industries to 15 sectors to match the emission data of the IEA (see Table B-I). Implicitly, we assume that all products within a sector are produced with the same CO_2 intensity. The high level of sectoral aggregation in our analysis gives rise to an aggregation bias when this assumption does not hold.[2]

Trade data

Bilateral trade data is obtained from the UN Comtrade database. It is translated from the Standard International Trade Classification (SITC) Rev. 3 to ISIC Rev. 3 with an industry concordance table provided by RAMON[3]. In the Comtrade database, imports are generally valued with CIF prices, exports with FOB prices. In order to have the same valuation for imports and exports, we use the FOB export price of the partner

[2]There is a trade-off between sectoral detail and having harmonized data for a large set of countries. Since we are interested in differences in the carbon footprints of Kyoto and non-Kyoto countries, we chose to include as many countries as possible at the cost of sectoral detail.

[3]`http://ec.europa.eu/eurostat/ramon/`

Table B-I: Industry classification

	ISIC code	Industry description
Traded Sectors		
1	1+2, 5	Agriculture, forestry, fishing
2	10-14,23,40	Electricity, gas and water supply, mining and quarrying
3	27	Basic metals
4	24	Chemicals and petrochemicals
5	26	Other non-metallic mineral products
6	34+35	Transport equipment
7	28-32	Machinery
8	15+16	Food products, beverages, tobacco
9	21+22	Paper, paper products, pulp and printing
10	20	Wood and wood products
11	17-19	Textile and leather
12	25,33,36,37	Non-specified industries
Non-traded Sectors		
13	45	Construction
14	60-62	Transport
15	41,50-52, 55,63-99	Other services

country as FOB price of imports. Thereby we ignore the carbon dioxide emissions caused by international transportation. For Russia, bilateral trade data is not available in the year 1995. Hence, we assume the trade relations in 1995 to be as in 1996 and use trade data of 1996 for the Russian Federation. Prior to 1999 bilateral trade data for Belgium and Luxembourg is reported jointly. Therefore trade, output and emissions data of both countries is aggregated in all years. It is assumed that both countries produce with Belgian technology, i.e. we apply the Belgian I-O table to the region Belgium-Luxembourg. Furthermore, service trade is assumed to be zero.

Sectoral CO_2 emissions

Sectoral CO_2 emissions are taken from the IEA CO_2 Emissions from Fuel Combustion (detailed estimates) Vol. 2009 database. The IEA estimates the CO_2 emissions from fossil fuel combustion with the default method and emission factors of different fuels suggested by the Intergovernmental Panel on Climate Change guidelines. Other sources of carbon dioxide emissions such as fugitive emissions, industrial processes or waste are disregarded. However, CO_2 emissions from fuel combustion make up around 80% of total CO_2 emissions. We also do not consider emissions from international bunker fuels.

Output data

In order to obtain the exporter's emission coefficients, we need to divide sectoral emission levels by some measure of sectoral output. This is the most challenging part of constructing our carbon footprint database. Whenever possible, output data come from the OECD Structural Analysis Database (STAN).[4] STAN output data is available in current national currency only and was converted to current U.S. dollars with the period average exchange rates from the IMF IFS database. Even though the coverage of STAN data is excellent, some data points are missing.[5] So country pairs with no information on the exporter's emission coefficients are dropped from the sample; which implies our database is unbalanced.

For countries not covered by STAN, sectoral output of the manufacturing industries was taken from the INDSTAT2 2011 database which is given in ISIC Rev. 3.[6] We complement this with non-manufacturing output (sectors 1, 2, 13-15) obtained from the UN SNA database where available, exceptions see below. In the SNA database, transport (ISIC 60-62) and storage (ISIC 63) are reported jointly, therefore our industry category 14 contains part of category 15 in those countries. Manufacturing output is interpolated

[4]The 27 countries are Austria, Belgium-Luxembourg, Canada, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, Netherlands, Norway, New Zealand, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, United Kingdom, and the United States.

[5]Swiss data is missing in 1995-96, Canadian in 2006-07 and New Zealand and Portuguese in 2007.

[6]The remaining 13 countries are Australia, Argentina, Brazil, Chile, China, India, Indonesia, Israel, Mexico, Romania, Russia, South Africa, and Turkey.

for the years 1995 and 1997 for South Africa. As in the STAN database, some countries are not covered in all sample years and therefore dropped as exporters. This is so for Argentina from 2003-07, Russia from 1995-2001 and Australia, Chile, Israel, Mexico and Turkey in 2007.

For Australia, China, Indonesia, and Turkey non-manufacturing sectoral output (sectors 1, 2, 13-15) was not available in the UN SNA. Instead, we interpolate output data from the OECD I-O tables. This gives imputed data for China and Indonesia from 1995-2005, Australia from 1998-2004, and Turkey from 1996-2002. I-O output data are again converted to U.S. dollars with period average exchange rates from the IFS database.

After matching all data, we end up with a data set of bilateral imports, carbon intensities and carbon content of trade spanning the years 1995 to 2007 comprising 12 sectors on a two digit ISIC Rev. 3 level and 1,560 country pairs. This amounts to 223,499 bilateral observations. 28 out of the 40 investigated countries face binding emissions restrictions due to the Kyoto Protocol and 11 are non-OECD member countries (Argentina, Brazil, Chile, China, Estonia, India, Indonesia, Israel, Russia, Slovenia and South Africa). The sample countries are responsible for about 80% of worldwide carbon dioxide emissions in the sample years.

Table B-II: Input-output table availability

Country	Input-output table for period		
	mid 1990s	early 2000s	mid 2000s
Argentina	1997		
Australia		1998/99	2004/05
Austria	1995	2000	2005
Belgium	1995	2000	2004
Brazil	1995	2000	2005
Canada	1995	2000	2005
China	1995	2000	2005
Chile	1996		2003
Czech Republic		2000	2005
Denmark	1995	2000	2005
Estonia	1997	2000	2005
Finland	1995	2000	2005
France	1995	2000	2005
Germany	1995	2000	2005
Greece	1995	2000	2005
Hungary		2000	2005
India	1993/94	1998/99	2003/04
Indonesia	1995	2000	2005
Ireland	1995	2000	2005
Israel	1995		2005
Italy	1995	2000	2005
Japan	1995	2000	2005
Korea		2000	2005
Mexico			2003
Netherlands	1995	2000	2005
New Zealand	1995/96		2002/03
Norway	1995	2000	2005
Poland	1995	2000	2005
Portugal	1995	2000	2005
Romania		2000	2005
Russia	1995	2000	
Slovakia	1995	2000	2005
Slovenia		2000	2005
South Africa	1993	2000	2002
Spain	1995	2000	2005
Sweden	1995	2000	2005
Switzerland		2000	
Turkey	1996	1998	2002
United Kingdom	1995	2000	2005
United States	1995	2000	2005

C Detailed Regression Results

Table C-I: Regressions on Pooled Data, Robustness Checks - Detailed Table

Panel A: Alternative measures of CO_2 imports								
	(A1)	(A2)	(A3)	(A4)	(A5)	(A6)	(A7)	(A8)
Measure:	MRIO				Technique fixed		MRIO I-O fixed	
Dependent variable:	Ln CO_2 intensity		Ln CO_2 imports		Ln CO_2 imports		Ln CO_2 imports	
Method:	FE	FE	FE	FE	FE	FE	FE	FE
Kyoto_m	-0.00		0.02		0.02		0.02	
	(0.00)		(0.02)		(0.01)		(0.01)	
Kyoto_x	-0.07***		-0.16***		-0.10***		-0.16***	
	(0.00)		(0.02)		(0.02)		(0.02)	
Kyoto_m-Kyoto_x		0.02***		0.07***		0.05***		0.07***
		(0.00)		(0.01)		(0.01)		(0.01)
ln GDP_m	0.03**		1.89***		1.86***		1.87***	
	(0.01)		(0.06)		(0.06)		(0.06)	
ln GDP_x	-1.22***		-0.14**		1.08***		0.11*	
	(0.01)		(0.07)		(0.06)		(0.06)	
Joint FTA (0,1)	0.00	0.01	0.00	0.01	-0.00	-0.01	0.01	0.01
	(0.01)	(0.01)	(0.04)	(0.04)	(0.04)	(0.03)	(0.04)	(0.03)
Joint WTO (0,1)	0.01	-0.00	-0.06	-0.14	-0.07	-0.14	-0.08	-0.14
	(0.03)	(0.03)	(0.16)	(0.16)	(0.16)	(0.16)	(0.16)	(0.16)
Joint EU (0,1)	0.00	-0.00	-0.09***	-0.09***	-0.09***	-0.09***	-0.09***	-0.09***
	(0.01)	(0.01)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
MR distance	0.00*		-0.02***		-0.02***		-0.02***	
	(0.00)		(0.01)		(0.01)		(0.01)	
MR contiguity	-0.06***		0.14**		0.20***		0.17***	
	(0.01)		(0.06)		(0.06)		(0.06)	
MR language	0.01**		-0.01		-0.03		-0.02	
	(0.00)		(0.02)		(0.02)		(0.02)	
MR FTA	-0.01***		0.02***		0.03***		0.02***	
	(0.00)		(0.00)		(0.00)		(0.00)	
MR WTO	0.00		0.03**		0.03**		0.03**	
	(0.00)		(0.01)		(0.01)		(0.01)	
MR EU	0.03***		0.02***		-0.01***		0.00	
	(0.00)		(0.01)		(0.00)		(0.01)	
MR terms[a]	yes		yes		yes		yes	
Year effects	yes		yes		yes		yes	
Country × year FE		yes		yes		yes		yes
Observations	223,460	223,460	223,460	223,460	223,384	223,384	223,499	223,499
adj. R^2	0.65	0.71	0.07	0.08	0.18	0.21	0.05	0.06

Note: Standard errors (in brackets) corrected for clustering within country-pair; ***,** and * denote statistical significance at the 1%, 5% and 10% level, respectively. [a] Multilateral resistance (MR) control variables (i.e., FTA, WTO, EU, distance, contiguity, common language) constructed according to Baier and Bergstrand (2009).

Table C-II: Regressions on Pooled Data, Robustness Checks - Detailed Table

Panel B: Alternative samples and estimators								
	(B1)	(B2)	(B3)	(B4)	(B5)	(B6)	(B7)	(B8)
Sample:	w/o China & transition countries[c]				Pre- and post-treatment averages			
Dependent variable:	Ln CO_2 intensity		Ln CO_2 imports		Ln CO_2 intensity		Ln CO_2 imports	
Method:	FE	FE	FE	FE	FE	FE	FE	FE
Kyoto_m	-0.00		-0.00		0.03***		-0.04	
	(0.01)		(0.02)		(0.01)		(0.04)	
Kyoto_x	0.02***		-0.12***		-0.08***		-0.29***	
	(0.01)		(0.02)		(0.01)		(0.04)	
Kyoto_m-Kyoto_x		-0.02***		0.03**		0.04***		0.10***
		(0.00)		(0.01)		(0.01)		(0.02)
ln GDP_m	-0.08***		2.14***		-0.03		1.05***	
	(0.03)		(0.10)		(0.04)		(0.15)	
ln GDP_x	-0.98***		-0.68***		-1.26***		-0.60***	
	(0.03)		(0.10)		(0.04)		(0.14)	
Joint FTA (0,1)					0.00	0.01	0.07	0.11
					(0.02)	(0.02)	(0.07)	(0.07)
Joint WTO (0,1)					-0.03	-0.09	-0.38	-0.47
					(0.08)	(0.06)	(0.35)	(0.41)
Joint EU (0,1)	0.00	0.00	-0.04	-0.04	-0.00	-0.00	-0.03	-0.01
	(0.01)	(0.01)	(0.03)	(0.03)	(0.02)	(0.02)	(0.07)	(0.07)
MR distance	0.02***		0.12***		0.01		-0.07***	
	(0.01)		(0.02)		(0.01)		(0.03)	
MR contiguity	0.02		0.45***		-0.10*		0.44**	
	(0.02)		(0.07)		(0.05)		(0.22)	
MR language	-0.00		-0.05**		-0.02		-0.21**	
	(0.01)		(0.02)		(0.02)		(0.09)	
MR FTA	-0.03***		-0.03***		-0.02***		0.04***	
	(0.00)		(0.01)		(0.00)		(0.01)	
MR WTO	-0.19***		-1.33***		0.02***		0.10***	
	(0.05)		(0.17)		(0.01)		(0.03)	
MR EU	0.03***		0.03***		0.04***		0.03**	
	(0.00)		(0.01)		(0.00)		(0.01)	
MR terms[a]	yes		yes		yes		yes	
Year effects	yes		yes		yes		yes	
Country × year FE		yes		yes		yes		yes
Observations	136,392	136,392	136,392	136,392	36,269	36,269	36,269	36,269
adj. R^2	0.53	0.65	0.03	0.06	0.72	0.77	0.07	0.11

Note: Standard errors (in brackets) corrected for clustering within country-pair; ***,** and * denote statistical significance at the 1%, 5% and 10% level, respectively. [a] Multilateral resistance (MR) control variables (i.e., FTA, WTO, EU, distance, contiguity, common language) constructed according to Baier and Bergstrand (2009). [c] Transition countries are CZE, EST, HUN, POL, ROU, RUS, SVN, SVK.

Table C-III: Regressions on Pooled Data, Robustness Checks - Detailed Table

	(C1)	(C2)	(C3)	(C4)	(C5)	(C6)	(C7)	(C8)
Panel C: Aggregate data								
Dependent variable:	Ln CO_2 intensity				Ln CO_2 imports			
Method:	FE	FE	FD	FD	FE	FE	FD	FD
Kyoto_m	0.02		0.00		0.20***		0.05***	
	(0.02)		(0.01)		(0.03)		(0.02)	
Kyoto_x	-0.20***		-0.06***		-0.16***		-0.02	
	(0.02)		(0.01)		(0.04)		(0.02)	
Kyoto_m-Kyoto_x		0.07***		0.03***		0.13***		0.04**
		(0.01)		(0.01)		(0.02)		(0.02)
ln GDP_m	0.25***		0.10		2.31***		3.01***	
	(0.08)		(0.09)		(0.16)		(0.17)	
ln GDP_x	-1.76***		-1.93***		-0.25		-0.93***	
	(0.09)		(0.10)		(0.17)		(0.18)	
Joint FTA (0,1)	-0.11***	0.01	-0.01	0.01	0.05	-0.07	-0.01	0.03
	(0.02)	(0.04)	(0.01)	(0.02)	(0.03)	(0.07)	(0.02)	(0.04)
Joint WTO (0,1)	-0.12***	-0.52***	-0.07*	-0.14	0.18	-1.37***	-0.10	-0.17
	(0.04)	(0.08)	(0.04)	(0.16)	(0.12)	(0.35)	(0.10)	(0.20)
Joint EU (0,1)	0.10***	0.01	0.03***	0.01	-0.05*	-0.08*	-0.00	-0.04
	(0.02)	(0.03)	(0.01)	(0.02)	(0.03)	(0.04)	(0.01)	(0.03)
MR distance	-0.02***		0.00		-0.01		-0.00	
	(0.00)		(0.00)		(0.01)		(0.01)	
MR contiguity	0.15**		-0.02		0.34***		0.04	
	(0.07)		(0.04)		(0.11)		(0.06)	
MR language	-0.11***		-0.07***		-0.07***		-0.03**	
	(0.02)		(0.01)		(0.03)		(0.02)	
MR FTA	0.04		0.01		-0.09		-0.03	
	(0.04)		(0.03)		(0.06)		(0.04)	
MR WTO	0.14***		-0.01		0.09		0.04	
	(0.03)		(0.02)		(0.08)		(0.05)	
MR EU	0.02		0.07***		0.11**		0.11***	
	(0.03)		(0.02)		(0.05)		(0.04)	
MR terms[a]	yes		yes		yes		yes	
Year effects	yes		yes		yes		yes	
Country × year FE		yes		yes		yes		yes
Observations	15422	15422	13864	13864	15422	15422	13864	13864
adj. R^2	0.56	0.60	0.16	0.25	0.19	0.24	0.06	0.09

Note: Standard errors (in brackets) corrected for clustering within country-pair; ***,** and * denote statistical significance at the 1%, 5% and 10% level, respectively. [a] Multilateral resistance (MR) control variables (i.e., FTA, WTO, EU, distance, contiguity, common language) constructed according to Baier and Bergstrand (2009).

Table C-IV: Sector-by-sector regressions: differential commitment - Detailed table

Sector:	Agriculture, forestry, fishing						Electricity, energy, mining, quarrying					
Dependent variable:	Ln imports		Ln CO_2 intensity		Ln CO_2 imports		Ln imports		Ln CO_2 intensity		Ln CO_2 imports	
Method:	FE	long FE	FE	long FE	FE	long FE	FE	long FE	FE	long FE	FE	long FE
Kyoto_m-Kyoto_x	-0.04	-0.02	0.02***	0.06***	-0.02	0.05	0.08	0.14	0.05***	0.10***	0.13**	0.24**
	(0.04)	(0.08)	(0.01)	(0.01)	(0.04)	(0.08)	(0.06)	(0.12)	(0.01)	(0.02)	(0.06)	(0.12)
Joint FTA membership	0.67***	0.83***	0.00	0.01	0.67***	0.83***	-0.42**	-0.31	0.00	-0.02	-0.42**	-0.32
	(0.14)	(0.27)	(0.03)	(0.05)	(0.14)	(0.28)	(0.17)	(0.36)	(0.03)	(0.05)	(0.17)	(0.36)
Joint WTO membership	-0.30	-0.23	0.02	0.02	-0.28	-0.20	-0.03	-1.23	0.01	-0.04	-0.02	-1.31
	(0.40)	(1.17)	(0.08)	(0.12)	(0.41)	(1.19)	(0.44)	(1.35)	(0.08)	(0.18)	(0.43)	(1.35)
Joint EU membership	0.11	0.37	0.01	0.01	0.12	0.39	-0.06	0.12	-0.00	-0.00	-0.06	0.12
	(0.09)	(0.23)	(0.02)	(0.05)	(0.09)	(0.23)	(0.13)	(0.40)	(0.02)	(0.06)	(0.14)	(0.40)
Country × year effects	yes	yes	yes	yes	yes	yes		yes		yes		yes
Observations	18,148	2,992	18,148	2,92	18,148	2,992	16,209	2,818	16,209	2,818	16,209	2,818
adj. R^2	0.16	0.24	0.74	0.79	0.08	0.10	0.10	0.15	0.78	0.82	0.08	0.15

Note: Country-pair fixed effect regression (sector-by-sector). Differential Kyoto commitment takes values (-1,0,1). The method of estimation is either fixed effects (within, FE) or long fixed-effects estimation on pre- and post-treatment averages (long FE). Heteroskedacticity-robust standard errors (in brackets) are adjusted for within country-pair clustering. ***, ** and * denote statistical significance at the 1%, 5% and the 10% levels, respectively.

Table C-V: Sector-by-sector regressions: differential commitment - Detailed table

Sector:	Basic metals						Chemicals and petrochemicals					
Dependent variable:	Ln imports		Ln CO_2 intensity		Ln CO_2 imports		Ln imports		Ln CO_2 intensity		Ln CO_2 imports	
Method:	FE	long FE	FE	long FE	FE	long FE	FE	long FE	FE	long FE	FE	long FE
Kyoto_m-Kyoto_x	0.20***	0.21**	-0.00	0.01	0.20***	0.21**	0.02	0.02	0.06***	0.07***	0.08***	0.09*
	(0.04)	(0.08)	(0.01)	(0.01)	(0.04)	(0.08)	(0.03)	(0.05)	(0.01)	(0.02)	(0.03)	(0.06)
Joint FTA membership	0.00	0.09	0.02	0.02	0.02	0.08	0.12	0.19	0.02	0.00	0.13	0.17
	(0.12)	(0.24)	(0.02)	(0.05)	(0.13)	(0.25)	(0.08)	(0.14)	(0.03)	(0.05)	(0.09)	(0.15)
Joint WTO membership	0.04	0.21	0.03	-0.37	0.07	-0.14	-0.12	-0.17	-0.02	-0.00	-0.14	-0.17
	(0.73)	(1.07)	(0.17)	(0.29)	(0.76)	(1.18)	(0.45)	(0.99)	(0.14)	(0.18)	(0.50)	(1.07)
Joint EU membership	-0.18*	-0.23	-0.01	-0.00	-0.18*	-0.20	-0.01	0.13	-0.00	-0.01	-0.02	0.12
	(0.10)	(0.25)	(0.02)	(0.05)	(0.10)	(0.26)	(0.06)	(0.16)	(0.03)	(0.06)	(0.07)	(0.17)
Country × year effects	yes	yes	yes	yes	yes	yes		yes		yes		yes
Observations	18,515	3,033	18,515	3,033	18,515	3,033	19,356	3,067	19,356	3,067	19,356	3,067
adj. R^2	0.29	0.47	0.84	0.88	0.13	0.21	0.36	0.58	0.77	0.82	0.15	0.21

Note: Country-pair fixed effect regression (sector-by-sector). Differential Kyoto commitment takes values (-1,0,1). The method of estimation is either fixed effects (within, FE) or long fixed-effects estimation on pre- and post-treatment averages (long FE). Heteroskedacticity-robust standard errors (in brackets) are adjusted for within country-pair clustering. ***, ** and * denote statistical significance at the 1%, 5% and the 10% levels, respectively.

Table C-VI: Sector-by-sector regressions: differential commitment - Detailed table

Sector:	Other non-metallic mineral products						Transport equipment					
Dependent variable:	Ln imports		Ln CO_2 intensity		Ln CO_2 imports		Ln imports		Ln CO_2 intensity		Ln CO_2 imports	
Method:	FE	long FE	FE	long FE	FE	long FE	FE	long FE	FE	long FE	FE	long FE
Kyoto_m-Kyoto_x	0.14***	0.17***	-0.00	0.00	0.14***	0.18**	0.15***	0.18**	0.01	0.01	0.16***	0.21**
	(0.03)	(0.07)	(0.01)	(0.02)	(0.03)	(0.07)	(0.04)	(0.08)	(0.01)	(0.02)	(0.04)	(0.09)
Joint FTA membership	-0.22**	-0.27	0.01	-0.00	-0.20**	-0.27	-0.08	0.02	0.03	0.02	-0.05	0.07
	(0.09)	(0.18)	(0.02)	(0.05)	(0.10)	(0.19)	(0.12)	(0.23)	(0.03)	(0.06)	(0.12)	(0.23)
Joint WTO membership	0.10	1.26	-0.02	-0.05	0.08	1.21	-0.17	-0.71	0.02	-0.10	-0.14	-0.91
	(0.65)	(1.45)	(0.13)	(0.19)	(0.61)	(1.46)	(0.66)	(1.30)	(0.03)	(0.23)	(0.66)	(1.29)
Joint EU membership	-0.11	-0.10	-0.01	-0.01	-0.11	-0.12	-0.33***	-0.17	-0.02	-0.01	-0.35***	-0.15
	(0.08)	(0.21)	(0.02)	(0.06)	(0.08)	(0.23)	(0.09)	(0.24)	(0.02)	(0.07)	(0.09)	(0.25)
Country × year effects	yes	yes	yes	yes	yes	yes		yes		yes		yes
Observations	18,751	3,028	18,751	3,028	18,751	3,028	18,407	3,003	18,407	3,003	18,407	3,003
adj. R^2	0.24	0.40	0.78	0.81	0.10	0.17	0.32	0.53	0.77	0.80	0.17	0.29

Note: Country-pair fixed effect regression (sector-by-sector). Differential Kyoto commitment takes values (-1,0,1). The method of estimation is either fixed effects (within, FE) or long fixed-effects estimation on pre- and post-treatment averages (long FE). Heteroskedacticity-robust standard errors (in brackets) are adjusted for within country-pair clustering. ***, ** and * denote statistical significance at the 1%, 5% and the 10% levels, respectively.

Table C-VII: Sector-by-sector regressions: differential commitment - Detailed table

Sector:	Machinery						Food products, beverages, tobacco					
Dependent variable:	Ln imports		Ln CO_2 intensity		Ln CO_2 imports		Ln imports		Ln CO_2 intensity		Ln CO_2 imports	
Method:	FE	long FE	FE	long FE	FE	long FE	FE	long FE	FE	long FE	FE	long FE
Kyoto_m-Kyoto_x	0.13***	0.10**	0.01	0.00	0.15***	0.11**	0.01	0.06	0.01**	0.03**	0.02	0.10
	(0.02)	(0.05)	(0.01)	(0.02)	(0.03)	(0.05)	(0.03)	(0.08)	(0.01)	(0.01)	(0.04)	(0.08)
Joint FTA membership	-0.17**	-0.00	0.01	-0.00	-0.16**	-0.01	0.73***	1.05***	0.01	0.00	0.74***	1.03***
	(0.07)	(0.14)	(0.03)	(0.05)	(0.07)	(0.14)	(0.12)	(0.24)	(0.02)	(0.04)	(0.12)	(0.24)
Joint WTO membership	-0.15	-0.46	0.00	-0.08	-0.15	-0.45	-1.07**	-2.36	-0.01	-0.13	-1.08**	-2.43
	(0.56)	(1.40)	(0.09)	(0.22)	(0.62)	(1.54)	(0.44)	(1.45)	(0.05)	(0.16)	(0.44)	(1.48)
Joint EU membership	-0.09*	0.07	-0.01	-0.01	-0.10*	0.07	-0.00	-0.08	-0.00	-0.00	-0.01	-0.06
	(0.05)	(0.14)	(0.02)	(0.06)	(0.05)	(0.15)	(0.07)	(0.18)	(0.02)	(0.04)	(0.08)	(0.18)
Country × year effects	yes	yes	yes	yes	yes	yes		yes		yes		yes
Observations	19,488	3,074	19,488	3,074	19,488	3,074	19,134	3,061	19,134	3,061	19,134	3,061
adj. R^2	0.51	0.70	0.80	0.83	0.28	0.40	0.21	0.33	0.82	0.85	0.10	0.18

Note: Country-pair fixed effect regression (sector-by-sector). Differential Kyoto commitment takes values (-1,0,1). The method of estimation is either fixed effects (within, FE) or long fixed-effects estimation on pre- and post-treatment averages (long FE). Heteroskedacticity-robust standard errors (in brackets) are adjusted for within country-pair clustering. ***, ** and * denote statistical significance at the 1%, 5% and the 10% levels, respectively.

Table C-VIII: Sector-by-sector regressions: differential commitment - Detailed table

Sector:	Paper, paper products, pulp and printing						Wood and wood products					
Dependent variable:	Ln imports		Ln CO_2 intensity		Ln CO_2 imports		Ln imports		Ln CO_2 intensity		Ln CO_2 imports	
Method:	FE	long FE	FE	long FE	FE	long FE	FE	long FE	FE	long FE	FE	long FE
Kyoto_m-Kyoto_x	0.15***	0.16**	0.02***	0.04***	0.17***	0.19***	-0.11**	-0.15	0.02**	0.05***	-0.08*	-0.09
	(0.04)	(0.07)	(0.01)	(0.01)	(0.04)	(0.07)	(0.05)	(0.09)	(0.01)	(0.02)	(0.05)	(0.09)
Joint FTA membership	-0.11	-0.06	0.01	0.00	-0.10	-0.07	-0.01	0.16	0.02	0.01	0.00	0.17
	(0.11)	(0.20)	(0.02)	(0.04)	(0.11)	(0.20)	(0.14)	(0.25)	(0.03)	(0.06)	(0.14)	(0.25)
Joint WTO membership	0.21	0.08	-0.01	-0.07	0.20	0.13	-0.89	-1.45	-0.03	-0.11	-0.92	-1.56
	(0.24)	(0.93)	(0.16)	(0.12)	(0.22)	(1.01)	(0.73)	(1.29)	(0.06)	(0.15)	(0.71)	(1.27)
Joint EU membership	-0.01	-0.05	-0.00	0.00	-0.02	-0.05	-0.06	0.06	-0.01	-0.01	-0.07	0.06
	(0.08)	(0.21)	(0.02)	(0.05)	(0.09)	(0.22)	(0.11)	(0.31)	(0.02)	(0.06)	(0.11)	(0.32)
Country × year effects	yes	yes	yes	yes	yes	yes		yes		yes		yes
Observations	19,045	3,057	19,045	3,057	19,045	3,057	17,717	2,992	17,717	2,992	17,717	2,992
adj. R^2	0.20	0.36	0.76	0.83	0.11	0.18	0.21	0.36	0.76	0.78	0.12	0.21

Note: Country-pair fixed effect regression (sector-by-sector). Differential Kyoto commitment takes values (-1,0,1). The method of estimation is either fixed effects (within, FE) or long fixed-effects estimation on pre- and post-treatment averages (long FE). Heteroskedacticity-robust standard errors (in brackets) are adjusted for within country-pair clustering. ***, ** and * denote statistical significance at the 1%, 5% and the 10% levels, respectively.

Table C-IX: Sector-by-sector regressions: differential commitment - Detailed table

Sector:	Textile and leather						Non-specified industries					
Dependent variable:	Ln imports		Ln CO_2 intensity		Ln CO_2 imports		Ln imports		Ln CO_2 intensity		Ln CO_2 imports	
Method:	FE	long FE	FE	long FE	FE	long FE	FE	long FE	FE	long FE	FE	long FE
Kyoto_m-Kyoto_x	-0.12***	-0.19***	0.02***	0.03*	-0.09***	-0.15**	-0.01	-0.02	0.09***	0.11***	0.09***	0.10**
	(0.03)	(0.06)	(0.01)	(0.02)	(0.03)	(0.06)	(0.02)	(0.04)	(0.01)	(0.02)	(0.03)	(0.05)
Joint FTA membership	-0.11	0.08	0.01	-0.00	-0.10	0.08	-0.30***	-0.26*	0.02	0.01	-0.27***	-0.24*
	(0.09)	(0.17)	(0.03)	(0.05)	(0.10)	(0.18)	(0.08)	(0.13)	(0.03)	(0.05)	(0.08)	(0.14)
Joint WTO membership	0.35	-0.27	-0.02	-0.11	0.33	-0.32	-0.03	0.14	-0.02	-0.12	-0.05	0.05
	(0.35)	(1.15)	(0.08)	(0.17)	(0.37)	(1.23)	(0.38)	(0.97)	(0.09)	(0.23)	(0.42)	(1.03)
Joint EU membership	-0.18***	-0.11	-0.00	-0.01	-0.19***	-0.10	-0.11**	-0.15	-0.00	-0.00	-0.12*	-0.15
	(0.07)	(0.16)	(0.02)	(0.05)	(0.07)	(0.17)	(0.05)	(0.12)	(0.03)	(0.08)	(0.06)	(0.15)
Country × year effects	yes	yes	yes	yes	yes	yes		yes		yes		yes
Observations	19,266	3,070	19,266	3,070	19,266	3,070	19,463	3,074	19,463	3,074	19,463	3,074
adj. R^2	0.19	0.33	0.78	0.81	0.12	0.26	0.52	0.73	0.78	0.83	0.28	0.41

Note: Country-pair fixed effect regression (sector-by-sector). Differential Kyoto commitment takes values (-1,0,1). The method of estimation is either fixed effects (within, FE) or long fixed-effects estimation on pre- and post-treatment averages (long FE). Heteroskedacticity-robust standard errors (in brackets) are adjusted for within country-pair clustering. ***, ** and * denote statistical significance at the 1%, 5% and the 10% levels, respectively.