FORSCHUNGSZENTRUM FZID
UNIVERSITÄT HOHENHEIM

FZID Discussion Papers

CC Economics

Discussion Paper 10-2010

KYOTO AND THE CARBON CONTENT OF TRADE

Rahel Aichele and Gabriel Felbermayr

Universität Hohenheim | Forschungszentrum Innovation und Dienstleistung
www.fzid.uni-hohenheim.de

Discussion Paper 10-2010

KYOTO AND THE CARBON CONTENT OF TRADE

Rahel Aichele and Gabriel Felbermayr

ISSN 1867-934X (Printausgabe)
ISSN 1868-0720 (Internetausgabe)

Kyoto and the carbon content of trade*

Rahel Aichele, and Gabriel Felbermayr‡

Hohenheim University

January 2010

Abstract

A unilateral tax on CO_2 emissions may drive up indirect carbon imports from non-committed countries, leading to carbon leakage. Using a gravity model of carbon trade, we analyze the effect of the Kyoto Protocol on the carbon content of bilateral trade. We construct a novel data set of CO_2 emissions embodied in bilateral trade flows. Its panel structure allows dealing with endogenous selection of countries into the Protocol. We find strong statistical evidence for Kyoto commitments to affect carbon trade. On average, the Kyoto protocol led to substantial carbon leakage but its total effect on carbon trade was only minor.

JEL Classification: F18, Q54, Q56

Keywords: carbon leakage, gravity model, international trade, climate change, embodied emission, input-output analysis.

---

*We are grateful to seminar participants at the Universities of Kiel, Aarhus and Tübingen (GLAMOUR seminar) for comments. Special thanks to Benjamin Jung, Wilhelm Kohler, Sonja Peterson, Philipp J.H. Schröder, Marcel Smolka, M. Scott Taylor, and Andreas Zahn for helpful suggestions.

‡Corresponding author: Gabriel Felbermayr, Department of Economics, Box 520E, Universität Hohenheim. E-mail: g.felbermayr@uni-hohenheim.de.

1 Introduction

Global warming caused by anthropogenic CO_2 emissions has become a major policy concern. Because countries' greenhouse gas emissions have global effects, decentralized national regulation is inefficient. Therefore, starting 1992 in Rio de Janeiro, a series of international summits has taken place to coordinate action against climate warming; so far, with mixed results.

In the Kyoto Protocol of 1997, 37 industrialized countries and the European Community have committed to legally binding emission targets. In 2012, emissions in those countries should be down on average by 5.2% relative to the base year of 1990. The Protocol says little about how countries are to achieve this objective and it has not introduced a generalized scheme for international trade of emission permits. More importantly, guided by the *principle of common but differentiated responsibilities*, emerging and developing countries including major polluters like China or India do not face any binding emission limits. The U.S. did not ratify the protocol after a non-binding Senate Resolution (Byrd-Hagel resolution) urged the Clinton administration to not accept any treaty that did not include the "meaningful" participation of all developing as well as industrialized countries, arguing that to do so would unfairly put the U.S. at a competitive disadvantage.

International economists have long pointed out that unilateral climate policy may generate *carbon leakage*: production of CO_2 intensive goods may move to unregulated countries from where regulated countries would import those goods. Those imports would embody foreign countries' CO_2 emissions so that one can speak about the *carbon content of trade*. A recent study by Wang and Watson (2007) argues that about a quarter of China's CO_2 emissions result from production for exports, mainly to Europe and the USA. Findings of a study of the World Bank (2008) also indicate that energy-intensive industries relocate to developing countries. Indeed, Grether and Mathys (2009) argue that the global center of gravity of CO_2 emissions has shifted faster eastwards than the center of economic activity, a finding that is in line with the carbon leakage hypothesis. Carbon leakage can even lead to a global increase in emissions if non-committed countries operate out-dated carbon-intensive technologies or a carbon-intensive energy mix. Kyoto's

Clean Development Mechanism was designed as a way of funding the required technology transfer to mitigate this problem but measured sectoral CO_2 intensities of production still vary strongly across countries and converge only very slowly (see e.g. Baumert et al., 2005, p. 26).

In the U.S. and Europe, the issue of carbon leakage has triggered a debate about border adjustment measures against countries that do not take actions to prevent climate change. The American Clear Energy and Security (ACES) Act (the so called Waxman-Markey Bill) contains such a provision and the French president Nicolas Sarkozy has made similar proposals for the EU. The possibility of carbon leakage has prompted researchers to argue in favor of *consumption*-based rather than production-based regulation, see e.g. Eder and Narodoslawsky (1999).

In theory, trade in carbon need not imply an inefficiency. When all countries have binding (but potentially different) emission targets, and there is national and international trade of pollution permits, trade in carbon would just reflect the pattern of comparative advantage.[1] More generally, under the assumption that the global supply of pollution permits is fixed, trade would be efficient and environmentally neutral. The central problem, of course, is that only a minority of countries has binding emission caps. Moreover, only a few of them allocate pollution permits through the market mechanism,[2] technologies are different across countries,[3] and trade costs are important.

In this study, we address the positive side of carbon trade rather than the normative one. We are interested in understanding, whether and by what extent commitments made

[1]Note that trade in goods can suffice to equalize the price of pollution permits across countries (Copeland and Taylor, 2005). This happens when the standard assumptions of the factor price equalization theorem hold, i.e., that there are no trade costs, technologies are identical across countries, every country has a cap-and-trade system for CO_2 emissions, and emission targets relative to endowments of production factors are not too different across countries.

[2]Even the emission trading system in Europe (ETS) only covers about 40% of total CO_2 emissions (EC, 2009).

[3]In particular, the carbon intensity of production varies greatly across countries, even within narrowly defined industries (see e.g. the detailed estimates of Nakano et al., 2009, p. 30 f.).

under the Kyoto Protocol affect bilateral trade in carbon embodied in goods. To that purpose, we develop a multi-input multi-sector multi-country partial equilibrium model of trade in carbon as embodied in goods. The model allows for international trade in final output goods and in intermediate inputs; it also provides a guideline for computing the carbon content of international trade flows. We derive a gravity equation for bilateral trade in CO_2 emissions and discuss a number of comparative statics results. Most importantly, we show that a unilateral carbon tax in some country leads to increased net imports of carbon from countries without such taxes. This is driven by two mutually reinforcing channels: (i) a technique effect, by which producers shift toward less-carbon intensive modes of production, and (ii) a scale effect due to an increase in overall production costs. We also discuss subsidies and find that, within the framework of our model, the scale effect may have the opposite sign than the technique effect.

In the empirical part of this paper, we present evidence that committed countries have more incentives and subsidy programs targeted toward emission reductions and that they reserve a more important role for environment-related taxes in their governments' budgets. We argue that the comprehensive use of country $\times$ year effects in our gravity equation 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 carbon imports of a committed country from an uncommitted exporter are about 10% higher than if the country had no commitments. This effect is mainly driven by a change in trade structure and trade flows, and not by technological change. In contrast, the reduced carbon exports of a committed country are mainly due to technological change and the implied reduction in CO_2 intensity. These result are confirmed in regressions of *net* imports of carbon. We run the Wooldridge regression-based test of strict exogeneity of the Kyoto commitment variable and find that our estimates can be interpreted as causal effects. We also present evidence on the sectoral level and find robust evidence for carbon leakage for seven out of twelve sectors. The affected sectors include such likely candidates as chemicals and petrochemicals or pulp and paper. Evidence is weaker for sectors such as agriculture, food, or textiles. Also in terms of economic significance, carbon leakage is important: On average, about 40% of carbon savings due to the Protocol have been offset by increased emissions in non-Kyoto countries.

Related literature. In theoretical models such as Copeland and Taylor (2005), unilateral climate policy necessarily has implications for the location of production of dirty goods. Production of emission-intensive goods would concentrate in "pollution havens", i.e., countries with weak environmental regulation (Copeland and Taylor, 2004) and the ensuing gap between countries' pollution content of consumption and that of production would be filled by international trade. The carbon leakage phenomenon is only a special case of this.[4]

According to Copeland and Taylor (see e.g. Copeland and Taylor, 2004, p. 9), a *pollution haven effect* occurs when stricter environmental regulation leads to changes in trade flows and plant location. The *pollution haven hypothesis*, in contrast, states that trade liberalization leads to relocation of pollution-intensive industries into countries with weaker environmental regulation. An empirical body of literature has been in search of pollution havens for twenty years. The early literature (see Jaffe et al., 1995 for a summary) only finds small, insignificant or non-robust effects of environmental regulation on trade or FDI flows in a cross section. By employing panel methods to control for unobserved heterogeneity and instrumenting for environmental regulation, newer studies find significant pollution haven effects for trade flows (see e.g. Ederington et al., 2005; Levinson and Taylor, 2008) as well as FDI flows (see e.g. Keller and Levinson, 2002; List et al., 2003; Dean et al., 2009). Frankel and Rose (2005) use a cross section of countries to test the pollution haven hypothesis; they find little evidence that trade openness leads poor (i.e., unregulated) countries to become pollution havens.

Related to CO_2 emissions, most authors have used CGE modeling to quantify the extent of carbon leakage;[5] see Mattoo et al. (2009) for a recent example. The general

[4]However, carbon leakage might be lowered by induced technological effects (see e.g. Di Maria and van der Werf, 2008; Acemoglu et al., 2009).

[5]Results of CGE models typically depend on parameterization and modeling assumptions. Studies with an Armington specification for energy intensive goods such as Felder and Rutherford (1993) or Burniaux and Martins (2000) find only limited evidence of carbon leakage, whereas Babiker (2005) finds a carbon leakage effect of up to 130% when assuming that energy intensive goods are homogeneous.

conclusion there is that unilateral emission cuts have minimal carbon leakage effects. The only study that uses regression techniques, is World Bank (2008) who finds that carbon taxes do affect the *value* of bilateral trade *in goods*, but do not find evidence for carbon leakage. In contrast, our econometric analysis yields statistically strong and unambiguous evidence of the carbon leakage hypothesis. The reasons for this performance are that (i) our analysis studies bilateral rather than multilateral trade (which dramatically increases the number of observations), (ii) it looks at the carbon content of trade and not on the value of trade, (iii) it controls for unobserved heterogeneity and self-selection of countries into climate control policies by exploiting the panel structure of the data.

Calculations of the carbon content of trade flows are strongly influenced by the "factor content of trade" literature. Its analytical methods carry over easily to environmental services, see Leontief (1970). A growing body of literature has since analyzed the pollution embodiment of trade using input-output (I/O) techniques empirically, most recently Levinson (2009). Studies estimating the carbon content of trade in a multi-country framework are, however, scarce and focused on cross-sectional data, see e.g. Ahmad and Wyckoff (2003), Peters and Hertwich (2008) and Nakano et al. (2009).

Finally, our work is related to the empirical gravity literature that studies the effect of trade policy on bilateral trade volume. See, e.g., Rose (2004) or Baier and Bergstrand (2007). Similar to us, in the absence of good data about actual policies, these authors use institutional dummies in their gravity models: the former study looks at membership in the WTO, the latter at free trade agreements.

To our knowledge, so far no paper has tried to directly test for carbon leakage resulting from unilateral climate policy empirically. This paper intends to fill the gap and to assess the role played by the Kyoto Protocol in shaping the sectoral, cross-country, and time patterns of trade in CO_2 as embodied in goods.

Plan of the paper. The second chapter develops our theoretical framework and derives a number of comparative statics results. The second chapter discusses our data. It also provides a first descriptive shot at the effect of Kyoto membership on bilateral trade in carbon. The fourth part of this study turns to the econometric analysis. The

Appendix contains all proofs and a battery of robustness checks.

2 Gravity for CO_2

This section develops a model for indirect bilateral trade in CO_2 emissions. The model allows for international trade not only in final but also in intermediate goods and shows how input-output accounting can be integrated into the gravity context to compute the carbon content of bilateral trade. Focusing on the scale, technique and composition effects[6], the model provides a partial equilibrium treatment which leaves the international energy and capital markets outside of the analysis.

2.1 A simple multi-sector multi-input gravity model

There is a final non-traded output good Y_i in each country $i = 1, ..., K$, which is assembled under conditions of perfect competition and constant returns to scale using home-made or imported intermediary inputs from $H + 1$ sectors. One of these sectors acts as a numeraire sector, whose output q_0 is freely tradable and which uses only labor in a linear production function. The use of fossil energy in all other intermediary sectors causes carbon dioxide emissions and consequently a global externality. There are K countries, which are structurally similar, but may differ with respect to size.

The utility function of the representative household in country i is additively separable in the externality and linear in consumption of Y_i. That same good can be used as input for the production of intermediate goods as well. The aggregate production function is modeled as a two-tier function, where the upper tier is a Cobb-Douglas of sectoral output indices. Those are aggregated using a constant elasticity of substitution (CES) production function over varieties produced by a mass of monopolistically competitive identical firms.

$$Y_i = q_0^{\mu_0} \prod_{h=1}^{H} \left(Y_i^h\right)^{\mu_h}, \; Y_i^h = \sum_{j=1}^{K} N_j^h \left(x_{ij}^h\right)^{\frac{\sigma_h - 1}{\sigma_h}} \quad \text{with} \sum_{h=1}^{H} \mu_h + \mu_0 = 1, \sigma_h > 1. \tag{1}$$

[6]Those terms where introduced by Grossman and Krueger (1993) in their study on the environmental effects of NAFTA.

Quantities of varieties are denoted x_{ij}^h, where j denotes the country of production, and N_j^h is the number of producers in country j. The index h denotes a sector, μ_h is the cost share of sector-h varieties and σ_h is the elasticity of substitution.

The price index dual to Y_i is denoted by

$$P_i = \prod_{h=1}^{H} \left(P_i^h\right)^{\mu_h}, \text{ where } P_i^h = \left[\sum_{j=1}^{K} N_j^h \left(p_{ij}^h\right)^{1-\sigma_h}\right]^{\frac{1}{1-\sigma_h}}. \tag{2}$$

Prices of sector-h varieties delivered from country j to i have the c.i.f. price $p_{ij}^h = \tau_{ij}^h p_j^h$, where $\tau_{ij}^h \geq 1$ is the usual iceberg trade cost factor and p_j^h is the mill (ex-factory) price of a generic variety in country j.

In each sector a large number of input producers operate under conditions of increasing returns to scale and monopolistic competition. Firms combine primary factors, the final output good, and energy to produce other intermediary inputs. The minimum cost function of a firm that produces a generic variety is

$$C_i^h = c_i^h(\cdot)\left(y_i^h + f^h\right), \tag{3}$$

where $c_i^h(\cdot) = P_i^{\alpha_h} \varepsilon_i^{\beta_h} w^{1-\alpha_h-\beta_h}$ is a minimum unit cost function with the usual properties. y_i^h is the output level of a generic firm; f^h denotes a fixed input requirement at the firm level; P_i is the price index of the aggregate good; w is the wage rate which is equalized across all countries due to our modeling of the numeraire sector; and ε_i is the cost of energy.

The energy mix comprises climate-friendly and dirty energies, namely wind power and fossil fuels, which are assumed to be imperfect substitutes. Wind energy is produced with capital and wind and energy from fossil fuels is generated combining capital and fuel according to a Leontief production function. Capital and fossil fuel are each supplied by the world market at exogenous prices.[7] The cost of energy is $\varepsilon_i = (q_i^{fuel})^{\nu_i}(q_i^{wind})^{1-\nu_i}$, where q_i^{wind} and q_i^{fuel} are the prices of wind and fossil energy, respectively, and ν_i is the cost share of dirty energy. Both prices carry a country index because of country-specific taxes or subsidies. More precisely, we posit the price of dirty energy to be $q_i^{fuel} = r + q^{fuel}(1 + t_i)$

[7]Note that this assumption rules out "supply-side leakage" as discussed by Sinn (2008).

where t_i is an ad-valorem tax rate, r denotes the capital rental rate and q^{fuel} gives the world price of fossil fuel. Also the use of clean energy (as a carbon-free input) could be subsidized at rate s_i, which leads to a price of wind energy of $q_i^{wind} = r\left(1 - s_i\right)$.

Profits of a generic input producer in country j are $p_j^h y_j^h - c_j^h\left(\cdot\right)\left(y_j^h + f^h\right)$. Optimal behavior implies markup pricing of the form $p_j^h = c_j^h \sigma_h / (\sigma_h - 1)$. Due to free entry, profits are zero in equilibrium, and the size of the firm is pinned down by technological parameters: $\bar{y}_j^h = \left(\sigma_h - 1\right) f^h$.

Maximizing (1) subject to the appropriate budget constraint yields country i consumer demand for varieties of sector h produced in country j

$$d_{ij}^h = N_j^h \frac{\mu_h G_i}{P_i^h} \left(\frac{p_{ij}^h}{P_i^h} \right)^{-\sigma_h}, \tag{4}$$

where G_i is GDP of country i, $\mu_h G_i / P_i^h$ denotes real expenditure allocated to sector h and p_{ij}^h / P_i^h is the relative price of sector-h varieties from country j relative to the average of all consumed varieties.

Besides demand for consumption d_{ij}^h, differentiated goods are also used as intermediate inputs with α_h their cost share. This gives rise to the following Proposition.

Proposition 1. *Total imports of country i from j of sector-h varieties (in physical units) for consumption and intermediate usage are given by*

$$M_{ij}^h = (1 + \alpha_h) d_{ij}^h,$$

where

$$d_{ij}^h = Z^h N_j^h G_i \left(P_i^h\right)^{\sigma_h - 1} \left(\tau_{ij}^h\right)^{-\sigma_h} \left[c_j^h\left(\cdot\right)\right]^{-\sigma_h} \tag{5}$$

is a reformulation of (4) *and* $Z^h \equiv \mu_h (\frac{\sigma_h - 1}{\sigma_h})^{\sigma_h}$ *is a constant.*
Proof see Appendix.

2.2 Calculating the carbon content of bilateral trade

M_{ij}^h denotes the physical flow of goods in sector h from country j to i. The production of those goods mandates demand for labor, the final output good, and energy in country j.

However, while labor is immobile geographically, the final output good is itself a composite of domestic and imported goods from all sectors. Hence, the carbon content of M_{ij}^h depends also on the carbon content of intermediate inputs used for assembling sector-h output.

In a first step, we limit attention to indirect emissions caused by intermediate interdependence *in country* j only. We label this the *simple method* of CO_2 accounting of trade.

Proposition 2. *The CO_2 emission content of $h-$imports of i from j for the simple method is given by*

$$E_{ij}^h = \eta_j^h M_{ij}^h,$$

where $\eta_j^h \equiv \boldsymbol{e_j} \boldsymbol{A_j^h}$ is the scalar product between the vector of sectoral emission coefficients $\boldsymbol{e_j}$ and the vector of input requirements $\boldsymbol{A_j^h}$. The latter is given by the h^{th} column of $(\boldsymbol{I} - \boldsymbol{B_j})^{-1}$, where, by Shepard's lemma,

$$\boldsymbol{B_j} = \begin{pmatrix} \frac{\partial c_j^1}{\partial p_j^1} & \cdots & \frac{\partial c_j^h}{\partial p_j^1} & \cdots & \frac{\partial c_j^H}{\partial p_j^1} \\ \vdots & & \ddots & & \vdots \\ \frac{\partial c_j^1}{\partial p_j^h} & \cdots & \frac{\partial c_j^h}{\partial p_j^h} & \cdots & \frac{\partial c_j^H}{\partial p_j^h} \\ \vdots & & \cdots & & \vdots \end{pmatrix},$$

is the input-output matrix of country j, and $\boldsymbol{I}$ is the identity matrix.
Proof see Appendix.

Substituting for M_{ij}^h, sector-h embodied carbon imports of country i from country j are given by

$$E_{ij}^h = \eta_j^h (1 + \alpha_h) Z^h G_i N_j^h (P_i^h)^{\sigma_h - 1} (\tau_{ij}^h)^{-\sigma_h} \left[c_j^h (\cdot) \right]^{-\sigma_h}. \tag{6}$$

It is understood that η_j^h, N_j^h, P_i^h and $c_j^h(\cdot)$ depend on climate policy. The aggregate (bilateral) embodied carbon emission imports then result as the sum over all sectoral carbon imports of i from j, i.e. $E_{ij} = \sum_h E_{ij}^h$.

If the upstream emissions *in all countries* are taken into account, one requires a multi-region input-output model (MRIO). The calculation of the emission factor η_j^h gets more involved (see Appendix B.3 for a detailed explanation), but a gravity equation for carbon similar to (6) results.

2.3 Unilateral climate policy and the CO_2 content of bilateral trade

Next, we want to investigate the effect of unilateral climate policy in the trade partners i and j on bilateral trade flows. Climate policy can take the form of increasing the national carbon tax or subsidizing clean energies. Therefore we are interested in the reaction of emission imports to the exporter's and the importer's climate policies.

The effect of a stricter carbon tax in the exporting country j on emission imports of country i of sector-h varieties is decomposed as follows

$$\frac{\partial E_{ij}^h}{\partial t_j} = \frac{\partial \eta_j^h}{\partial t_j} M_{ij}^h + \eta_j^h \frac{\partial M_{ij}^h}{\partial t_j}. \tag{7}$$

The increased costs for fossil fuel energy will induce substitution toward cleaner energy in every sector, greening the technology in country j. But the cost increase also implies a loss in competitiveness for all sectors in country j. Therefore two channels act to reduce the carbon content of imports on the sectoral level. This carries over to more climate-friendly imports in the aggregate, i.e. on the bilateral level. Proposition 3 summarizes.

Proposition 3. *A stricter carbon tax in the exporting country j causes a technique and a scale effect for sectoral carbon imports and a composition effect of aggregate (bilateral) imports of carbon of country i.*

(i) The technique effect reduces the sectoral carbon content of imports: $\frac{\partial \eta_j^h}{\partial t_j} M_{ij}^h < 0$.

(ii) The carbon tax affects the extensive margin N_l^h for all countries l, and not the intensive margin (i.e. the quantity of an $h-$variety import).

(iii) The scale effect reduces the sectoral carbon content of imports: $\eta_j^h \frac{\partial M_{ij}^h}{\partial t_j} < 0$.

(iv) The composition effect shifts the bilateral (aggregate) imports toward less carbon-intensive sectors.

(v) The carbon intensity of sectoral and bilateral imports falls.

Proof see Appendix.

What will the effect on E_{ij}^h be, if instead the importing country i imposes a stricter climate policy? Domestic varieties lose competitiveness and hence the number of sector-h varieties imported from the trade partner j, N_j^h, increases:

$$\frac{\partial E_{ij}^h}{\partial t_i} = \eta_j^h \frac{\partial M_{ij}^h}{\partial t_i} = \eta_j^h \frac{M_{ij}^h}{N_j^h} \frac{\partial N_j^h}{\partial t_i} > 0.$$

In other words, there is again a scale or pollution haven effect at work which increases imports for a country with a more stringent environmental policy. This raises embodied carbon imports from trade partners j. Again this effect is strongest for dirty sectors because their costs increase most. Therefore, on the bilateral level, there is a composition effect toward dirtier imports. This leads to a rising carbon intensity of bilateral imports. In conclusion, if a country imposes a carbon tax its embodied emission imports rise and its embodied emission exports fall.

Next, we investigate the effect of an increase in the carbon tax of j on the demand for fuel in countries i and j. Demand for fuel in a country is given by sectoral emissions per unit of output times overall output

$$D_j^{fuel} = \sum_{h=1}^{H} e_j^h(\cdot) \left(\bar{y}_j^h + f^h\right) N_j^h. \tag{8}$$

The effect of a stricter climate policy in country j on its own fuel demand and hence its carbon dioxide emissions is negative, since emission intensity falls and the number of varieties produced shrinks in all sectors:

$$\frac{\partial D_j^{fuel}}{\partial t_j} = \sum_{h=1}^{H} \frac{\partial e_j^h}{\partial t_j} \left(\bar{y}_j^h + f^h\right) N_j^h + \sum_{h=1}^{H} e_j^h(\cdot) \left(\bar{y}_j^h + f^h\right) \frac{\partial N_j^h}{\partial t_j} < 0, \tag{9}$$

The effect of this climate policy change on carbon dioxide emissions in a trade partner i is

$$\frac{\partial D_i^{fuel}}{\partial t_j} = \sum_{h=1}^{H} e_i^h(\cdot) \left(\bar{y}_i^h + f^h\right) \frac{\partial N_i^h}{\partial t_j} > 0. \tag{10}$$

Therefore, the emission reductions in a country due to a stricter climate policy, $\frac{\partial D_j^{fuel}}{\partial t_j} < 0$ lead to an increase in emissions in another country $\frac{\partial D_i^{fuel}}{\partial t_j} > 0$ through the shift in production of varieties, which is exactly how the IPCC (2007, p. 811) defines carbon leakage. Therefore, the scale effect acts as carbon leakage. Note that the technique should not be mistaken for carbon leakage since it has no effect on the emissions of the country that does not change its climate policy.

The decomposition of the effects of a *subsidy* to alternative energies in an exporting and an importing country is similar to the one above but leads to different conclusions. Proposition 4 summarizes the effects.

Proposition 4. *Subsidization of clean energy.*

(i) A subsidy to clean energies in exporting country j causes a negative technique effect but a positive scale effect. The sign of $\frac{\partial E_{ij}}{\partial s_j}$ is unclear.

(ii) A subsidy to alternative energies in importing country i unambiguously reduces the carbon content of its imports, $\frac{\partial E_{ij}}{\partial s_i} < 0$.

(iii) The subsidization of clean energies does not lead to carbon leakage.

Proof see Appendix.

Summarizing, the simple multi-sector multi-input gravity model for carbon trade predicts that the unilateral use of *carbon taxes* leads to carbon leakage. In contrast, *subsidization of clean energy* does not lead to carbon leakage since lower emissions in the committed countries are generally not offset by higher emissions in non-committed countries. Hence, how Kyoto membership affects bilateral trade in emissions depends on details of countries' climate policies. This ambiguity calls for an empirical treatment.

Note that our simple model is subject to a number of caveats. First, we have not imposed balance of the government budget. If subsidies are financed by carbon taxes, they would also lead to carbon leakage. Second, we have left the price of fuel exogenous. In our empirical exercise we use year effects to control for any feedback of demand changes on the price of fuel. Third, the technique effect reflects a substitution effect but no genuine technological change. Fourth, we abstract from classical factor endowment motives for international trade. These limitations of the model contribute to its tractability and have no major bearing on our empirical exercise.

3 Data presentation

3.1 Data sources

In this section, we construct a novel dataset of CO_2 emissions embodied in bilateral trade flows for the period 1995 to 2005. The computations apply the input-output methodology suggested by our theoretical model. Three types of data are required: sectoral CO_2 emission coefficients, input-output tables, and bilateral trade data. Input-output tables are provided by the OECD (2009), bilateral trade data is obtained from the UN COMTRADE database and data on sectoral carbon dioxide emissions (in million tons, mt) are taken from the International Energy Agency (IEA, 2008)[8]. The latter were translated into sectoral CO_2 emission *coefficients* using sectoral output data from various sources. A detailed description of the data and the necessary adjustments is given in Appendix D. After matching all data, we end up with a dataset spanning the years 1995 to 2005 comprising 15 sectors[9] and 38 countries. 27 out of the investigated countries face binding emissions restrictions at some point in the period 1995-2005 due to the Kyoto Protocol and ten are non-OECD member countries (Argentina, Brazil, China, Estonia, India, Indonesia, Israel, Russia, Slovenia and South Africa). The sampled countries are responsible for about 70 to 80% of worldwide carbon dioxide emissions in the sample years.

3.2 A first exploration of the data

In this subsection, we take a descriptive look at the data. Figure 1 plots the percentage share of carbon imports from uncommitted countries over total carbon imports for the time period 1995 to 2005, thereby updating similar statistics found in Peters and Hertwich (2008). The solid curve shows that, on average, Kyoto countries (those that have binding commitments under the Kyoto Protocol) have carbon imports from non-Kyoto countries amounting to about 40% of their total carbon imports. That measure exhibits an increas-

[8]Note that those emissions stem from fuel combustion only and emissions from international transportation are exempt due to data limitations.

[9]12 out of 15 sectors comprise internationally tradable goods.

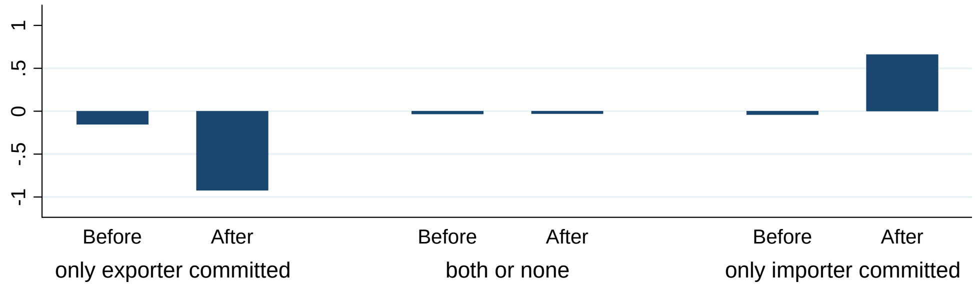
Figure 1: Carbon imports from non-Kyoto countries in % of total carbon imports.

ing trend from 1997 (the Kyoto summit) onwards which strengthens around the year of 2002 (when many countries ratified the Protocol). Hence, the figure provides descriptive evidence in favor of the leakage hypothesis. Looking at the main country blocs covered by Kyoto, it is apparent that the overall remoteness of countries matters: carbon leakage is higher for countries like Australia, Japan and Canada (not shown) which are remote from other Kyoto countries. While Figure 1 is instructive, it does not establish any causal relationship between climate policy and carbon leakage. In particular, the results could be driven by the entry of China into the WTO (in 2001).

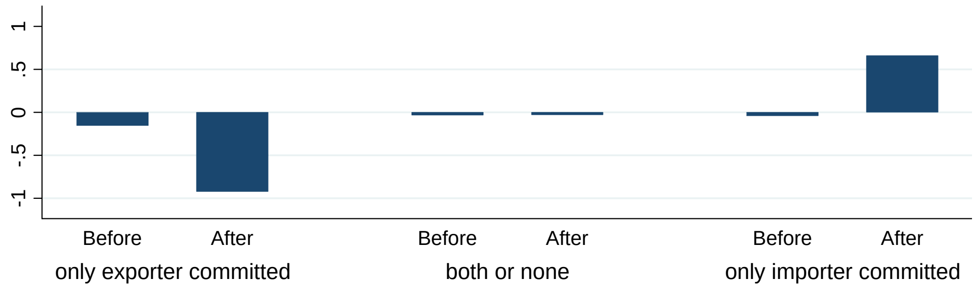
Figure 2 moves closer toward the identification of a causal effect. It reports evidence on bilateral net imports of carbon (in the upper panel) and on the carbon intensity (in the lower panel). More precisely, it looks at *differences* between Kyoto and non-Kyoto countries and between time periods before and after ratification of the Protocol. It therefore emulates the differences-in-differences analysis that will guide our econometric work and effectively controls for observable and unobservable time-invariant country as well as country-pair characteristics that may affect carbon trade. The figure suggests that ratification of the Kyoto Protocol had an influence on the bilateral net embodied carbon

Figure 2: CO_2 imports and intensities pre- and post-Kyoto ratification

(a) Net bilateral CO_2 imports



(b) CO_2 intensity, difference between importer and exporter



dioxide imports as well as on the carbon intensity of trade flows. Post-ratification net imports are larger then pre-ratification when only the importer is committed (the right pair of columns in the figure), while the reverse is true if only the exporter is committed (the left pair of columns). The same holds for carbon intensities. This finding is in line with the carbon leakage hypothesis. However, Figure 2 still does not account for the self-selection of countries into the Kyoto Protocol. This issue is tackled in the next section.

4 Empirical analysis

4.1 Controlling for unobserved heterogeneity

Taking logarithms on equation (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. That equation contains a number of variables that are potentially endogenous (such as GDP, the aggregate price level, or the number of firms) and possibly hard to observe directly. Following Feenstra (2004), we deal with this problem by adding a full host of interaction terms between country dummies and year dummies and estimate our gravity equation by OLS.

This strategy has the additional advantage that it deals with the potentially endogenous selection of countries into the Kyoto protocol. This is a serious issue: countries with lower carbon intensities of production, lower costs of reducing emissions, or ex-communist countries in the process of updating out-dated technologies with modern, carbon-saving ones, could be more willing to commit to climate policy targets as the costs of meeting those targets would be lower. Kyoto membership is then endogenous and a possible correlation between emissions embodied in trade and Kyoto status could be spurious. Including country × year interaction terms controls for all reasons why a country may join the agreement at some point in time.[10] Failing to account for selection into the Protocol would introduce correlation between the Kyoto commitment variable and the error term and therefore lead to endogeneity bias. The drawback of including those interaction terms is that only variables with a country-pair dimension can be identified. Moreover, only the *average* effect of Kyoto membership on bilateral carbon trade can be estimated with potential country-heterogeneity remaining undisclosed.

Another challenge in gravity modeling is how to deal with country-pair specific unobserved heterogeneity, due, for instance, to imperfect observability of trade costs. Usually, time-invariant variables such as geographical distance, contiguity, the existence of a common language, and so forth, are used as proxies. The bilateral stance of trade policy is proxied by two countries' joint membership in free trade areas (FTA), the world trade organization (WTO), a currency zone, and the like. However, trade costs depend on the availability of infrastructure and are only partly influenced by geography. Moreover, joint membership in FTAs may be endogenous. For this reason, Baier and Bergstrand (2007) propose to use fixed-effects estimation (i.e., include country-pair effects into the regression) or to time-differentiate equation (6), which has the advantage of controlling for all

[10]In other words, the country × year effects make the inclusion of odds-ratios for selection into treatment redundant.

historical and geographical determinants that may have lead to self-selection of countries into FTAs or into international climate-policy agreements. The fixed-effects model uses only the within-country-pair variance to identify the effect of policy variables on emissions trade. The strategy therefore accounts for country characteristics that are strictly time-invariant. However, it fails to control for unobserved 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).[11]

4.2 Measuring the Kyoto effect

The OECD has started to collect data on climate-related taxes;[12] however, there still is no harmonized data base that could be exploited in econometric analysis. Moreover, data typically refers to tax revenue which is clearly endogenous to the carbon leakage phenomenon. Similarly, the International Energy Agency collects information on national legislation pertaining to subsidy and incentive programs.[13] These data suggest that Kyoto member states do have stricter policies: they have higher environmental taxes as a percent of total tax income, or in terms of GDP per capita. A simple count of subsidy and incentives programs shows that committed countries have about 3 times more of them than non-committed countries and that most of the difference has emerged since the ratification of the Kyoto Protocol. While suggestive, these statistics are only partially informative about the general stance of climate control policies.[14]

We will therefore assume that there is a link between Kyoto commitment and actual climate policies and then use Kyoto commitment as our key independent variable of

[11]Alternatively, we could work with first differences. If $T = 2$, this strategy gives exactly the same results as the within estimator. If $T = 3$, results can differ if the error term exhibits serial correlation. We provide robustness checks based on first differences in the Appendix.

[12]http://www2.oecd.org/ecoinst/queries/index.htm

[13]http://www.iea.org/textbase/pm/

[14]See also the discussion in Levinson and Taylor (2008, p. 230) who also use a summary measure of environmental regulation in their empirical analysis.

interest.[15] In most of our regressions we use

$$Kyoto_{it} = \begin{cases} 1 & \text{if country } i \text{ has a binding emission cap and } t \geq \text{year of ratification} \\ 0 & \text{else} \end{cases} . \tag{11}$$

For instance, $Kyoto_{it} = 0$ for a country i that has not ratified the Protocol yet or has no binding emission targets under the Protocol. This variable has variance across countries and time: we have 38 countries in our sample, 12 have no commitments over the entire period 1995-2005. The ratification of the Protocol by national parliaments started in 2000 (Mexico). Some countries have ratified the Protocol in 2004 (India, Israel, Russia), and most have ratified in the years 2001, 2002, 2003.

Alternatively, we may summarize the stance of climate-saving policies in country i by

$$Kyoto_{it} = \begin{cases} -1 & \text{if} \quad i \text{ has no commitments at time } t \\ 0 & \text{if} \quad EM_{it} \leq CAP_i \text{ and } t \geq \text{year of ratification} \\ 1 & \text{if} \quad EM_{it} > CAP_i \text{ and } t \geq \text{year of ratification} \end{cases} , \tag{12}$$

where EM_{it} is the level of recorded CO_2 emissions at time t and CAP_i is the level of emissions promised for the year of 2012. While the definition in (11) measures whether a country is committed to keep carbon emissions below some target level, the definition in (12) also takes into account the restrictiveness of that target. We prefer the former, simpler measure, because the assumed linearity in (12) may be problematic. However, we present robustness checks that use (12).[16]

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

$$\ln E_{ijt}^{h} = \kappa_h \left(Kyoto_{it} - Kyoto_{jt} \right) + \gamma_h POL_{ijt} + \nu_i \times \nu_t + \nu_j \times \nu_t + \nu_{ij} + \upsilon_{ijt} \tag{13}$$

where E_{ijt}^{h} is the amount of CO_2 emissions embodied in country $i's$ imports from country j at time t. POL_{ijt} is a vector of trade policy variables in dummy form (common WTO

[15] This strategy is commonly used in empirical modeling of trade policy when researchers, for instance, proxy the stance of trade policy by a WTO membership dummy (Rose, 2004).

[16] We have also experimented with setting $Kyoto_{it} = 1$ if $EM_{it} \geq CAP_i$ and $t \geq$ year of ratification and 0 else and have obtained almost identical results as compared to (11).

membership, common FTA membership, Euro-zone), ν_{ij} is the country-pair specific intercept, and the vectors ν_i, ν_j, ν_t collect country i, country j, and year dummies. The error term υ_{ijt} is assumed to have the usual properties. We run (13) separately for each of our 12 sectors. Note that we cannot separately estimate the effects of the importer and the exporter being committed as long as we maintain the term $\nu_i \times \nu_t + \nu_j \times \nu_t$. Hence, we have bilateralized the Kyoto variable. To make the effect of importer commitment relative to exporter commitment visible, we drop the country × year effects in some regressions but give warning about the interpretation of the coefficients obtained. We will also work with regressions on aggregate bilateral data, which correspond to (13) with the $h-$index dropped.

A more demanding alternative specification uses the bilateral net balance of carbon imports as the dependent variable:

$$\ln E_{ijt}^{h} - \ln E_{jit}^{h} = 2\kappa_h \left(Kyoto_{it} - Kyoto_{jt} \right) + \bar{\nu}_i \times \bar{\nu}_t + \bar{\nu}_j \times \bar{\nu}_t + \bar{\nu}_{ij} + \bar{\upsilon}_{ijt}, \qquad (14)$$

which follows from (13) and where POL_{ijt} drops out due to its assumed symmetric effect on importers and exporters. The country × year interaction terms remain in the equation since nothing ensures that the terms (13) are symmetric across importers and exporters. Again, in some regressions, to make the separate effects of importer or exporter country commitments visible, we drop the country × year effects.

4.3 Does carbon trade obey the law of gravity?

As a first step in our empirical analysis we run a standard gravity model of bilateral trade in embodied carbon emissions. We work with the *pure cross-section of aggregate bilateral trade* for the year of 2004. The analysis covers 33 out of our 38 countries (we lack recent sectoral output data for 5 countries). One would expect that indirect bilateral trade in carbon emissions should be affected very similarly by economic, political, and geographical determinants of trade in goods since the former is derived from the latter.

Table 1 reports results. Most regressions are 'naive' (i.e., they omit importer and exporter effects) so that the separate effect of Kyoto commitments by the exporter and the importer can be estimated. As proposed by Baier and Bergstrand (2009), we compute a multilateral resistance term and include it into the regression to account for third country effects as well. We add an array of country-specific geographical controls which are also meant to capture country-specific unobserved heterogeneity.[17] While our theoretical model does not explicitly ask for it, we also include GDP per capita of the exporter and the importer. The reason is the well-known environmental Kuznets curve: richer countries have smaller emissions per unit of GDP than poorer ones. Column (1) reports a standard gravity equation with the value of bilateral trade as the dependent variable. Results are as expected: the elasticity of bilateral trade with respect to either the importer's or the exporter's GDP is very close to unity, and the elasticity with respect to geographical distance is virtually identical to minus one. In column (2), this changes little when the dependent variable is the log of carbon emissions as embodied in bilateral trade instead as the log of the (deflated by importer CPI) trade values.

However, column (2) contains a surprise: while GDP per capita of both the exporter and the importer increase the value of trade in goods (as in the empirical literature on the Linder hypothesis), richer countries appear to import more carbon than poorer ones, holding market size constant. However, those imports are lower when the export partner has higher GDP per capita. This finding suggests that climate policies (and hence emissions) may be endogenous to country characteristics, with richer countries having greener policies than poorer ones.[18]

Columns (3) and (4) add the Kyoto commitment dummies as given in (11) to the regression. Kyoto commitment of both the importer and the exporter appears to reduce the value of bilateral trade and the amount of emissions embodied in that trade flow. In both equations, commitment of the exporter has a stronger trade-defeating effect than commitment of the importer. Again, we find the change in sign across columns (3) and (4) of the coefficient of GDP per capita of the exporter. Columns (3) and (4) may fail to

[17]The inclusion of those variables is of little importance for parameter estimates.

[18]Including the exporter's squared GDP per capita results in a positive sign for the linear term and a negative for the squared one, both statistically significant. This is further evidence in favor of a Kuznets-curve effect.

control for countries' multilateral resistance and for their endogenous selection into the climate policy agreement. Column (5) therefore includes a comprehensive set of importer and exporter fixed effects. Country-specific effects can no longer be identified and drop out. Controls with bilateral dimension (such as distance) remain and do not change much relative to the 'naive' regressions. However, the difference in Kyoto commitment between the importer and the exporter now appears strongly significant and with the expected sign: on average, a committed importer imports about 56% more carbon emissions from a non-committed exporter; or, equivalently, a committed exporter exports about 56% less carbon emissions to a non-committed country.

Columns (6) to (8) repeat the above exercise, but use the Kyoto restrictiveness measure as defined in (12) instead of the commitment dummies. Results from (8) are qualitatively and quantitatively comparable to those from (5), with the additional insight that the strength of commitments matters: imports of a strongly committed importer ($Kyoto_{it} = 1$) from a totally uncommitted exporter ($Kyoto_{jt} = -1$) are again about 56% higher than in a situation where both countries have the same commitment ($0.279 * 2 = 0.558$).

4.4 CO_2 accounting and carbon imports in the panel

Next, we extend the analysis to a panel setup using yearly data from 1995-2005. Table 2 looks at aggregate trade and varies the exact definition of the dependent variable. This allows to control for country-pair specific unobserved heterogeneity using a within-transformation of the data. The strategy accounts for all time-invariant determinants of trade in emissions, i.e., also exporter- and importer-specific factors as long as they do not change over time. This may cover endowment structures, preferences, and so on. All regressions in Table 2 include a full set of year dummies to control for changes in the price of fuel, or the global business cycle. Even numbered regressions use country-specific year dummies (i.e., interaction terms between country dummies and year dummies), which, of course, precludes the estimation of country-specific influences on carbon trade.

The dependent variable in columns (1) and (2) in Table 2 is based on the "simple" method of carbon accounting. It draws only on the *domestic* CO_2 emissions that are required to produce the exports of some country and disregards CO_2 emissions that are embodied in imported inputs. Columns (3) and (4) use a broader definition (MRIO), where the carbon content of a country's exports is based on all CO_2 emissions, regardless of the place where they occur.[19] That is, the carbon content of *imported* inputs that are required for a country's exports is booked in the exporter's carbon account. Columns (5) and (6) compute the carbon content of trade based on the simple method and ruling out the technique effect. That is, the input-output table and the sectoral CO_2 emission coefficients are held constant at the 1995 level. Then, variation in the dependent variable can only derive from changes in the structure of bilateral trade flows and not from emission-saving technical change. Thus, the importance of the technique and scale effect are singled out, as motivated by the decomposition exercise in equation (7). Finally, columns (7) and (8) use the carbon intensity of imports as the dependent variable. It uses the (log of) carbon content of trade (simple method) divided by the (log of the) value of bilateral imports (deflated by the base-2000 GDP deflator of the exporter).[20] The loss in competitiveness should be strongest for the most carbon-intensive sectors. Therefore, we expect a higher carbon intensity of imports for Kyoto countries on the aggregate level.

The most important insight from Table 2 is that carbon imports of a committed country are by about 14% larger than those of a non-committed country, and carbon imports from a committed exporter are by about 15% smaller than those from a non-committed exporter. This is shown, for the simple method, in column (1). When including a full set of country $\times$ year interaction terms (column (2)), only the effect of differential

[19]Note that in a MRIO model there are many feedback effects due to vertical integration which makes it hard to disentangle effects in the investigated country from effects in other countries. Hence, in the MRIO approach, a Kyoto country's exports could embody more carbon *because of* carbon leakage. For example consider a case where a carbon-intensive intermediate which is used to produce those exports is imported from a carbon-intensively producing non-Kyoto country after ratification due to the Kyoto commitments. Therefore, in our context, we prefer the simple specification over the MRIO model for the empirical tests of the carbon leakage hypothesis, but always report results for the MRIO model as well.

[20]Defining the carbon intensity measure as the ratio of carbon imports over the deflated value of imports (i.e., not taking logs) leads to very similar results.

Kyoto commitment can be estimated. The estimated coefficient of 0.125 implies that carbon imports are about 12.5% higher if the importer is committed and the exporter not, and 12.5% lower if the exporter is committed and the importer is not. Comparing this estimate with the one obtained in Table 1 for the cross-section of 2004, one notes that controlling for country-pair specific unobserved heterogeneity strongly reduces the estimate. This may be due to unobserved details of *differential comparative advantage*: if the importer has a comparative advantage in non-carbon-intensive products and the exporter in carbon-intensive products, then self-selection into the Kyoto Protocol is more likely for the importer. This leads to spurious regression as the importer has both higher carbon emissions embodied in imports and commitments under Kyoto.

When turning to the MRIO definition of carbon imports, the picture barely changes. There are two important observations. Measured carbon leakage is somewhat smaller in column (4) as compared to column (2). This is as expected, since the MRIO definition blurs the link between the effect of domestic carbon emissions and the carbon content of domestically assembled goods (final or intermediate). Moreover, carbon leakage seems to be driven primarily by an increase in carbon imports and not so much by a decrease in carbon exports. This is also not surprising: carbon emissions of foreign input producers are factored into a country's exports, but have a much weaker influence on imports.

Columns (5) and (6) fix the technology used in producing final and intermediate goods. Imports of committed countries do not differ much as parameter estimates are similar between columns (1) and (5). The coefficient for committed exporters, in contrast, turns insignificant. Committed exporters seem to reduce the overall carbon content of their exports primarily by adopting greener (i.e., less carbon-intensive) technologies and not by altering the structure of production and, hence, of trade. The effect of differential Kyoto commitments (column (6)) is now only half of the one estimated in column (2). But relocation of production (the aggregate scale effect) still leads to about 7% more carbon imports of Kyoto countries from non-Kyoto countries. Keeping in mind that the scale effect is interpreted as the carbon leakage channel, we again find evidence in favor of the carbon leakage hypothesis.

Finally, we turn to the carbon intensity of imports. Results suggest that differential Kyoto commitment leads to carbon leakage in the sense that the carbon intensity of imports grows and that of exports falls if the importer is committed. This result is complementary to the one shown in columns (5) and (6): The carbon intensity of a committed country's exports falls precisely because of technological change and not because of a change in trade volumes or trade structure. In contrast, the carbon intensity of imports barely changes as increased carbon imports are matched with increased trade volumes.

To better assess the economic significance of our results, one needs to have answers to the following two questions: By how much would an average non-Kyoto country's carbon imports increase if it had ratified the Protocol in 2002 (the average date of ratification)? And by how much would domestic emission fall? Using sample averages for the year of 2002 and the coefficient of 0.125 found in column (2) of Table 2, the answer to the first question is 3.07 mt. The second question is much harder to answer. In our data, average yearly growth rates of emissions are 0.33% lower in committed relative to uncommitted countries.[21] Hence, from year of ratification to 2005, accumulated savings would have been about 1.327%. Again, evaluating at the sample mean of 2002, this results in emissions savings of 6.92 mt: approximately 44.4% of all savings would leak. This result is robust over columns (2), (4) and (6). Hence, historically, the Kyoto Protocol has led to a fairly strong leakage effect. This does, however, not allow predicting the effects of more ambitious (and more successful) carbon saving initiatives. Also note that the portion of total world imports (in our sample) per year caused by Kyoto is only about 5%.[22]

[21] In our data, from ratification onwards, Kyoto countries have average emission growth rates of 0.38% p.a. while non-Kyoto countries have 0.71%.

[22] In our sample, total carbon imports in 2005 amount to 2,191 mt, thereof 755 mt of Kyoto countries from non-Kyoto countries and 236 mt of the non-Kyoto countries from Kyoto members. Hence, additional carbon imports from non-Kyoto countries caused by Kyoto are approximately 83.9 mt ($= 755 \times 0.125/[1+0.125]$) while imports from Kyoto countries fall by approximately -33.7 mt ($= 236 \times [-0.125]/[1-0.125]$). Relative to observed carbon imports, Kyoto is responsible for about 5.1% ($= [83.9-33.7]/[755+236]$).

4.5 Net carbon imports and the Kyoto effect

Still using aggregate data, Table 3 proposes the most demanding test of the carbon leakage hypothesis. Rather than using carbon imports as the dependent variable, it uses net imports, as defined in (14). The hypothesis is that a committed importer should increase its net imports of carbon from a non-committed exporter. Clearly, when looking at *net* imports, the number of independent observations is half than when looking at imports.

Deviating from the specification in (14) by adding policy variables and the log product of GDPs (without consequences for results), we provide results for Kyoto commitment (according to definition (11)) and Kyoto restrictiveness (according to definition (12)). All models use the within estimator and include a full set of exporter × year and importer × year dummies. Robustness checks using the first-differenced model are in the Appendix.

The results are generally in line with the leakage hypothesis. Across all models, differential Kyoto commitment (i.e., the importer committed while the exporter is not) leads to increased net imports of carbon. Because we are looking at the bilateral trade balance, the effect of Kyoto commitment is expected to be larger than when focusing on imports. Again, the phenomenon of carbon leakage is economically relevant: when the exporter displays maximum restrictiveness and the exporter minimum restrictiveness, the net imports of carbon can increase by as much as 185% ($0.927 * 2 = 1.854$; simple method of CO_2 accounting). Also the carbon intensity of net imports reacts positively to differential Kyoto commitment, signaling that Kyoto influences both, technologies and the structure and volume of bilateral trade.

Table 3 also presents the p-values associated to the regression-based *test of strict exogeneity* proposed by Wooldridge (2002, p. 285).[23] In all cases, the test is easily passed. Hence, our variable of interest can be considered as strictly exogenous in the context of the specific model analyzed and its effect of the bilateral balance of carbon trade can be understood as a causal effect.

[23] The idea of the test is that including the lead of the independent variable should yield an insignificant coefficient if the contemporaneous level is strictly exogenous. Similarly, the level of the independent variable should not be significant in a first-differenced model.

4.6 CO_2 imports and carbon leakage across sectors

Finally, we look at sectoral bilateral imports and the sectoral bilateral trade balance (net imports) of carbon. Hallak (forthcoming) has shown that estimation of the gravity equation using aggregate data can suffer from aggregation bias. While his paper is about the Linder hypothesis, a similar problem may arise in the present context if patterns of comparative advantage correlate with adopted climate control policies. Hence, looking at sectors separately may lead to more consistent results than studying aggregate trade flows.

Table 4 presents the most important results from estimating sectoral gravity equations. The carbon content of trade is computed using the 'simple' method. The econometric model is again a within panel estimator with country $\times$ year interaction terms (where applicable). The table only reports the key parameters; the remaining details of the regressions and additional results can be found in the Appendix.

The overall picture again strongly confirms the carbon leakage hypothesis. Estimated coefficients of differential Kyoto commitment have the correct sign (with the only exception being the wood industry). The sign pattern of the separate estimates for the importer's and the exporter's commitment are also in line with expectations (except in the agricultural and the textiles sector). The size of the effects is similar in magnitude to the ones found in Table 2 for aggregate trade. The aggregate effects turn out to be close to the average of the sectoral effects.

The effect of Kyoto commitment is larger in more carbon-intensive sectors such as basic metals, chemicals and petrochemicals, non-metallic mineral products, transport equipment, machinery or paper and pulp. Evidence is much weaker in low-carbon sectors such as agriculture, forestry, and fishing, food, wood, or textiles. There is no evidence for carbon leakage in the electricity sector, probably because formal and informal trade costs are very high in this sector. Electricity being a major input in all other sectors may, however, play an important indirect role, since the carbon intensity of domestically produced inputs importantly affects the carbon content of exports. Finally, since we have no direct information about countries' policies (carbon taxes versus subsidies), failure to detect evidence for carbon leakage in a specific industry may signal the importance of subsidies as compared to taxes.

5 Conclusions

We have developed a multi-sector multi-input multi-country gravity model of trade in CO_2 emissions as embodied in goods. We have shown strong structural similarity to the standard gravity equation, from which our equation is derived by applying appropriately computed emission coefficients. Consequently, the emissions embodied in trade also depend on standard gravity variables such as tariffs and country size and their implied emissions per unit of trade. If a country unilaterally adopts a tax on CO_2 emissions, the carbon intensity of its production and of its exports falls. The tax also lowers price competitiveness so that indirect carbon imports from non-committed countries rise. The result is carbon leakage. In the case of a subsidy to alternative energy no such clear pattern arises.

We calculate the CO_2 emissions embodied in bilateral trade flows for a large sample of countries over the period 1995 to 2005. With the resulting panel dataset we try to detect the effect of the Kyoto Protocol on the carbon content of trade. The descriptive evidence reveals that carbon imports of Kyoto countries from non-Kyoto countries rose since the ratification process of the Kyoto Protocol started. This indicates potential carbon leakage as result of the non-global deal to curb greenhouse gas emissions.

While suggestive, the descriptive evidence cannot clarify whether the Kyoto Protocol has any causal effect on measured trade in carbon. To investigate this issue, we have used panel econometrics. Using a complete array of time-varying country-specific effects in theory-based gravity regressions, we can control for all potential reasons that may explain why some country has ratified the Protocol or not. We also account for country-pair and year specific determinants of carbon trade.

Our main result is that carbon imports of a committed country from a non-Kyoto exporter are about 10% higher than if the country had no commitments. This carbon leakage effect is strongest in the most carbon-intensive sectors. Hence, asymmetric commitment to policies geared toward the reduction of carbon emissions may have measurable consequences on bilateral trade patterns. The reduced emissions caused by domestic production are then offset by increased emissions in foreign countries; the total effect of the Kyoto Protocol on global emissions is therefore unclear. On average, we find a carbon leakage effect of about 44%. However, the volume of trade in carbon caused by Kyoto is rather small.

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. Policy-makers in the European Union and the U.S. have called for carbon tariffs to tackle the problem. Establishing the existence of carbon leakage as a result of unilateral climate policy, our analysis justifies the importance that policy-makers accord to international trade. However, rather than advocating carbon tariffs the use of which can have important negative side-effects on world trade, we propose that willing countries commit to binding restrictions not of their emission levels but of the amount of carbon embodied in consumption. These could be achieved by domestic consumption taxes and/or subsidies. However, such taxes pose important informational problems.

Importantly, our results also imply that simulations by climatologists (such as the one by Sawin et al., 2009), which disregard the possibility of carbon leakage, may overestimate the effect of unilateral emission control policies on the carbon concentration in the atmosphere.

Before closing, we want to stress that our empirical strategy was geared toward identifying the *average* causal 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.

References

Acemoglu, Daron, Philippe Aghion, Leonardo Bursztyn, and David Hemous, "The Environment and Directed Technical Change," *NBER Working Paper Series*, October 2009, *No. 15451.*

Ahmad, Nadim and Andrew Wyckoff, "Carbon Dioxide Emissions Embodied in International Trade of Goods," *OECD, Directorate for Science, Technology and Industry Working Papers*, November 2003, *No. 2003/15.*

Babiker, Mustafa H., "Climate change policy, market structure, and carbon leakage," *Journal of International Economics*, March 2005, *65* (2), 421–445.

Baier, Scott L. and Jeffrey H. Bergstrand, "Do free trade agreements actually increase members' international trade?," *Journal of International Economics*, March 2007, *71* (1), 72–95.

_ **and** _ , "Bonus vetus OLS: A simple method for approximating international trade-cost effects using the gravity equation," *Journal of International Economics*, February 2009, *77* (1), 77–85.

Baumert, Kevin A., Timothy Herzog, and Jonathan Pershing, *Navigating the Numbers: Greenhouse Gas Data and International Climate Policy*, Washington: World Resources Institute, 2005.

Burniaux, Jean-Marc and Joaquim Oliveira Martins, "Carbon Emission Leakages – A general equilibrium view," *OECD Economics Department Working Paper*, 2000, *No. 242.*

Copeland, Brian R. and M. Scott Taylor, "Trade, Growth, and the Environment," *Journal of Economic Literature*, March 2004, *42* (1), 7–71.

_ **and** _ , "Free trade and global warming: a trade theory view of the Kyoto protocol," *Journal of Environmental Economics and Management*, March 2005, *49* (2), 205–234.

Dean, Judith M., Mary E. Lovely, and Hua Wang, "Are foreign investors attracted to weak environmental regulations? Evaluating the evidence from China," *Journal of Development Economics*, September 2009, *90* (1), 1–13.

EC, "Progress towards achieving the Kyoto objectives," *Report from the Commission to the European Parliament and the Council*, 2009, *SEC(2009)1581*, Commission of the European Communities.

Eder, Peter and Michael Narodoslawsky, "What environmental pressures are a region's industries responsible for? A method of analysis with descriptive indices and input-output models," *Ecological Economics*, June 1999, *29* (3), 359–374.

Ederington, Josh, Arik Levinson, and Jenny Minier, "Footloose and Pollution-Free," *Review of Economics and Statistics*, February 2005, *87* (1), 92–99.

Feenstra, Robert C., *Advanced International Trade: Theory and Evidence*, Princeton: Princeton University Press, 2004.

Felder, Stefan and Thomas F. Rutherford, "Unilateral CO_2 Reductions and Carbon Leakage: The Consequences of International Trade in Oil and Basic Materials," *Journal of Environmental Economics and Management*, September 1993, *25* (2), 162–176.

Frankel, Jeffrey A. and Andrew K. Rose, "Is Trade Good or Bad for the Environment? Sorting Out the Causality," *Review of Economics and Statistics*, February 2005, *87* (1), 85–91.

Grether, Jean-Marie and Nicola A. Mathys, "How fast are CO_2 emissions moving to Asia?," *http://www.voxeu.org/index.php?q=node/4243*, 2009.

Grossman, Gene M. and Alan B. Krueger, "Environmental Impacts of a North American Free Trade Agreement," in Peter M. Garber, ed., *The Mexico-U.S. Free Trade Agreement*, Chicago: MIT Press, 1993, pp. 13–56.

Hallak, Juan Carlos, "A product quality view of the Linder hypothesis," *Review of Economics and Statistics*, forthcoming.

IEA, "CO_2 Emissions from Fuel Combustion (detailed estimates)," 2008, *Vol. 2008 release 01*, Paris.

IPCC, "Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories," *http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.html*, 1996.

_ , *Climate Change 2007: Mitigation of Climate Change* Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2007.

Jaffe, Adam B., Steven R. Peterson, Paul R. Portney, and Robert N. Stavins, "Environmental Regulation and the Competitiveness of U.S. Manufacturing: What Does the Evidence Tell Us?," *Journal of Economic Literature*, March 1995, *33* (1), 132–163.

Keller, Wolfgang and Arik Levinson, "Pollution Abatement Costs and Foreign Direct Investment Inflows to U.S. States," *Review of Economics and Statistics*, November 2002, *84* (4), 691–703.

Leontief, Wassily, "Environmental Repercussions and the Economic Structure: An Input-Output Approach," *The Review of Economics and Statistics*, August 1970, *52* (3), 262–271.

Levinson, Arik, "Technology, International Trade, and Pollution from US Manufacturing," *American Economic Review*, December 2009, *99* (5), 2177–2192.

_ **and M. Scott Taylor**, "Unmasking The Pollution Haven Effect," *International Economic Review*, February 2008, *49* (1), 223–254.

List, John A., Daniel L. Millimet, Per G. Fredriksson, and W. Warren McHone, "Effects of Environmental Regulations on Manufacturing Plant Births: Evidence from a Propensity Score Matching Estimator," *The Review of Economics and Statistics*, November 2003, *85* (4), 944–952.

Maria, Corrado Di and Edwin van der Werf, "Carbon leakage revisited: unilateral climate policy with directed technical change," *Environmental and Resource Economics*, February 2008, *39* (2), 55–74.

Mattoo, Aaditya, Arvind Subramanian, Dominique van der Mensbrugghe, and Jianwu He, "Reconciling Climate Change and Trade Policy," *Peterson Institute for International Economics Working Paper Series*, 2009, *No. 09-15.*

Nakano, Satoshi, Asako Okamura, Norihisa Sakurai, Masayuki Suzuki, Yoshiaki Tojo, and Norihiko Yamano, "The Measurement of CO_2 Embodiments in International Trade: Evidence from the Harmonised Input-Output and Bilateral Trade Database," *OECD Science, Technology and Industry Working Papers*, 2009, *No. 2009/3.*

OECD, "Input-Output Tables (2009)," 2009, *Paris.*

Peters, Glen P. and Edgar G. Hertwich, "CO_2 Embodied in International Trade with Implications for Global Climate Policy," *Environmental Science & Technology*, March 2008, *42* (5), 1401–1407.

Rose, Andrew K., "Do We Really Know That the WTO Increases Trade?," *American Economic Review*, March 2004, *94* (1), 98–114.

Sawin, Elizabeth R., Andrew P. Jones, Tom Fiddaman, Lori S. Siegel, Diana Wright, Travis Franck, Andreas Barkman, Tom Cummings, Felicitas von Peter, Jacqueline McGlade, Robert W. Correll, and John Sterman, "Current emissions reductions proposals in the lead-up to COP-15 are likely to be insufficient to stabilize atmospheric CO_2 levels: Using C-ROADS – A simple computer simulation of climate change – to support long-term climate policy development," 2009, *Paper presented at the Climate Change – Global Risks, Challenges, and Decisions Conference, Copenhagen, Denmark.*

Sinn, Hans-Werner, "Public policies against global warming: a supply side approach," *International Tax and Public Finance*, August 2008, *15* (4), 360–394.

Trefler, Daniel and Susan Chun Zhu, "The Structure of Factor Content Predictions," *NBER Working Paper*, March 2005, *No. 11221.*

UNFCCC, "National greenhouse gas inventory data for the period 1990–2006," *http://unfccc.int/resource/docs/2008/sbi/eng/12.pdf*, 2008.

Unido, "Industrial Statistics Database at the 4-digit Level of ISIC (Revision 2 and 3)," *CD-Rom*, 2009, *Vienna.*

Wang, T. and J. Watson, "Who Owns China's Carbon Emissions?," *Tyndall Centre Briefing Note*, 2007, *No. 23.*

Wooldridge, Jeffrey, *Econometric Analysis of Cross Section and Panel Data*, Chicago: MIT Press, 2002.

World Bank, *International Trade and Climate Change - Economic, Legal, and Institutional Perspectives*, Washington: IBRD/The World Bank, 2008.

A Tables

Table 1: Indirect *bilateral trade* of emissions: the standard gravity model, aggregate data, cross-section of 2004

			Kyoto commitment			Kyoto restrictiveness		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dep.var. (in logs):	*Trade*	*Carbon*	*Trade*	*Carbon*	*Carbon*	*Trade*	*Carbon*	*Carbon*
Kyoto_m			-0.278*	-0.437***		-0.161	-0.275***	
			(0.164)	(0.158)		(0.104)	(0.103)	
Kyoto_x			-0.773***	-0.677***		-0.419***	0.00991	
			(0.145)	(0.158)		(0.0939)	(0.0998)	
Kyoto_m - Kyoto_x					0.558***			0.279***
					(0.140)			(0.0698)
ln GDP_m	0.863***	0.964***	0.873***	0.963***		0.895***	0.931***	
	(0.0436)	(0.0438)	(0.0448)	(0.0460)		(0.0448)	(0.0455)	
ln GDP_x	1.033***	1.155***	1.000***	1.131***		1.004***	1.189***	
	(0.0424)	(0.0459)	(0.0421)	(0.0469)		(0.0412)	(0.0469)	
ln (GDP/POP)_m	0.630***	0.380***	0.616***	0.405***		0.454***	0.327***	
	(0.104)	(0.110)	(0.105)	(0.115)		(0.112)	(0.118)	
ln (GDP/POP)_x	0.463***	-0.400***	0.585***	-0.309***		0.322***	-0.492***	
	(0.108)	(0.105)	(0.112)	(0.111)		(0.118)	(0.111)	
Joint WTO membership	0.343	0.385	0.218	0.252	-0.0700	0.340	0.385	-2.743***
	(0.241)	(0.253)	(0.243)	(0.251)	(0.210)	(0.240)	(0.252)	(0.270)
Joint FTA membership	0.590***	0.710***	0.643***	0.766***	0.864***	0.676***	0.749***	0.864***
	(0.102)	(0.107)	(0.101)	(0.106)	(0.132)	(0.105)	(0.108)	(0.132)
Joint Euro membership	-0.0743	-0.0444	-0.0801	-0.0506	-0.314***	-0.194*	-0.0987	-0.314***
	(0.103)	(0.107)	(0.103)	(0.105)	(0.105)	(0.109)	(0.111)	(0.105)
ln distance	-0.990***	-1.007***	-0.970***	-0.986***	-0.990***	-0.986***	-1.005***	-0.990***
	(0.0544)	(0.0570)	(0.0538)	(0.0563)	(0.0578)	(0.0542)	(0.0561)	(0.0578)
Contiguity (0,1)	0.347***	0.240*	0.358***	0.252*	0.278*	0.326**	0.231	0.278*
	(0.124)	(0.145)	(0.123)	(0.144)	(0.144)	(0.127)	(0.146)	(0.144)
Common language (0,1)	0.260**	0.534***	0.238**	0.510***	0.509***	0.238**	0.523***	0.509***
	(0.110)	(0.151)	(0.111)	(0.150)	(0.144)	(0.111)	(0.150)	(0.144)
Colonial past (0,1)	0.461***	0.626***	0.466***	0.632***	0.666***	0.489***	0.639***	0.666***
	(0.154)	(0.175)	(0.158)	(0.176)	(0.152)	(0.159)	(0.176)	(0.152)
Multilateral resistance	0.0926***	0.0147	0.0628**	-0.0169	0.242***	0.0186	-0.0192	0.538***
	(0.0269)	(0.0266)	(0.0270)	(0.0270)	(0.0235)	(0.0341)	(0.0344)	(0.0293)
Additional geo-controls	YES	YES	YES	YES		YES	YES	
Importer & exporter effects					YES			YES
N	1055	1055	1055	1055	1055	1055	1055	1055
adj. R2	0.797	0.802	0.802	0.806	0.861	0.800	0.803	0.861
F	135.9	152.4	130.2	149.2	105.9	131.4	143.8	105.9
RMSE	0.933	0.974	0.922	0.965	0.815	0.926	0.971	0.815

Kyoto commitment [0,1]: Kyoto_m (Kyoto_x) is a dummy variable which takes value 1 if the importer (the exporter) is committed by the Kyoto Protocol to cap its CO_2 emissions and which is 0 else. Kyoto commitment [-1,0,1]: Kyoto_m (Kyoto_x) takes into account the restrictiveness of the commitment such that -1 no commitment, 0 weak commitment, 1 strong commitment. Details are found in the text. Robust standard errors in parenthesis; * $p<0.1$, ** $p<0.05$, *** $p<0.01$. All regressions contain a constant (not shown). Additional geographical controls include, separately for the importer and the exporter: the ln of area, a landlockedness dummy, the degrees of longitude and latitude, continent dummies.

Table 2: Indirect *bilateral* trade of emissions: panel gravity model, aggregate data

Dep.var.: ln of emissions embodied in aggregate imports

Method of CO_2 accounting:	simple		MRIO		Fixed technology		CO_2 intensity	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Kyoto_m	0.142***		0.140***		0.134***		0.00358	
	(0.0287)		(0.0273)		(0.0281)		(0.0134)	
Kyoto_x	-0.151***		-0.0788**		-0.0198		-0.0528***	
	(0.0337)		(0.0327)		(0.0330)		(0.0119)	
Kyoto_m - Kyoto_x		0.125***		0.0861***		0.0665***		0.0394***
		(0.0243)		(0.0229)		(0.0227)		(0.00901)
ln GDP_m	0.956*		0.873*		1.019**		-0.214	
	(0.526)		(0.506)		(0.501)		(0.217)	
ln GDP_x	-0.314		-0.432		0.433		0.0798	
	(0.709)		(0.648)		(0.668)		(0.262)	
ln (GDP/POP)_m	1.420***		1.481***		1.349***		0.290	
	(0.537)		(0.516)		(0.509)		(0.204)	
ln (GDP/POP)_x	0.202		0.453		0.877		-1.583***	
	(0.709)		(0.657)		(0.676)		(0.254)	
Multilateral resistance	-0.103***		-0.0752**		-0.0202		-0.0529***	
	(0.0396)		(0.0374)		(0.0388)		(0.0186)	
Joint WTO membership	0.190**	-1.401***	0.203**	-1.341***	0.211**	-1.322***	0.0354	-0.454***
	(0.0824)	(0.357)	(0.0794)	(0.323)	(0.0823)	(0.296)	(0.0242)	(0.0568)
Joint FTA membership	0.0405	0.0301	0.0698**	0.0250	0.113***	0.0280	-0.0719***	0.000398
	(0.0355)	(0.0700)	(0.0352)	(0.0674)	(0.0364)	(0.0659)	(0.0170)	(0.0317)
Joint Euro membership	0.00712	-0.0676	-0.0120	-0.0764*	-0.105***	-0.0717*	0.103***	-0.0102
	(0.0240)	(0.0439)	(0.0235)	(0.0421)	(0.0234)	(0.0409)	(0.0110)	(0.0203)
Year effects	YES		YES		YES		YES	
Country × year effects		YES		YES		YES		YES
N	12288	12288	12288	12288	12288	12288	12288	12288
adj. R2	0.193	0.215	0.274	0.294	0.402	0.446	0.435	0.487
F	35.18	9.179	59.15	13.37	141.7	36.04	215.0	91.72
RMSE	0.368	0.363	0.354	0.349	0.355	0.342	0.157	0.150

Kyoto commitment [0,1]: Kyoto_m (Kyoto_x) is a dummy variable which takes value 1 if the importer (the exporter) is committed by the Kyoto Protocol to cap its CO_2 emissions and which is 0 else. "Simple" method ignores carbon content of imported inputs; "MRIO" (multi-region input/output method) includes them; "CO_2 intensity" is tons of CO_2 per dollar of imports; "fixed technology" fixes the input/output table and the emission coefficients.Robust standard errors in parenthesis; * p<0.1, ** p<0.05, *** p<0.01. Year effects or interactions of year effects with country effects are included but not shown.

Table 3: *Net* indirect imports of CO_2 emissions: fixed-effects panel model, aggregate data

Dep.var.: ln of net bilateral imports of CO_2 emissions (ln imports - ln exports)								
Method of CO_2 accounting:	simple		MRIO		Fixed technology		CO_2 intensity	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Differential Kyoto commitment		0.596***		0.572***		0.846***		0.589***
		(0.0391)		(0.0878)		(0.114)		(0.0882)
Differential Kyoto restrictiveness	0.927***		0.394***		0.704***		0.396***	
	(0.107)		(0.0319)		(0.0385)		(0.0320)	
Joint WTO membership	2.666***	2.789***	2.433***	2.360***	2.477***	2.384***	3.751***	3.674***
	(0.337)	(0.335)	(0.284)	(0.285)	(0.361)	(0.373)	(0.329)	(0.331)
Joint FTA membership	-0.319	-0.0210	-0.100	-0.288*	-0.209	-0.507**	-0.112	-0.304*
	(0.208)	(0.187)	(0.160)	(0.173)	(0.190)	(0.243)	(0.173)	(0.183)
Joint Euro membership	0.0147	0.000445	-0.0306	-0.0189	-0.0405	-0.0101	0.0210	0.0320
	(0.144)	(0.141)	(0.132)	(0.134)	(0.141)	(0.147)	(0.141)	(0.144)
ln(GDP_m*GDP_x)	-3.778***	-3.852***	-3.247***	-3.210***	-3.508***	-3.489***	-7.053***	-7.011***
	(0.709)	(0.696)	(0.614)	(0.624)	(0.730)	(0.754)	(0.656)	(0.666)
Importer × year effects	YES	YES	YES	YES	YES	YES	YES	YES
Exporter × year effects	YES	YES	YES	YES	YES	YES	YES	YES
N	6131	6131	6131	6131	6131	6131	6131	6131
adj. R2	0.0598	0.0912	0.0724	0.0351	0.145	0.0472	0.187	0.157
RMSE	1.381	1.348	1.158	1.181	1.371	1.447	1.185	1.207
Wooldridge exogeneity test (p-value)	0.509	0.312	0.319	0.253	0.967	0.577	0.259	0.192

Differential Kyoto commitment [-1,1]: Kyoto_m - Kyoto_x, where Kyoto_j is a dummy variable which takes value 1 if country j is committed by the Kyoto Protocol to cap its CO_2 emissions and which is 0 else. Differential Kyoto restrictiveness [-2,2] takes into account the toughness of commitment, with Kyoto_j taking integers from the interval [-1,1]. "Simple" method ignores carbon content of imported inputs; "MRIO" (multi-region input/output method) includes them; "CO_2 intensity" is tons of CO_2 per dollar of imports; "fixed technology" fixes the I/O table and the emission coefficients. Robust standard errors in parenthesis; * $p<0.1$, ** $p<0.05$, *** $p<0.01$. All regressions include full sets of exporter and year as well as importer and year dummy variable interactions (not shown). The Wooldridge test is a regression-based test, where the base equation is augmented by the lead of the Kyoto variable (i.e., as of $t+1$). Under strict exogeneity, the coefficient of the lead variable is zero (Wooldridge, 2002, p. 285).

Table 4: Indirect *bilateral* trade of emissions: panel gravity model, sectoral data

Dep.var.: ln of emissions embodied in aggregate imports (simple method)												
	(1)		(2)		(3)		(4)		(5)		(6)	
Sector:	Agriculture, forestry, fishing		Electricity, mining		Basic metals		Chemicals & petrochemicals		Other non-metallic mineral products		Transport equipment	
Kyoto_m	0.0416		0.125		0.105*		0.0991**		0.0574		0.161**	
	(0.0601)		(0.0951)		(0.0593)		(0.0436)		(0.0509)		(0.0700)	
Kyoto_x	0.00958		-0.144		-0.115		-0.117**		-0.234***		-0.169**	
	(0.0567)		(0.0957)		(0.0740)		(0.0460)		(0.0622)		(0.0707)	
Kyoto_m - Kyoto_x		-0.0144		0.0841		0.157***		0.0953***		0.149***		0.107**
		(0.0427)		(0.0653)		(0.0449)		(0.0322)		(0.0356)		(0.0445)
Year effects	YES		YES		YES		YES		YES		YES	
Country × year effects		YES		YES		YES		YES		YES		YES
N	11461	11461	10391	10391	11655	11655	12180	12180	11762	11762	11742	11742
adj. R2	0.0360	0.0761	0.0270	0.0714	0.0825	0.0976	0.114	0.137	0.0878	0.101	0.0959	0.145
RMSE	0.731	0.716	1.078	1.053	0.834	0.827	0.533	0.526	0.645	0.641	0.853	0.830

continued on next page

Table 4: cont'd.

Dep.var.: ln of emissions embodied in aggregate imports (simple method)

Sector:	(7) Machinery		(8) Food products, beverages, tobacco		(9) Paper, pulp paper products		(10) Wood & wood products		(11) Textile & leather		(12) Non-specified industries	
Kyoto_m	0.168***		0.267***		0.202***		0.229***		0.171***		0.127***	
	(0.0386)		(0.0592)		(0.0663)		(0.0852)		(0.0455)		(0.0384)	
Kyoto_x	-0.239***		-0.0128		-0.316***		-0.0712		0.0191		-0.263***	
	(0.0450)		(0.0524)		(0.0655)		(0.0928)		(0.0432)		(0.0427)	
Kyoto_m - Kyoto_x		0.169***		0.0297		0.138***		-0.0559		0.00603		0.0627**
		(0.0282)		(0.0423)		(0.0473)		(0.0571)		(0.0290)		(0.0282)
Year effects	YES		YES		YES		YES		YES		YES	
Country × year effects		YES		YES		YES		YES		YES		YES
N	12171	12171	12039	12039	11994	11994	11238	11238	12119	12119	12224	12224
adj. R2	0.209	0.269	0.0546	0.0755	0.0502	0.0890	0.0646	0.103	0.0641	0.116	0.192	0.260
RMSE	0.501	0.482	0.671	0.663	0.749	0.734	0.859	0.842	0.543	0.528	0.494	0.473

Kyoto commitment [0,1]: Kyoto_m (Kyoto_x) is a dummy variable which takes value 1 if the importer (the exporter) is committed by the Kyoto Protocol to cap its CO_2 emissions and which is 0 else. Sectors are based on ISIC 2 digits definitions; see the Appendix for details. Robust standard errors in parenthesis; * $p<0.1$, ** $p<0.05$, *** $p<0.01$. Year effects or interactions of year effects with country effects are included but not shown. All regressions include trade policy variables (WTO, FTA, Euro-zone membership); regressions with year effects only also include measures of GDP, GDP per capita, and the multilateral resistance term.

B Mathematical appendix

B.1 Proof to Proposition 1

We must pin down demand for sector-h varieties from country j for the use of intermediate inputs in country i. We can do this by applying *Shephard's Lemma* and noting that the demand of a generic firm of country i for sector-h varieties from j is given by

$$m_{ij}^{h}=\sum_{k\in 1}^{H}\frac{\partial c_{i}^{k}\left(\cdot\right)}{\partial p_{ij}^{h}}N_{i}^{k}\left(y_{i}^{k}+f^{k}\right), \tag{B.1}$$

where

$$\frac{\partial c_{i}^{k}\left(.\right)}{\partial p_{ij}^{h}}=\alpha_{h}\mu_{h}c_{i}^{k}\left(\cdot\right)\frac{N_{j}^{h}\left(p_{ij}^{h}\right)^{-\sigma_{h}}}{\sum_{l=1}^{K}N_{l}^{h}\left(p_{il}^{h}\right)^{1-\sigma_{h}}}. \tag{B.2}$$

After rearranging and substituting $(P_{i}^{h})^{1-\sigma_{h}}$ in the denominator of (B.2) we write

$$m_{ij}^{h}=\alpha_{h}\mu_{h}N_{j}^{h}(p_{ij}^{h})^{-\sigma_{h}}(P_{i}^{h})^{\sigma_{h}-1}\sum_{k=1}^{H}N_{i}^{k}c_{i}^{k}(\cdot)(y_{i}^{k}+f^{k}).$$

Knowing that $\sum_{k=1}^{H}N_{i}^{k}c_{i}^{k}(\cdot)(\bar{y}_{i}^{k}+f^{k})=G_{i}$, we can further write

$$m_{ij}^{h}=\alpha_{h}Z^{h}N_{j}^{h}G_{i}\left(P_{i}^{h}\right)^{\sigma_{h}-1}\left(\tau_{ij}^{h}\right)^{-\sigma_{h}}\left[c_{j}^{h}\left(\cdot\right)\right]^{-\sigma_{h}}=\alpha_{h}d_{ij}^{h}.$$

Total demand for sector-h imports from country j is therefore

$$M_{ij}^{h} \;=\; m_{ij}^{h}+d_{ij}^{h}=(1+\alpha_{h})d_{ij}^{h}. \quad \square$$

B.2 Proof to Proposition 2

Assuming that one unit of fossil fuel yields one unit of CO_2 emissions, by Shephard's lemma the direct domestic carbon content of one unit of imports is simply

$$e_{j}^{h}\left(\cdot\right)=\frac{\partial c_{j}^{h}\left(w_{j},P_{j},\varepsilon_{j}(q_{j}^{wind},q_{j}^{fuel})\right)}{\partial q_{j}^{fuel}}=\beta_{h}\nu_{j}\frac{c_{j}^{h}(\cdot)}{\varepsilon_{j}}(q_{j}^{fuel})^{\nu_{j}-1},$$

which we collect into the national emissions vector $\boldsymbol{e_j}\left(\cdot\right)$.

Let's only consider the indirect emissions *in country* j due to intermediate interdependence. The unit input requirement of sector h for intermediates is given by *Shephard's* *lemma* as $\frac{\partial c_j^h}{\partial p_j^k}$ with $k = 1, \ldots, H$. The associated carbon emissions $\frac{\partial c_j^h}{\partial p_j^k} \frac{\partial c_j^k}{\partial q_j^{fuel}}$ have to be added to the direct carbon emissions of sector h. However, those intermediates again embody intermediates. So similarly, the third round indirect carbon emissions should be added and this logic repeats ad infinitum. Adding up the direct and all indirect emissions associated with sector-h varieties , the total carbon emissions in country j associated with the imports of country i result as

$$E_{ij}^h = \boldsymbol{e_j} \boldsymbol{A_j^h} M_{ij}^h. \quad \square$$

B.3 The carbon content of trade in a MRIO model

If we relax the assumption that the embodied intermediates are sourced in country j, the carbon content of sector-h imports from country j depends on emissions directly attributable to sector h in country j as well as on the emissions embodied in intermediate inputs from other sectors required for the production in sector h. Clearly, those inputs could be produced in country j or be imported from elsewhere into country j. Repeating the same logic as above but replacing $\sum_{k=1}^{H} \frac{\partial c_j^h(\cdot)}{\partial p_{jj}^k} \frac{\partial c_j^k(\cdot)}{\partial q_j}$ with $\sum_{l=1}^{K} \sum_{k=1}^{H} \frac{\partial c_j^h(\cdot)}{\partial p_{jl}^k} \frac{\partial c_l^k(\cdot)}{\partial q_l}$, and so on, we end up with a similar equation for the sectoral embodied carbon imports of country i from country j, where the input-output matrix is a blown up intermediate usage matrix for the whole world economy

$$E_{ij}^{h,MRIO} = \left(\boldsymbol{e_1} \cdots \boldsymbol{e_j} \cdots \boldsymbol{e_K} \right) \boldsymbol{A_j^{h,MRIO}} M_{ij}^h. \tag{B.3}$$

$\boldsymbol{A_j^{h,MRIO}}$ corresponds to the total input requirement of sector h in country j from all other sectors worldwide. $\boldsymbol{A_j^{h,MRIO}}$ is the $(H(j-1)+h)^{\text{th}}$ column of the inverse of the world matrix of intermediate usage $\boldsymbol{B}$, 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 with

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

See Trefler and Chun Zhu (2005, p. 6 ff.) for a detailed derivation of this result.

B.4 Proof to Proposition 3

Proof to 3 (i). The first term in (7) is labeled the technique effect: $\frac{\partial \eta_j^h}{\partial t_j} M_{ij}^h$. It gives the fall in emissions per unit of output of sector-h varieties. This effect can be decomposed further as $(\nabla_{t_j}\boldsymbol{e_j} \cdot \boldsymbol{A_j^h} + \boldsymbol{e_j} \cdot \nabla_{t_j}\boldsymbol{A_j^h})M_{ij}^h$, where ∇ denotes the gradient vector. First, the price increase of fossil fuel energy induces a substitution toward cleaner energy in all sectors of country j, with $\frac{\partial e_j^h}{\partial t_j} = \frac{(\beta_h \nu_j - 1)e_j^h(\cdot)q^{fuel}}{q_j^{fuel}} < 0$ for all sectors h. Second, there is a shift toward the use of cleaner intermediates in the input-output matrix, $\nabla_{t_j}\boldsymbol{A_j} < 0$. Both effects reduce the carbon intensity of production in country j and hence the technique effect reduces the carbon content of imports of i from j. □

Proof to 3 (ii). We must pin down the effect on the numbers of varieties produced. In line with the literature on the home market effect (see e.g. Feenstra, 2004, p. 163 ff.) we calculate the change in the number of varieties due to a cost increase instead of directly solving for N_j^h. Let u_{ij}^h be the demand per variety in sector h, which is just $\frac{d_{ij}^h}{N_j^h}$. The market clearing condition ensures that the production of a sector in country j is equal to the c.i.f. demand from all countries, i.e. including the part that melts away.

$$y_j^h = (\sigma_h - 1)f_h = \sum_i (1 + \alpha_h)u_{ij}\tau_{ij}. \tag{B.4}$$

Since output is fixed by technology parameters, the right-hand side also has to be fix. Let's assume that u_{ij}^h is fix, that is a carbon tax will lead to changes at the extensive margin N_k^h not the intensive margin u_{ij}^h. Totally differentiating the consumption of a variety from j to i yields:

$$\hat{P}_i^h = \frac{\sigma_h}{\sigma_h - 1}\hat{c}_j^h, \tag{B.5}$$

where $\hat{z} = \frac{dz}{z}$ denotes the growth rate of a variable z. The change in the price index is proportional to the increase in costs in a country if the assumption of fixed consumption per variety holds.

Next we check whether there is a change in the number of varieties produced that is consistent with this change in the price index. Totally differentiate the price index to obtain

$$\hat{P}_i^h = \frac{1}{1-\sigma_h} \sum_k \phi_{ik}^h \hat{N}_k^h + \sum_k \phi_{ik}^h \hat{c}_j^h, \tag{B.6}$$

where $\phi_{ik}^h = (\frac{p_{ik}^h}{P_i^h})^{1-\sigma_h} N_k^h$ denotes the share of country k products in sector h of country i and these shares add up to one. Plug in (B.5) into (B.6) to obtain

$$\sum_k \phi_{ik}^h \hat{N}_k^h = (\sigma_h - 1) \sum_k \phi_{ik}^h \hat{c}_j^h - \sigma_h \hat{c}_j^h. \tag{B.7}$$

This gives a system of K equations that can be expressed in matrix notation as

$$\mathbf{\Phi^h} \begin{pmatrix} \hat{N}_1^h \\ \vdots \\ \hat{N}_j^h \\ \vdots \\ \hat{N}_K^h \end{pmatrix} = (\sigma_h - 1)\mathbf{\Phi^h} \begin{pmatrix} \hat{c}_1^h \\ \vdots \\ \hat{c}_j^h \\ \vdots \\ \hat{c}_K^h \end{pmatrix} - \sigma_h \begin{pmatrix} 0 \\ \vdots \\ \hat{c}_j^h \\ \vdots \\ 0 \end{pmatrix} \tag{B.8}$$

where $\mathbf{\Phi^h}$ is a $K \times K$ matrix that collects all ϕ_{ik}^h. $\mathbf{\Phi^h}$ is for example invertible when $\phi_{ii}^h > \phi_{ik}^h$ for $i \neq k$, i.e. a country devotes more of its budget to own varieties (Feenstra, 2004, p. 164). Then

$$\begin{pmatrix} \hat{N}_1^h \\ \vdots \\ \hat{N}_j^h \\ \vdots \\ \hat{N}_K^h \end{pmatrix} = (\sigma_h - 1) \begin{pmatrix} \hat{c}_1^h \\ \vdots \\ \hat{c}_j^h \\ \vdots \\ \hat{c}_K^h \end{pmatrix} - \sigma_h \, \mathbf{\Phi^h}^{-1} \begin{pmatrix} 0 \\ \vdots \\ \hat{c}_j^h \\ \vdots \\ 0 \end{pmatrix} \tag{B.9}$$

constitutes a solution to the equation system. Put differently an increase in costs indeed induces changes at the extensive not the intensive margin. A cost increase (for example due to a higher carbon tax) will lead to a relocation of firms. □

Proof to 3 (iii). The second term in (7) is the scale or pollution haven effect: $\eta_j^h \frac{\partial M_{ij}^h}{\partial t_j}$. It shows how the h-sector exports of country j react to a stricter climate policy. More specifically

$$\frac{\partial M_{ij}^h}{\partial t_j} = -\sigma_h \frac{\partial c_j^h(\cdot)}{\partial t_j} \frac{M_{ij}^h}{c_j^h(\cdot)} + \frac{M_{ij}^h}{N_j^h} \frac{\partial N_j^h}{\partial t_j}, +(\sigma_h - 1) \frac{M_{ij}^h}{P_i^h} \frac{\partial P_i^h}{\partial t_j}. \tag{B.10}$$

This can be simplified further. We can express (B.5) alternatively with partial derivatives with respect to t_j as

$$\frac{\partial P_i^h}{\partial t_j} = \frac{\sigma_h}{\sigma_h - 1} \frac{P_i^h}{c_j^h} \frac{\partial c_j^h}{\partial t_j} \tag{B.11}$$

Thus, the change in the price index and the costs in (B.10) cancel each other out. This leaves

$$\frac{\partial M_{ij}^h}{\partial t_j} = \frac{M_{ij}^h}{N_j^h} \frac{\partial N_j^h}{\partial t_j}.$$

Only the change in the location of firms – the extensive margin – matters for the carbon content of trade. Next, we have to determine the sign of $\frac{\partial N_j^h}{\partial t_j}$.

Let ${\phi_{ik}^h}^{-1}$ denote the entries of the inverse of $\boldsymbol{\Phi^h}$. This gives the total weight of country-k varieties in consumption of country i after considering all input-output relations. Then we can write (B.9) as

$$\hat{N}_j^h = (\sigma_h - 1 - \sigma_h \, {\phi_{jj}^h}^{-1}) \hat{c}_j^h, \tag{B.12}$$

$$\hat{N}_i^h = (\sigma_h - 1)\hat{c}_i^h - \sigma_h \, {\phi_{ij}^h}^{-1} \, \hat{c}_j^h \quad \forall \, i \neq j. \tag{B.13}$$

A carbon tax leads to a cost increase in country j, $\hat{c}_j^h > 0$. If ${\phi_{jj}^h}^{-1} > \frac{\sigma_h - 1}{\sigma_h}$, this implies a decrease in the number of varieties country j produces, i.e. $\hat{N}_j^h < 0$. Country j loses competitiveness in sector h. Put differently there is a pollution haven effect, because stricter environmental regulation in a country causes its exports to fall. The change in the numbers of varieties $\hat{N}_i^h$ other countries i produce will be positive if the cost-weighted fraction of country-j varieties in consumption $\frac{\hat{c}_j^h}{\hat{c}_i^h} \, {\phi_{ij}^h}^{-1} < \frac{\sigma_h - 1}{\sigma_h}$.

The intuition of this finding is straightforward. The unilateral climate policy puts country j to a comparative disadvantage in the energy-intensive differentiated goods sector compared to the labor-intensive numeraire sector. Thus other countries will produce more of the differentiated goods and export them while country j produces more of the homogeneous numeraire good. This sectoral scale effect feeds through to less carbon imports in country i from country j in all sectors h. $\square$

Proof to 3 (iv). The dislocation of firms is governed by cost increases, which are given by

$$\frac{\partial c_j^h(.)}{\partial t_j} = e_j^h q^{fuel} = \beta_h \nu_j \frac{c_j^h(\cdot)}{\varepsilon_j}(q_j^{fuel})^{\nu_j - 1} q^{fuel}. \tag{B.14}$$

The cost increase will be highest for dirty sectors, i.e. sectors with a high β_h. In other words, the loss in competitiveness is highest for carbon-intensive sectors. This means there is a negative correlation between sectoral emission intensity and the change in sectoral imports due to a carbon tax increase. That said, on the aggregate bilateral level, there will be a change in the composition of M_{ij} toward cleaner sectors beside the fall in trade volume when the exporter j imposes a stricter climate policy. $\square$

Proof to 3 (v). The carbon intensity of country i's sectoral imports from j is given by $\frac{E_{ij}^h}{M_{ij}^h} = \eta_j^h$. As shown in the proof to proposition 3 (i) the sectoral emission coefficient falls with a rising carbon tax in the very country. $\square$

The carbon intensity of country i's bilateral imports is given by $\bar{\eta}_j = \frac{E_{ij}}{M_{ij}} = \frac{\sum_h E_{ij}^h}{\sum_h M_{ij}^h}$.

$$\begin{aligned}
\frac{\partial(\frac{E_{ij}}{M_{ij}})}{\partial t_j} &= \frac{M_{ij}\sum_h(\frac{\partial \eta_j^h}{\partial t_j}M_{ij}^h + \eta_j^h \frac{\partial M_{ij}^h}{\partial t_j}) - E_{ij}\sum_h \frac{\partial M_{ij}^h}{\partial t_j}}{(M_{ij})^2} \\
&= \frac{\sum_h TE_j^h + \sum_h(\eta_j^h - \bar{\eta}_j)\frac{\partial M_{ij}^h}{\partial t_j}}{M_{ij}} \\
&= \frac{\sum_h TE_j^h + \sum_h(\eta_j^h - \bar{\eta}_j)(\frac{\partial M_{ij}^h}{\partial t_j} - \frac{\partial \bar{M}_{ij}}{\partial t_j}) + \frac{\partial \bar{M}_{ij}}{\partial t_j}\sum_h(\eta_j^h - \bar{\eta}_j)}{M_{ij}} \\
&= \frac{\sum_h TE_j^h + \sum_h(\eta_j^h - \bar{\eta}_j)(\frac{\partial M_{ij}^h}{\partial t_j} - \frac{\partial \bar{M}_{ij}}{\partial t_j})}{M_{ij}} < 0
\end{aligned} \tag{B.15}$$

where $TE_j^h = \frac{\partial \eta_j^h}{\partial t_j}M_{ij}^h$ is the sectoral technique effect in country j, $\frac{\partial \bar{M}_{ij}^h}{\partial t_j}$ is the average change of sectoral imports due to the tax increase and $\sum_h(\eta_j^h - \bar{\eta}_j) = \sum_h \eta_j^h - h\bar{\eta}_j = 0$. The technique effect is negative for every sector which implies that the aggregate technique effect, the first term in the denominator of (B.15), is also negative. The composition effect states that the sectoral emission coefficient and the change in the sectoral imports due to a carbon tax are negatively correlated. Therefore also the second term in the denominator of (B.15) is negative. Taken together, a tax increase reduces the carbon intensity of bilateral imports. □

B.5 Proof to Proposition 4

The proofs are analogous to the one of Proposition 3.

Proof to 4 (i). The effect of a subsidy of alternative energies in exporting country j can be decomposed as in (7).

$$\frac{\partial E_{ij}^h}{\partial s_j} = \frac{\partial \eta_j^h}{\partial s_j} M_{ij}^h + \eta_j^h \frac{\partial M_{ij}^h}{\partial s_j}. \tag{B.16}$$

The subsidy has similar effects on the emission of one unit of sector-h variety as a carbon tax due to a substitution toward wind energy: $\frac{\partial e_j^h}{\partial s_j} < 0$ in all sectors h. Put differently, the subsidy causes a negative technique effect: $\frac{\partial \eta_j^h}{\partial s_j} M_{ij}^h < 0$.

However, it lowers the costs of sectors h in country j

$$\frac{\partial c_j^h(\cdot)}{\partial s_j} = -\beta_h(1-\nu_j) r \frac{c_j^h(\cdot)}{\varepsilon_j (q_j^{wind})^{v_j}} < 0. \tag{B.17}$$

Hence, the subsidy leads to an increase in the number of varieties country j exports to i (see the proof to Proposition 3). This constitutes a positive scale effect: $\eta_j^h \frac{\partial M_{ij}^h}{\partial s_j} > 0$, where we use the finding of Proposition 3 (ii). The composition changes in favor of dirty industries because they profit most from a decrease in overall energy costs governed by β_h. Taken together the sign of $\frac{\partial E_{ij}}{\partial s_j}$ is unclear. □

Proof to 4 (ii). The effect of a subsidy of alternative energies in the importing country i is

$$\frac{\partial E_{ij}^h}{\partial s_i} = \eta_j^h \frac{\partial M_{ij}^h}{\partial s_i} = \eta_j^h \frac{M_{ij}^h}{N_j^h} \frac{\partial N_j^h}{\partial s_i} < 0, \tag{B.18}$$

where we use the fact that the subsidy only induces changes at the extensive margin (see proof to Proposition 3). The subsidy in the importing country i will reduce the number of varieties imported from its trade partners due to the gains in competitiveness in country

i (see the proof to Proposition 3). Since the benefits are highest in the most energy-intensive domestic sectors the composition of bilateral carbon imports from country j will become cleaner. Summing up, when a country grants a subsidy to clean energies its bilateral carbon imports decline unambiguously. □

Proof to 4 (iii). The effect of a subsidy to alternative energy in country j on its own fuel demand and hence its carbon dioxide emissions is unclear, since emission intensity falls but the number of varieties produced increases in all sectors:

$$\frac{\partial D_j^{fuel}}{\partial s_j} = \sum_{h=1}^{H} \overbrace{\frac{\partial e_j^h}{\partial s_j}}^{<0} \left(\bar{y}_j^h + f^h\right) N_j^h + \sum_{h=1}^{H} e_j^h(\cdot) \left(\bar{y}_j^h + f^h\right) \overbrace{\frac{\partial N_j^h}{\partial s_j}}^{>0} =?. \tag{B.19}$$

The effect of this climate policy change on carbon dioxide emissions in a trade partner i is unambiguously negative:

$$\frac{\partial D_i^{fuel}}{\partial s_j} = \sum_{h=1}^{H} e_i^h(\cdot) \left(\bar{y}_i^h + f^h\right) \frac{\partial N_i^h}{\partial s_j} < 0. \tag{B.20}$$

Hence, the promotion of alternative energies does not lead to a pattern of carbon leakage: the emissions of the subsidizing country might rise or fall depending on which channel outweighs while the emissions in other countries fall unambiguously. □

C Robustness checks and detailed results

Table C.1: Robustness checks to Table 2. Kyoto restrictiveness rather than commitment, within estimator

Dep. var.: ln of emissions embodied in aggregate imports								
Method of CO_2 accounting:	simple		MRIO		Fixed technology		CO_2 intensity	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Kyoto_m	0.103***		0.102***		0.0895***		0.000691	
	(0.0195)		(0.0187)		(0.0185)		(0.0135)	
Kyoto_x	-0.0740***		-0.0367		0.0446*		-0.178***	
	(0.0249)		(0.0239)		(0.0244)		(0.0161)	
Kyoto_m - Kyoto_x		0.0884***		0.0693***		0.0221		0.0897***
		(0.0164)		(0.0158)		(0.0158)		(0.00861)
ln GDP_m	1.062**		0.983**		1.003**		-0.0646	
	(0.507)		(0.482)		(0.482)		(0.347)	
ln GDP_x	-0.0349		-0.271		1.080		-2.862***	
	(0.750)		(0.676)		(0.702)		(0.404)	
ln (GDP/POP)_m	1.196**		1.257**		1.242**		0.406	
	(0.530)		(0.506)		(0.505)		(0.332)	
ln (GDP/POP)_x	0.0354		0.348		0.242		0.781**	
	(0.766)		(0.698)		(0.720)		(0.386)	
Multilateral resistance	-0.110***		-0.0801**		-0.0314		-0.0166	
	(0.0386)		(0.0364)		(0.0380)		(0.0215)	
Joint WTO membership	0.197**	-1.399***	0.210***	-1.338***	0.226***	-1.321***	-0.122***	-0.508***
	(0.0834)	(0.393)	(0.0804)	(0.362)	(0.0832)	(0.314)	(0.0360)	(0.0634)
Joint FTA membership	0.0372	0.0285	0.0630*	0.0235	0.0989***	0.0272	-0.150***	0.00344
	(0.0354)	(0.0663)	(0.0350)	(0.0640)	(0.0362)	(0.0656)	(0.0257)	(0.0373)
Joint Euro membership	0.00845	-0.0668	-0.00258	-0.0756*	-0.0869***	-0.0714*	0.195***	0.00151
	(0.0245)	(0.0427)	(0.0239)	(0.0407)	(0.0238)	(0.0408)	(0.0206)	(0.0303)
Year effects	YES		YES		YES		YES	
Country × year effects		YES		YES		YES		YES
N	12288	12288	12288	12288	12288	12288	12288	12288
adj. R2	0.192	0.262	0.274	0.335	0.402	0.451	0.611	0.717
F	34.73	9.126	57.89	13.03	140.8	30.45	277.3	82.63
RMSE	0.368	0.352	0.354	0.338	0.355	0.341	0.235	0.200

Kyoto restrictiveness [-1,0,1]: Kyoto_m (Kyoto_x) takes into account the restrictiveness of the commitment such that -1 no commitment, 0 weak commitment, 1 strong commitment. "Simple" method ignores carbon content of imported inputs; "MRIO" (multi-region input/output method) includes them; "CO_2 intensity" is tons of CO_2 per dollar of imports; "fixed technology" fixes the input/output table and the emission coefficients. Robust standard errors in parenthesis; * $p<0.1$, ** $p<0.05$, *** $p<0.01$. Year effects or interactions of year effects with country effects are included but not shown.

Table C.2: Robustness checks to Table 2. First differenced model: Kyoto commitment

Dep. var.: ln of emissions embodied in aggregate imports

Method of CO_2 accounting:	simple		MRIO		Fixed technology		CO_2 intensity	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Kyoto_m	0.0279		0.0286		0.0377**		-0.0107	
	(0.0197)		(0.0187)		(0.0192)		(0.0110)	
Kyoto_x	-0.0487**		-0.0154		0.0340		-0.0908***	
	(0.0228)		(0.0217)		(0.0222)		(0.0113)	
Kyoto_m-Kyoto_x		0.0495***		0.0317**		0.00948		0.0425***
		(0.0161)		(0.0152)		(0.0149)		(0.00750)
Year effects	YES		YES		YES		YES	
Country × year effects		YES		YES		YES		YES
N	10886	10886	10886	10886	10886	10886	10886	10886
adj. R2	0.0706	0.0856	0.0835	0.0899	0.132	0.160	0.254	0.369
F	30.39	6.104	38.90	7.119	102.3	18.05	175.8	36.05
RMSE	0.375	0.372	0.357	0.355	0.363	0.357	0.219	0.201

continued on next page

Table C.2 cont'd. First differenced model: Kyoto restrictiveness

Dep. var.: ln of emissions embodied in aggregate imports

Method of CO_2 accounting:	simple		MRIO		Fixed technology		CO_2 intensity	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Kyoto_m	0.0140		0.0128		0.0184		-0.00689	
	(0.0128)		(0.0121)		(0.0121)		(0.00749)	
Kyoto_x	-0.0254		-0.0100		0.0331*		-0.0803***	
	(0.0172)		(0.0167)		(0.0174)		(0.00764)	
Kyoto_m-Kyoto_x		0.0377***		0.0278**		0.00423		0.0424***
		(0.0115)		(0.0110)		(0.0109)		(0.00490)
Year effects	YES		YES		YES		YES	
Country × year effects		YES		YES		YES		YES
N	10886	10886	10886	10886	10886	10886	10886	10886
adj. R2	0.0704	0.0860	0.0834	0.0903	0.132	0.160	0.257	0.372
F	30.31	6.129	38.74	7.148	102.4	18.07	179.9	36.88
RMSE	0.375	0.371	0.357	0.355	0.363	0.357	0.218	0.201

Kyoto commitment [0,1]: Kyoto_m (Kyoto_x) is a dummy variable which takes value 1 if the importer (the exporter) is committed by the Kyoto Protocol to cap its CO_2 emissions and which is 0 else. Kyoto restrictiveness [-1,0,1]: Kyoto_m (Kyoto_x) takes into account the restrictiveness of the commitment such that -1 no commitment, 0 weak commitment, 1 strong commitment. Details are found in the text. Robust standard errors in parenthesis; * $p<0.1$, ** $p<0.05$, *** $p<0.01$. All regressions contain trade policy controls (FTA, WTO, Euro-zone membership), and, where applicable, exporter and importer GDP and GDP per capita and the multilateral resistance term.

Table C.3: Robustness checks to Table 3: Bilateral net imports in logs, first-differenced models

	simple		MRIO		Fixed technology		CO_2 intensity	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Differential Kyoto commitment	0.777***		0.469***		0.722***		0.480***	
	(0.0796)		(0.0654)		(0.0822)		(0.0654)	
Differential Kyoto restrictiveness		0.116**		0.0446		-0.0332		0.0518
		(0.0511)		(0.0417)		(0.0533)		(0.0418)
N	5429	5429	5429	5429	5429	5429	5429	5429
adj. R2	0.351	0.335	0.289	0.280	0.367	0.354	0.293	0.284
F	4.338	3.938	3.566	3.369	4.332	3.996	3.750	3.527
RMSE	1.681	1.702	1.471	1.480	1.737	1.755	1.492	1.501
Wooldridge	0.0517	0.0132	0.1454	0.1553	0.1407	0.2277	0.1151	0.1658

Differential Kyoto commitment [-1,1]: Kyoto_m - Kyoto_x, where Kyoto_j is a dummy variable which takes value 1 if country j is committed by the Kyoto Protocol to cap its CO_2 emissions and which is 0 else. Differential Kyoto restrictiveness [-2,2] takes into account the toughness of commitment, with Kyoto_j taking integers from the interval [-1,1]. "Simple" method ignores carbon content of imported inputs; "MRIO" (multi-region input/output method) includes them; "CO_2 intensity" is tons of CO_2 per dollar of imports; "fixed technology" fixes the input/output table and the emission coefficients. Robust standard errors in parenthesis; * p<0.1, ** p<0.05, *** p<0.01. All regressions include full sets of exporter and year as well as importer and year dummy variable interactions (not shown). The Wooldridge test is a regression-based test, where the base equation is augmented by the lead of the Kyoto variable (i.e., as of $t + 1$). Under strict exogeneity, the coefficient of the lead variable is zero (Wooldridge, 2002, p. 285).

Table C.4: Details to Table 5. Indirect *bilateral* trade of emissions: panel gravity model, sectoral data

Dep.var.: ln of emissions embodied in aggregate imports (simple method)

	(1)		(2)		(3)		(4)		(5)		(6)	
Sector:	Agriculture, Forestry, Fishing		Electricity, gas and water supply, mining and quarrying		Basic metals		Chemicals and petrochemicals		Other non-metallic mineral products		Transport equipment	
Kyoto_m	0.0416		0.125		0.105*		0.0991**		0.0574		0.161**	
	(0.0601)		(0.0951)		(0.0593)		(0.0436)		(0.0509)		(0.0700)	
Kyoto_x	0.00958		-0.144		-0.115		-0.117**		-0.234***		-0.169**	
	(0.0567)		(0.0957)		(0.0740)		(0.0460)		(0.0622)		(0.0707)	
Kyoto_m - Kyoto_x		-0.0144		0.0841		0.157***		0.0953***		0.149***		0.107**
		(0.0427)		(0.0653)		(0.0449)		(0.0322)		(0.0356)		(0.0445)
ln GDP_m	1.997**		3.084**		0.00206		0.733		1.047		-0.491	
	(0.963)		(1.465)		(1.010)		(0.673)		(0.880)		(1.134)	
ln GDP_x	1.055		2.798*		2.669**		0.0313		-0.233		-2.980**	
	(0.868)		(1.651)		(1.056)		(0.686)		(0.932)		(1.298)	
ln (GDP/POP)_m	0.0537		-0.211		3.313***		0.832		2.042**		2.354**	
	(0.930)		(1.419)		(0.981)		(0.662)		(0.850)		(1.011)	
ln (GDP/POP)_x	-1.038		-2.876*		-2.994***		-0.795		-0.864		3.829***	
	(0.864)		(1.642)		(1.052)		(0.701)		(0.914)		(1.279)	
Multilateral resistance	0.158*		-0.193*		-0.375***		-0.119**		0.0496		-0.175**	
	(0.0956)		(0.101)		(0.0838)		(0.0505)		(0.0609)		(0.0774)	
Joint WTO membership	0.248***	0.588***	-0.0731	-0.300	0.172**	-0.0646	0.132**	0.0814	0.00315	-0.200*	0.148*	0.0139
	(0.0850)	(0.163)	(0.124)	(0.220)	(0.0859)	(0.144)	(0.0562)	(0.108)	(0.0632)	(0.109)	(0.0856)	(0.141)
Joint FTA membership	0.184*	-2.507***	0.125	-1.015*	0.153	-7.206***	0.120	-1.621***	-0.0874	0.567	0.102	0.718
	(0.107)	(0.220)	(0.207)	(0.521)	(0.126)	(0.241)	(0.110)	(0.284)	(0.110)	(2.134)	(0.124)	(1.125)
Joint Euro membership	0.0916	0.0331	0.219***	-0.153	0.0552	-0.122	0.104**	-0.0488	-0.188***	-0.116	-0.107*	-0.239**
	(0.0677)	(0.0953)	(0.0787)	(0.140)	(0.0623)	(0.102)	(0.0415)	(0.0686)	(0.0518)	(0.0818)	(0.0571)	(0.101)
Year effects	YES		YES		YES		YES		YES		YES	
Country × year effects		YES		YES		YES		YES		YES		YES
N	11461	11461	10391	10391	11655	11655	12180	12180	11762	11762	11742	11742
adj. R2	0.0360	0.0761	0.0270	0.0714	0.0825	0.0976	0.114	0.137	0.0878	0.101	0.0959	0.145
F	8.575	.	6.987	.	19.75	.	25.71	7.996	13.73	4.099	18.26	4.391
RMSE	0.731	0.716	1.078	1.053	0.834	0.827	0.533	0.526	0.645	0.641	0.853	0.830

Kyoto commitment [0,1]: Kyoto_m (Kyoto_x) is a dummy variable which takes value 1 if the importer (the exporter) is committed by the Kyoto Protocol to cap its CO_2 emissions and which is 0 else. Sectors are based on ISIC 2 digits definitions; see the Appendix for details. Robust standard errors in parenthesis; * $p<0.1$, ** $p<0.05$, *** $p<0.01$. Year effects or interactions of year effects with country effects are included but not shown. All regressions include trade policy variables (WTO, FTA, Euro-zone membership); regressions with year effects only also include measures of GDP, GDP per capita, and the multilateral resistance term.

continued on next page

Table C.4, cont'd.

Dep.var.: ln of emissions embodied in aggregate imports (simple method)												
	(7)		(8)		(9)		(10)		(11)		(12)	
Sector:	Machinery		Food products, beverages, tobacco		Paper, paper products, pulp and printing		Wood and wood products		Textile and leather		Non-specified industries	
Kyoto_m	0.168***		0.267***		0.202***		0.229***		0.171***		0.127***	
	(0.0386)		(0.0592)		(0.0663)		(0.0852)		(0.0455)		(0.0384)	
Kyoto_x	-0.239***		-0.0128 -0.316***		-0.0712		0.0191		-0.263***			
	(0.0450)		(0.0524)		(0.0655)		(0.0928)		(0.0432)		(0.0427)	
Kyoto_m - Kyoto_x		0.169***		0.0297		0.138***		-0.0559		0.00603		0.0627**
		(0.0282)		(0.0423)		(0.0473)		(0.0571)		(0.0290)		(0.0282)
ln GDP_m	0.267		4.209***		0.961		3.257***		2.623***		3.509***	
	(0.725)		(0.908)		(0.951)		(1.235)		(0.814)		(0.700)	
ln GDP_x	-1.375*		-0.862		-4.481***		-5.409***		-0.493		-2.513***	
	(0.713)		(0.875)		(0.914)		(1.213)		(0.767)		(0.761)	
ln (GDP/POP)_m	2.374***		-2.062**		1.181		-0.0168		-0.628		-0.747	
	(0.707)		(0.890)		(0.901)		(1.181)		(0.785)		(0.671)	
ln (GDP/POP)_x	2.484***		-0.121		4.233***		4.960***		0.289		2.666***	
	(0.679)		(0.900)		(0.921)		(1.212)		(0.753)		(0.744)	
Multilateral resistance	-0.114**		-0.0951		-0.0673		-0.218**		-0.130**		-0.0663	
	(0.0469)		(0.0605)		(0.0655)		(0.0865)		(0.0551)		(0.0462)	
Joint WTO membership	0.170***	-0.146*	0.396***	0.668***	0.0602	-0.140	0.134	-0.121	0.0811	0.0559	0.0365	-0.222**
	(0.0520)	(0.0846)	(0.0766)	(0.142)	(0.0688)	(0.131)	(0.0832)	(0.166)	(0.0507)	(0.0968)	(0.0499)	(0.0895)
Joint FTA membership	0.107	-1.151	0.118	-2.307***	0.267**	0.156	0.296**	-2.471	0.362***	1.335*	0.170**	-1.256***
	(0.0940)	(1.557)	(0.112)	(0.480)	(0.113)	(0.346)	(0.133)	(1.547)	(0.0920)	(0.795)	(0.0859)	(0.161)
Joint Euro membership	-0.0543	-0.0707	0.143***	0.0408	-0.000579	0.101	0.0707	-0.0516	0.0694	-0.129*	-0.0900**	-0.0461
	(0.0380)	(0.0621)	(0.0468)	(0.0777)	(0.0553)	(0.0871)	(0.0848)	(0.121)	(0.0475)	(0.0692)	(0.0356)	(0.0583)
Year effects	YES		YES		YES		YES		YES		YES	
Country × year effects		YES		YES		YES		YES		YES		YES
N	12171	12171	12039	12039	11994	11994	11238	11238	12119	12119	12224	12224
adj. R2	0.209	0.269	0.0546	0.0755	0.0502	0.0890	0.0646	0.103	0.0641	0.116	0.192	0.260
F	42.12	10.29	13.08	4.715	11.43	3.930	12.94	3.671	14.65	6.689	34.23	50.20
RMSE	0.501	0.482	0.671	0.663	0.749	0.734	0.859	0.842	0.543	0.528	0.494	0.473

Kyoto commitment [0,1]: Kyoto_m (Kyoto_x) is a dummy variable which takes value 1 if the importer (the exporter) is committed by the Kyoto Protocol to cap its CO_2 emissions and which is 0 else. Sectors are based on ISIC 2 digits definitions; see the Appendix for details. Robust standard errors in parenthesis; * $p<0.1$, ** $p<0.05$, *** $p<0.01$. Year effects or interactions of year effects with country effects are included but not shown. All regressions include trade policy variables (WTO, FTA, Euro-zone membership); regressions with year effects only also include measures of GDP, GDP per capita, and the multilateral resistance term.

Table C.5: Additional results to Table 4. Indirect *bilateral* trade of emissions: panel gravity model, sectoral data

Dep.var.: ln of emissions embodied in aggregate imports (simple method)

	(1)		(2)		(3)		(4)		(5)		(6)	
Sector:	Agriculture, Forestry, Fishing		Electricity, gas and water supply, mining and quarrying		Basic metals		Chemicals and petrochemicals		Other non-metallic mineral products		Transport equipment	
Kyoto_m	0.946***		0.273		-0.716***		-0.342***		-1.340***		-0.772***	
	(0.232)		(0.407)		(0.253)		(0.131)		(0.193)		(0.224)	
Kyoto_x	-0.913***		-0.623		0.515**		0.111		1.161***		0.790***	
	(0.229)		(0.402)		(0.249)		(0.134)		(0.197)		(0.225)	
Kyoto_m - Kyoto_x		2.100***		1.606***		0.182		0.119		-0.0833		0.411**
		(0.184)		(0.262)		(0.208)		(0.105)		(0.164)		(0.205)
ln GDP_m	-1.699		1.043		-0.881		-2.058*		-1.426		0.250	
	(1.847)		(3.225)		(2.808)		(1.194)		(1.890)		(1.966)	
ln GDP_x	-1.672		1.526		-0.630		-1.940		-1.156		1.425	
	(1.841)		(3.237)		(2.803)		(1.193)		(1.891)		(1.976)	
ln (GDP/POP)_m	2.823		-1.069		1.444		1.706		3.173*		-1.177	
	(1.764)		(3.317)		(2.758)		(1.085)		(1.764)		(1.832)	
ln (GDP/POP)_x	0.258		-3.194		-0.212		1.025		0.678		-2.644	
	(1.757)		(3.316)		(2.743)		(1.086)		(1.766)		(1.837)	
Multilateral resistance	-0.145		0.451		-0.156		-0.115		-0.143		-0.394*	
	(0.252)		(0.277)		(0.209)		(0.158)		(0.295)		(0.224)	
Joint WTO membership	-0.0518	0.339	-0.441	-1.229	-0.0893	-0.149	0.0163	0.0139	-0.108	-0.330	0.473*	0.149
	(0.250)	(0.477)	(0.422)	(0.817)	(0.262)	(0.491)	(0.143)	(0.253)	(0.183)	(0.328)	(0.248)	(0.542)
Joint FTA membership	0.00815	-0.931	0.295	2.446	0.159	0.260	0.0691	-0.341	-0.0417	-4.184***	0.238	0.262
	(0.299)	(1.129)	(0.505)	(2.525)	(0.320)	(0.844)	(0.266)	(0.520)	(0.275)	(1.359)	(0.285)	(0.925)
Joint Euro membership	0.182	0.313	-0.312	0.0949	-0.0177	-0.0611	0.0954	-0.181	-0.00545	0.0819	-0.0629	0.354
	(0.325)	(0.440)	(0.222)	(0.423)	(0.184)	(0.308)	(0.145)	(0.210)	(0.152)	(0.304)	(0.169)	(0.315)
Year effects	YES		YES		YES		YES		YES		YES	
Country × year effects		YES		YES		YES		YES		YES		YES
N	5472	5472	4719	4719	5627	5627	6032	6032	5691	5691	5670	5670
adj. R2	0.231	0.0768	0.126	0.0584	0.0871	0.0198	0.0412	0.0112	0.258	0.00781	0.232	0.00743
Wooldridge test	0.8858	0.4005	0.5383	0.3852	0.5364	0.7936	0.6181	0.2484	0.6812	0.9349	0.4989	0.1143
RMSE	2.534	2.776	3.219	3.341	2.535	2.627	1.591	1.616	1.946	2.250	2.210	2.514

Kyoto commitment [0,1]: Kyoto_m (Kyoto_x) is a dummy variable which takes value 1 if the importer (the exporter) is committed by the Kyoto Protocol to cap its CO_2 emissions and which is 0 else. Sectors are based on ISIC 2 digits definitions; see the Appendix for details. Robust standard errors in parenthesis; * $p<0.1$, ** $p<0.05$, *** $p<0.01$. Year effects or interactions of year effects with country effects are included but not shown.

continued on next page

Table C.5, cont'd.

Dep.var.: ln of emissions embodied in aggregate imports (simple method)												
	(7)		(8)		(9)		(10)		(11)		(12)	
Sector:	Machinery		Food products, beverages, tobacco		Paper, paper products, pulp and printing		Wood and wood products		Textile and leather		Non-specified industries	
Kyoto_m	-0.259*		-0.0342		-0.684***		-0.687**		-0.0383		-0.0383	
	(0.148)		(0.198)		(0.216)		(0.296)		(0.160)		(0.133)	
Kyoto_x	0.0420		-0.244		0.767***		0.636**		0.134		0.251*	
	(0.138)		(0.228)		(0.199)		(0.289)		(0.184)		(0.130)	
Kyoto_m - Kyoto_x		0.530***		0.975***		-0.430**		0.871***		1.768***		1.142***
	(0.122)		(0.173)		(0.181)		(0.279)		(0.210)		(0.142)	
ln GDP_m	-1.145		-1.107		-0.0887		-2.581		-0.428		0.203	
	(1.343)		(1.703)		(1.928)		(2.685)		(1.450)		(1.226)	
ln GDP_x	-0.508		-1.164		-0.0745		-3.009		-0.0931		0.617	
	(1.349)		(1.704)		(1.931)		(2.685)		(1.457)		(1.225)	
ln (GDP/POP)_m	1.233		1.810		0.237		4.881**		2.673*		0.985	
	(1.232)		(1.508)		(1.798)		(2.464)		(1.422)		(1.159)	
ln (GDP/POP)_x	0.402		-0.155		-0.473		1.287		-1.297		-1.330	
	(1.228)		(1.502)		(1.803)		(2.453)		(1.439)		(1.159)	
Multilateral resistance	-0.0861		0.00895		-0.0244		-0.126		0.0891		-0.184	
	(0.185)		(0.217)		(0.208)		(0.281)		(0.194)		(0.131)	
Joint WTO membership	0.228	-0.147	0.0915	-0.0885	0.218	0.178	-0.0824	0.295	-0.0746	0.332	-0.0807	0.197
	(0.154)	(0.265)	(0.196)	(0.401)	(0.202)	(0.382)	(0.243)	(0.577)	(0.142)	(0.374)	(0.122)	(0.280)
Joint FTA membership	-0.0492	-1.462***	0.354	-1.482***	-0.166	-2.015***	-0.0581	5.765***	0.315	1.105	-0.0503	-1.622***
	(0.233)	(0.442)	(0.312)	(0.544)	(0.322)	(0.656)	(0.361)	(1.557)	(0.288)	(0.971)	(0.204)	(0.556)
Joint Euro membership	-0.0187	0.202	0.0564	-0.00810	-0.166	-0.369	-0.176	0.511	0.00855	0.545*	-0.111	-0.0536
	(0.142)	(0.231)	(0.120)	(0.231)	(0.229)	(0.349)	(0.326)	(0.496)	(0.132)	(0.300)	(0.115)	(0.200)
Year effects	YES		YES		YES		YES		YES		YES	
Country × year effects		YES		YES		YES		YES		YES		YES
N	6021	6021	5919	5919	5887	5887	5292	5292	5990	5990	6073	6073
adj. R2	0.149	0.0212	0.178	0.0321	0.0221	-0.00184	0.299	0.0181	0.568	0.0650	0.406	0.0577
Wooldridge test	0.3871	0.4977	0.5956	0.6990	0.2343	0.1204	0.7512	0.4378	0.2992	0.0818	0.3456	0.0366
RMSE	1.660	1.780	2.084	2.261	2.339	2.368	2.693	3.187	1.726	2.539	1.453	1.830

Kyoto commitment [0,1]: Kyoto_m (Kyoto_x) is a dummy variable which takes value 1 if the importer (the exporter) is committed by the Kyoto Protocol to cap its CO_2 emissions and which is 0 else. Sectors are based on ISIC 2 digits definitions; see the Appendix for details. Robust standard errors in parenthesis; * $p<0.1$, ** $p<0.05$, *** $p<0.01$. Year effects or interactions of year effects with country effects are included but not shown.

Table C.6: Summary statistics to Tables 1-2

	2004 cross-section (N=1055)		Panel (1995-2005, N=12288)	
Variable	Mean	Std. Dev.	Mean	Std. Dev.
CO_2 imports (ln)				
Simple method				
Sector 1	7.46	2.95		
Sector 2	8.28	3.56		
Sector 3	9.61	3.05		
Sector 4	10.11	2.51		
Sector 5	8.70	2.64		
Sector 6	8.19	3.17		
Sector 7	10.05	2.60		
Sector 8	8.70	2.64		
Sector 9	7.97	2.92		
Sector 10	6.37	3.04		
Sector 11	8.33	2.80		
Sector 12	9.39	2.57		
aggregate	12.58	2.19	12.16	2.30
MRIO	13.17	2.07	12.64	2.25
CO_2 intensity	-7.03	0.61	-7.39	0.97
Fixed technology	12.94	2.17	12.22	2.32
Kyoto membership				
Kyoto commitment (m,x)	0.73	0.45	0.25	0.43
Kyoto restrictiveness (m,x)	0.03	1.00		
Differential commitment	0.00	0.64	0.00	0.39
Differential restrictiveness	0.00	1.44		
Selected controls				
ln GDP (m,x)	27.00	1.37	26.80	1.38
ln GDP per capita (m,x)	9.88	0.74	9.79	0.73
Multilateral resistance	-0.78	3.02	-0.67	3.01
WTO	0.94	0.24	0.93	0.26
FTA	0.33	0.47	0.18	0.38
Euro	0.09	0.28	0.05	0.22

Table C.7: Summary statistics to Table 3 (N=6131)

Variable	Mean	Std. Dev.
Net CO_2 imports		
Simple method (ln)	-0.03	1.51
MRIO (ln)	-0.03	1.27
Fixed technology (ln)	-0.04	1.58
CO_2 intensity of imports relative to exports (ln)	-19.73	2.56
Differential restrictiveness	0.00	0.84
Differential commitment	0.00	0.39
WTO	0.93	0.26
FTA	0.18	0.39
EURO	0.05	0.22
ln product of GDPs	52.56	2.11

Table C.8: Summary statistics to Table 4. Sectoral data

Sector	Obs.	Mean	Std. Dev.	Min	Max
1	11461	7.46	2.95	-7.07	14.75
2	10391	8.28	3.56	-6.04	16.65
3	11655	9.61	3.05	-6.92	16.78
4	12180	10.11	2.51	-1.50	16.68
5	11762	8.70	2.64	-4.53	16.04
6	11742	8.19	3.17	-5.03	16.65
7	12171	10.05	2.60	-3.50	18.64
8	12039	8.70	2.64	-7.80	15.66
9	11994	7.97	2.92	-7.06	15.68
10	11238	6.37	3.04	-8.01	15.08
11	12119	8.33	2.80	-6.51	17.24
12	12224	9.39	2.57	-3.18	17.90

D Data description

Input-output tables Input-output tables describe the economic structure of an economy for a given point in time. They allow to track the intermediate and factor usage along the production chain. The OECD collects input-output tables for its members and various other countries. Table D.2 gives an overview of the availability of those IO tables. In the case where no input-output table was available for the years under investigation we chose the input-output table of the nearest year possible. Thereby we assume that the economic structure (and the relative prices) has not changed between these two points in time. The OECD input-output tables contain 48 industries, mostly on the 2 digit ISIC level. We aggregated these IO industries to 15 industries to match the emission data of the IEA (see Table D.1). Since we apply a highly aggregated sectoral analysis the problem of an aggregation bias arises. That is, we assume that all products within a sector are produced with the same CO_2 intensity which might lead to an error in the estimation of the carbon content of trade the higher the sectoral aggregation. A more disaggregated sectoral detail would be highly desirable, but was impeded in this study by data availability issues.

Another issue arising when calculating the carbon content of trade with a MRIO model empirically is that bilateral input-output tables are not available.[24] Hence, the amount of an intermediate good from country j used to produce a good in country i is constructed with a proportionality assumption. Basically we assume that in country i the intermediate usage produced by country j in a sector h is proportional to the overall fraction of imports of this intermediate from country j. That is, when Germany imports 20% of its steel from China and a sector uses steel as intermediate input, then it is assumed that 20% of the utilized steel was sourced in China. Therefore we construct the bilateral input-output tables as follows. Let θ_{ij}^h denote country i's share of domestic absorption of intermediate

[24]Note that this information is not needed in the simplified model.

input h sourced in country j, which is defined as

$$\theta_{ij}^h \equiv \frac{M_{ij}^h}{(Y_i^h + M_i^h - X_i^h)} \qquad \text{for} \quad i \neq j,$$
$$\theta_{ii}^h \equiv 1 - \sum_{j \neq i} \theta_{ij}^h,$$

where Y_i denotes production in country i.

Then the bilateral input-output table of country i with country j is assumed to be:

$$\boldsymbol{B_{ji}} = \theta_{ij} \boldsymbol{\bar{B}_i},$$

where $\bar{B}_i$ is the reported input-output table of country i. This assumption is used by the OECD and GTAP to distinguish between domestically produced and imported intermediates and is a typical assumption in the vertical specialization literature (Trefler and Chun Zhu, 2005, p. 15 f.).

Table D.1: Industry classification

	ISIC code	Industry description
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
13	45	Construction
14	60-62	Transport
15	41,50-52, 55,63-99	Other services

Trade data Bilateral trade data is obtained from the UN COMTRADE database. It is translated from Standard International Trade Classification (SITC) Rev. 3 to ISIC

Rev. 3 with an industry concordance table provided by Eurostat[25]. Imports are valued with CIF prices, exports with FOB prices for most countries. In order to have the same valuation for imports and exports, we use the FOB export price of the partner country as FOB price of imports. That is, the trade matrix T becomes

$$\boldsymbol{T} = \begin{pmatrix} \boldsymbol{X_1} & -\boldsymbol{X_{12}} & \cdots & -\boldsymbol{X_{1N}} \\ -\boldsymbol{X_{21}} & \boldsymbol{X_2} & \cdots & -\boldsymbol{X_{2N}} \\ \vdots & \vdots & \ddots & \vdots \\ -\boldsymbol{X_{N1}} & -\boldsymbol{X_{N2}} & \cdots & \boldsymbol{X_N} \end{pmatrix}$$

where the ith column refers to the trade vector of country i. The results presented in the main text are in this FOB FOB valuation. Thereby we ignore the carbon dioxide emissions caused by international transportation. The main results do not change but in the latter case the emissions embodied in trade do not add up to zero across all countries. 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. It is assumed that both countries produce with Belgian technology and therefore we apply the Belgian IO table to the region Belgium-Luxembourg. Furthermore, service trade is assumed to be zero. Therefore the bilateral trade vectors contain zero entries for all service industries.

Sectoral CO_2 emissions Sectoral CO_2 emissions are taken from the IEA, which estimates the CO_2 emissions from fossil fuel combustion with the default method and emission factors suggested by the Intergovernmental Panel on Climate Change (IPCC, 1996) guidelines. We only consider CO_2 emissions, but they contribute to around 80% to greenhouse gas emissions. These are only the emissions due to fossil fuel combustion. 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

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

emissions.[26]

Output data Sectoral output data is not obtained by a single source. Output data come from the Structural Analysis Database (STAN) of the OECD[27], the Industrial Statistics Database of the Unido (2009) or the System of National Accounts of the UN[28]. For some countries and years however, sectoral output data is missing altogether (see below for details). Therefore we created an unbalanced sample in which countries were melted into the rest of world aggregate in the respective year when their observation was missing and could not be interpolated. This unbalanced sample is used for econometric analysis. In the balanced sample we imputed the missing data by applying growth rates of output or where those were not available growth rates of real GDP of the respective country and year. The balanced sample is used for descriptive statistics.

For most OECD countries (i.e. for Austria, Belgium, Luxembourg, Canada, Switzerland, Czech Republic, Germany, Denmark, Spain, Finland, France, United Kingdom, Greece, Hungary, Italy, Japan, Korea, Netherlands, Norway, Poland, Portugal, Slovakia, Sweden and the United States) sectoral output data comes from STAN. Agricultural output is missing for Spain in 2002, 2003 and 2005. We interpolated the agricultural output for 2002 and 2003 and applied the growth rate of the output of the total economy to obtain the agricultural output in 2005, where this growth rate comes from Table 2.3 of the UN SNA. For Switzerland manufacturing output (category 3-12) is missing in 1995 and 1996 and is therefore calculated by the growth rate of manufacturing output obtained from STAN. In 1995 and 1996 the transportation sector output is also missing in Switzerland and is calculated by applying the growth rate of the output of the total economy, where this growth rate comes from the STAN database. The STAN output data is only available in current national currency and was converted to current U.S. dollars with the period average exchange rates from the IFS database. Except for the United States (market prices) and Japan (producer's prices) STAN output data is given at basic prices.

[26]Own calculation, see UNFCCC (2008, p. 12).

[27]http://www.oecd.org/document/62/0,3343,en_2649_34445_40696318_1_1_1_1,00.html

[28]http://data.un.org/Data.aspx?d=SNA&f=group_code%3a203

For countries not covered by STAN, sectoral output for the manufacturing industries was taken from the INDSTAT4 2009 (ISIC Rev. 3) and complemented by UN SNA data for non-manufacturing output (industry categories 1, 2, 13-15). These countries are Argentina, Brazil, Estonia, India, Israel, Mexico, Russia, Slovenia and South Africa. In the UN SNA 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 for the years 1995 and 1997 for South Africa. Manufacturing output is not available for Argentina from 2002-2005, Brazil in the year 1995, India between 1995 and 1998 and in 2005, Mexico from 2001-2005 and Russia from 1995-2001. For Argentina, Brazil, India and Mexico the unavailable data were calculated with the growth rate of manufacturing output from the UN SNA. For Russia, missing non-manufacturing output data for the years 1995-2001 and missing manufacturing output data for the years 1995-1999 were constructed with the growth rate of the output of the total economy from the UN SNA. Data for Mexico in 2005 is neither available in the INDSTAT4 2009 nor in the UN SNA. For the balanced sample, sectoral output for Mexico in 2005 is therefore constructed with the growth rate of real GDP from the OECD[29] because no information on output growth was available. Manufacturing output data are available in producer's prices for Argentina, India and Russia, while the Brazilian manufacturing output is given in factor values. For the rest of the countries the valuation in the INDSTAT4 2009 is not defined. In the UN SNA output is valued in basic prices except for Argentina, where data is given in producer's prices. For Argentina, Brazil, Israel, Mexico, Russia and Slovenia we only used one series of the UN SNA (series 100, 300, 100, 100, 300 and 200 respectively) whereas for Estonia we had to prolong the series 300 with the series 400 in the year 2005, for South Africa we had to extend the series 100 with the series 200 in the year 2005 and for India we used the series 100 from 1999-2004 and had to complement the output data with series 30 of the SNA68 prior to 1999.

For Australia, China, Indonesia, Ireland, New Zealand and Turkey sectoral output was not available in either the INDSTAT4 2009 or the UN SNA. Therefore we construct

[29] OECD Economic Outlook, 2008, No. 84.

output data for the unbalanced sample by interpolating the output data from the OECD IO tables. Therefore, the unbalanced sample covers China and Indonesia from 1995-2005, Australia from 1998 until 2004, Ireland between 1998 and 2000, Turkey from 1996-1998 and New Zealand from 1995 until 2002. To get the balanced sample, growth rates of the industrial output – obtained from the IFS – where applied for the missing years for those countries except Turkey. Since no output growth data was available for Turkey we constructed data for the missing years by applying the growth rate of real GDP from the OECD[30]. Australian, Irish, New Zealand and Turkish IO tables are given in basic prices whereas the IO tables of China and Indonesia are valued with producer's prices. IO data are converted to U.S. dollars to match the trade data with period average exchange rates from the International Financial Statistics (IFS)[31] database of the International Monetary Fund. Prior to 1999 the Euro-U.S. dollar exchange rate is obtained from the Federal Reserve Board[32].

GDP deflators Emission intensities were calculated using GDP deflators for the trade volume. The GDP deflators were obtained from the 2008 WDI database of the World Bank.

[30] OECD Economic Outlook, 2008, No. 84.

[31] `http://www.imfstatistics.org/imf/`

[32] `http://www.federalreserve.gov/releases/G5A/`

Table D.2: Input-output table availability

Country	Input-output table for year		
	1995	2000	2005
Argentina		1997	
Australia		1998/99	2004/05
Austria	1995	2000	2004
Belgium	1995	2000	2004
Brazil	1995	2000	2005
Canada	1995	2000	
China	1995	2000	2005
Czech Republic		2000	2005
Denmark	1995	2000	2004
Estonia	1997	2000	2005
Finland	1995	2000	2005
France	1995	2000	2005
Germany	1995	2000	2005
Greece	1995	2000	2005
Hungary	1998	2000	2005
India	1993/94	1998/99	
Indonesia	1995	2000	2005
Ireland	1998	2000	
Israel	1995		
Italy	1995	2000	2004
Japan	1995	2000	2005
Korea		2000	
Mexico		2003	
Netherlands	1995	2000	2005
New Zealand	1995/96	2002/03	
Norway	1995	2000	2001
Poland	1995	2000	2004
Portugal	1995	2000	2005
Russia	1995	2000	
Slovakia	1995	2000	
Slovenia		2000	2005
South Africa	1993	2000	
Spain	1995	2000	2004
Sweden	1995	2000	2005
Switzerland*		2001	
Turkey	1996	1998*	2002
United Kingdom	1995	2000	2003
United States	1995	2000	2005

Source: OECD (2009).

* OECD input-output tables (edition 2006).

FZID Discussion Papers

Competence Centers:

IK:	Innovation and Knowledge
ICT:	Information Systems and Communication Systems
CRFM:	Corporate Finance and Risk Management
HCM:	Health Care Management
CM:	Communication Management
MM:	Marketing Management
ECO:	Economics
SE:	Sustainability and Ethics

Download FZID Discussion Papers from our homepage: https://fzid.uni-hohenheim.de/71978.html

Nr.	**Autor**	**Titel**	**CC**
01-2009	Julian Phillip Christ	NEW ECONOMIC GEOGRAPHY RELOADED: Localized Knowledge Spillovers and the Geography of Innovation	IK
02-2009	André P. Slowak	MARKET FIELD STRUCTURE & DYNAMICS IN INDUSTRIAL AUTOMATION	IK
03-2009	Pier Paolo Saviotti & Andreas Pyka	GENERALIZED BARRIERS TO ENTRY AND ECONOMIC DEVELOPMENT	IK
04-2009	Uwe Focht, Andreas Richter und Jörg Schiller	INTERMEDIATION AND MATCHING IN INSURANCE MARKETS	HCM
05-2009	Julian P. Christ and André P. Slowak	WHY BLU-RAY VS. HD-DVD IS NOT VHS VS. BETAMAX: THE CO-EVOLUTION OF STANDARD-SETTING CONSORTIA	IK
06-2009	Gabriel Felbermayr, Mario Larch and Wolfgang Lechthaler	UNEMPLOYMENT IN AN INTERDEPENDENT WORLD	ECO
07-2009	Steffen Otterbach	MISMATCHES BETWEEN ACTUAL AND PREFERRED WORK TIME: Empirical Evidence of Hours Constraints in 21 Countries	HCM
08-2009	Sven Wydra	PRODUCTION AND EMPLOYMENT IMPACTS OF NEW TECHNOLOGIES – ANALYSIS FOR BIOTECHNOLOGY	IK
09-2009	Ralf Richter, Jochen Streb	CATCHING-UP AND FALLING BEHIND KNOWLEDGE SPILLOVER FROM AMERICAN TO GERMAN MACHINE TOOL MAKERS	IK
10-2010	Rahel Aichele, Gabriel Felbermayr	KYOTO AND THE CARBON CONTENT OF TRADE	ECO

FORSCHUNGSZENTRUM FZID

Universität Hohenheim
Forschungszentrum
Innovation und Dienstleistung
Fruwirthstr. 12
D-70593 Stuttgart
Phone +49 (0)711 / 459-22476
Fax +49 (0)711 / 459-23360
Internet www.fzid.uni-hohenheim.de