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CO_2 embedded in trade: trends and fossil fuel drivers

Abstract

The amount of CO_2 embedded in trade has substantially increased over the last decades. We study the trends and some drivers of the carbon content of trade over the period 1995-2009. Our main findings are the following. First, the mix of traded goods tends to have higher emission intensity than the average mix of final demand. Second, dirty countries tend to specialize in emission-intensive sectors. This finding suggests that trade liberalization may increase global emissions. Third, the share of goods produced in emission-intensive countries is rising, consequently increasing global emissions. Finally, we find that coal abundance is an important driver of net CO_2 exports, and abundance increases exports. These findings highlight the importance of considering trade when designing CO_2 reduction strategies. They also suggest that, if left unattended, continued growth in global trade will increase – not decrease – global CO_2 emissions.

JEL-Codes: F180, Q430, Q540, C670.

Keywords: international trade, embodied emissions, carbon leakage, multi-region input-output analysis, fossil fuels, Kyoto Protocol.

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1. Introduction

Carbon embodied in trade, that is emitted during the production of goods that are later exported, has increased dramatically over the last decades (see e.g., IPCC 2014, chapter 5.4). Hence, it is crucial to understand the role of trade in order to design effective international climate policies and avoid distortions in firms' and countries' incentives (Jakob and Marschinski 2013, Kander *et al* 2015, Anouliès 2016). Building on recent literature on drivers and trends of global (de)carbonization, such as Guan *et al*'s (2014) study of carbon intensity in China or de Melo and Mathys' (2010) survey of the linkages between trade and global climate change, this paper investigates the consequences of trade on global emissions and some drivers of embedded carbon.

After the introduction of the Kyoto Protocol, it was suspected that carbon emissions could "leak", in the sense that production of carbon-intensive goods could be relocated from Annex B countries (those with commitments in the Kyoto Protocol) to non-Annex B countries, and those goods be then imported back to Annex B countries. If not coordinated, unilateral policies targeting emission reduction could then appear as effective at the country-level but in fact be undermined or even counterproductive at the global level. In response to these concerns, the consumption-based accounting (also called carbon footprint) principle was developed. According to this principle, it should be the final consumer of a good, not the producer, who is held accountable for emissions. Implementing such a principle is challenging since it requires the representatives of final consumers to understand the mechanisms involved and have instruments to influence emissions up in the production chain, even if these emissions occur abroad.

As shown in Figure 1, carbon emissions embodied in trade constitute a substantial share of global emissions. Over the last 15 years, they have risen from about one quarter of global emissions to approximately one third. This evolution mirrors the growth in the traded portion of global GDP over the same period. The sharp decline after 2008 is likely due to the global economic downturn, but the long-run upward trend is expected to continue. Figure 1 also displays the development of emission-intensities over time, for worldwide consumption and worldwide exports, respectively. We observe that emission intensities remained stable between 1995 and 2003, and then rapidly declined. Nevertheless, traded goods tend to have substantially higher emission intensities, relative to the average final consumption, implying that the sheltered sectors have lower emission intensities.

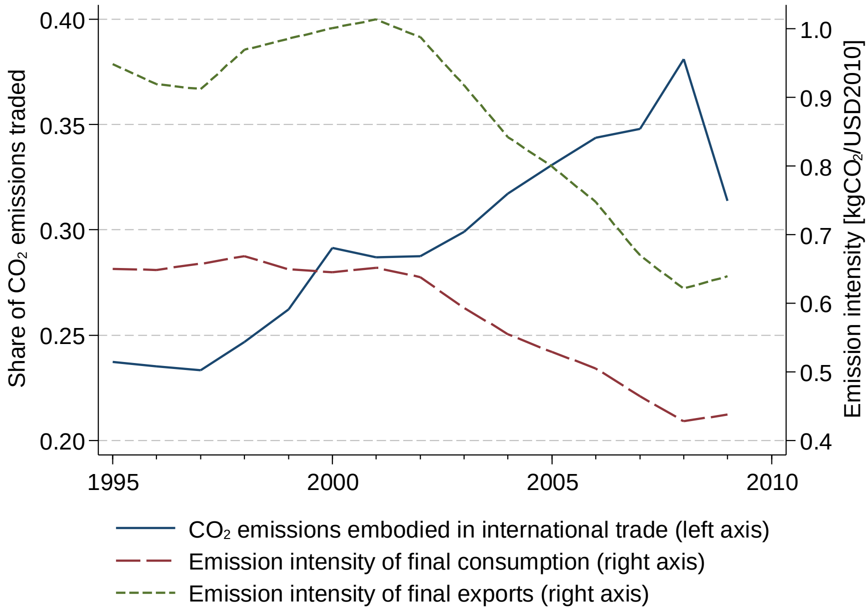

Figure 1: Evolution of the share of CO_2 emissions embodied in international trade and of the emission intensity of final consumption and exports. Source: World input-output database (WIOD, Dietzenbacher et al. 2013b), own calculations.[1]

In this paper, we start by decomposing net CO_2 exports into *trade deficits*, *sectoral structure* of the exporting country, and *average emission intensity* of the country. The relative importance of these three components and their relationships is interesting per se. For instance, if the latter two components are correlated in the sense that emission-intensive countries tend to specialize in dirty sectors, increased trade would, everything else held equal, lead to increased emissions at the worldwide level. We then go one step further and identify determinants of sectoral structure and emission intensities. Based on the literature (Aichele and Felbermayr 2012, 2015, Gerlagh *et al* 2015, Grether *et al* 2014, Michielsen 2013; Steckel *et al* 2015), we focus on fossil fuel reserves and climate policies such as the Kyoto Protocol as potential drivers. By identifying these drivers, our study provides insight into the impacts of fossil fuel market developments and future carbon policies on the evolution of emissions at the global level.

The remainder of the paper is structured as follows. Section 2 gives an overview of the literature. Section 3 describes the data used and the methodology applied to compute embodied carbon emissions. Section 4 presents and discusses the results. Section 5 concludes.

[1] If a commodity is imported, repackaged and exported, emissions are counted as if traded twice. In this sense, there is double counting and the share of traded emissions is overestimated.

2. Literature review

Our analysis builds on and combines several strands of the literature. It is first connected to the literature concerned with decomposing trade's impact on emissions. In an influential paper, Grossman and Krueger (1993) decompose the effect of trade on domestic emissions into three factors. The *scale* effect captures the mechanism whereby trade leads to increased economic activity and hence to increased emissions. The *composition* effect refers to a country's sectoral specialization, and implies that trade liberalization increases (decreases) domestic emissions when a country specializes in 'dirty' ('clean') sectors. The *technique* effect captures the mechanism whereby trade leads to more efficient production technologies, and thus to lower emissions. Using the above decomposition, Antweiler *et al* (2001) conclude that increased trade tends to reduce SO_2 concentrations. A series of papers followed, assessing the link between trade and the environment. Cole (2006), Frankel and Rose (2005) and Managi *et al* (2009) looked at energy and trade, and also addressed endogeneity issues of trade and income. Some recent papers use firm level data, but are limited to one or a few countries (e.g., Cole *et al* 2014).

With increasing interests in climate change, number of studies have investigated the global carbon content of trade (Atkinson *et al* 2011, Chen and Chen 2011, Davis and Caldeira 2010, Davis *et al* 2011, Hertwich and Peters 2009, Peters and Hertwich 2008, Peters *et al* 2011, Wiebe *et al* 2012). These papers typically provide descriptive discussions (cf. Peters *et al* 2011) without analyzing structural causes for the observed pattern of the carbon content of trade. A related strand of literature based on the Heckscher-Ohlin-Vanek model analyzes the factor content of trade and its determinants. It complements classic production factors (i.e., labor and capital) with environmental factors (e.g., Grether *et al* 2012). We connect to this literature by considering fossil fuel endowments as explanatory variables for carbon embedded in trade.

More recently, theory has been extended (Johnson and Noguera 2012, Trefler and Zhu 2010) and better data on world input-output data became available, resulting in a large number of contributions. Grether and Mathys (2013) extend Antweiler's (1996) work on the pollution terms of trade for SO_2 with new and more detailed data. They find that large, poor and emerging countries (i.e., Indonesia, China, Chile) exhibit high emission intensities for exports relative to imports, while large and rich countries (i.e., US, Germany, Japan) are characterized by lower export emission intensities compared to their import emission intensities. Kanemoto *et al* (2014) use the Eora input-output database to investigate the evolution of international flows of embodied CO_2 and other greenhouse gases over the period 1970-2011. They conclude that global air pollution emissions have remained flat despite successful regulation in major emitters. In developed countries, air pollution footprints have increased, since reduced domestic emissions are more than offset by increased pollution embodied in imports.

Xu and Dietzenbacher (2014) exploit the world input-output database (WIOD, Dietzenbacher *et al* 2013b) dataset and provide a dynamic structural decomposition analysis where they distinguish between emission intensities, trade structure of intermediate products, production technology, trade structure of final products, and total final demand. For many developed countries, they find that the growth of emissions embodied in imports is much higher than the growth of emissions embodied in exports, being driven mainly by a change in the structure of trade, both in intermediate and final products. They also observe that emerging economies like the BRIC countries have increased their share in global production and trade at the expense of developed countries, which tends to increase global average emission intensity. Su and Thomson (2016) also use structural decomposition analysis on the WIOD database to investigate the drivers of China's changing carbon intensity of exports between 2006 and 2012, finding that exports become cleaner (i.e., lower carbon intensity) but grew in total volume during that period. We use the same database, and extend the analysis with an econometric approach allowing to uncover systematic relationships between economic growth and CO_2 flows.

Aichele and Felbermayr (2012, 2013) evaluate the effect of the Kyoto Protocol on carbon embodied in trade. They control for the endogenous selection of countries having ratified the Kyoto Protocol, and find that binding commitments have increased committed countries' embodied carbon imports from non-committed countries by around 8% and the emission intensity of their imports by about 3%. In the same vein but applied to the energy content of trade and looking at energy endowments as determinants of comparative advantages, Gerlagh *et al* (2015) find for a high-income country sample that a one standard deviation increase in energy abundance raises energy embodied in trade by about 20%. The authors also find that energy-abundant countries have 7-10% higher employment and 13-17% higher net exports in energy-intensive sectors vis-à-vis otherwise comparable countries. Sato and Dechezleprêtre (2015) study the effect of energy prices on trade for a panel of 42 countries. Estimating a gravity-equation they find statistically significant but very small effects of energy prices on trade flows. Douglas and Nishioka (2012) test trade-theoretical predictions from the Heckscher-Ohlin-Vanek and Trefler and Zhu (2010) framework. They find no evidence that developing countries specialize in emissions-intensive sectors. Instead, evidence suggests that emission intensities differ systematically across countries because of differences in production techniques. Results confirm that international differences in emission intensity are substantial, but suggest that they do not play a significant role in determining patterns of trade. We build on this literature, using a comprehensive worldwide dataset, separating effects from trade deficits, sectoral structure, and average emission intensities and including fossil fuel endowments into the analysis.

3. Data and Methodology

3.1. Data

All data on production, trade, consumption, sectoral CO_2 emissions, and carbon footprints were taken from the World Input-Output Database (WIOD) (Dietzenbacher *et al* 2013b, Timmer 2012), which is one dataset of a new generation of global trade databases being used for tracing flows of carbon embodied in trade along the whole value chain. WIOD was chosen over the EXIOBASE (Tukker *et al* 2013), Eora (Lenzen *et al* 2012, Lenzen *et al* 2013), and GTAP (Andrew and Peters 2013, Narayan *et al* 2012) databases because of its homogenous sector classification and its sectoral, spatial, and temporal detail and coverage. For a discussion of the relative strengths and weaknesses of these databases, see Dietzenbacher *et al* (2013a), Owen *et al* (2014), and Tukker and Dietzenbacher (2013). The WIOD database covers 41 countries (listed in appendix Table 3) each containing 35 sectors (listed in appendix Table 4) over the period 1995-2009.

Several additional variables are used to complement the database. Income, population and natural resource rents are taken from the World Development Indicators (World Bank). A dummy variable is also used to indicate whether a country has ratified the Kyoto Protocol in a given year or not. As an alternative to the latter indicator, a CO_2 stringency index is borrowed from Sauter (2014) and constructed by counting supra-national, national and sub-national laws, which explicitly refer to the goal of reducing CO_2 emissions.

3.2. Empirical methodology

Our empirical methodology derives from a standard input-output analysis (see e.g., Miller and Blair 2009 for an extensive presentation). In this framework, CO_2 emissions in sector s of country i can be expressed as territorial emissions T (also known as production-based) or consumption-based emissions C as follows:[2]

(1) $$T_{is} = e_{is}x_{is} = \varepsilon_{is}z_{is}$$

(2) $$C_{is} = \varphi_{is}y_{is}$$

where e represents emission intensity of output, i.e., the quantity of CO_2 emitted per unit of output, x represents total output, ε represents emission intensity of value added, z represents value added, φ is emission intensity of demand inclusive of embodied carbon emissions, and y is final demand. Note that $\sum_{is} T_{is} = \sum_{is} C_{is}$ by definition.

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[2] A year subscript t is omitted to keep the notation as light as possible. We add time subscripts in the econometrics sections.

Figure 2 plots emission intensities of a typical sector in a typical country in 2009. Values are obtained by regressing the emission intensities on time fixed effects, country-time fixed effects normalized to average to zero in each year, and sector-time fixed effects normalized to average to zero in each year. Note the logarithmic scale. Dark labels indicate trade intensive sectors (i.e., sectors with exports above average), while light labels indicate sheltered sectors (i.e., sectors with exports below average). This table provides a first look at the differences in emission intensities between sectors. Emission intensities of value added (ε) are shown on the horizontal axis, while emission intensities of demand (φ) are presented on the vertical axis. We observe that a few sectors are much more emission intensive than all others. In particular, "Electricity, Gas and Water Supply" (ELCT), "Air Transport" (AIR), "Other non-metallic minerals" (MRLS) and "Water Transport" (WTR) are classified as the most emission intensive sectors, both in terms of value added and consumption. No clear-cut picture emerges concerning the degree of trade exposure and emission intensity.

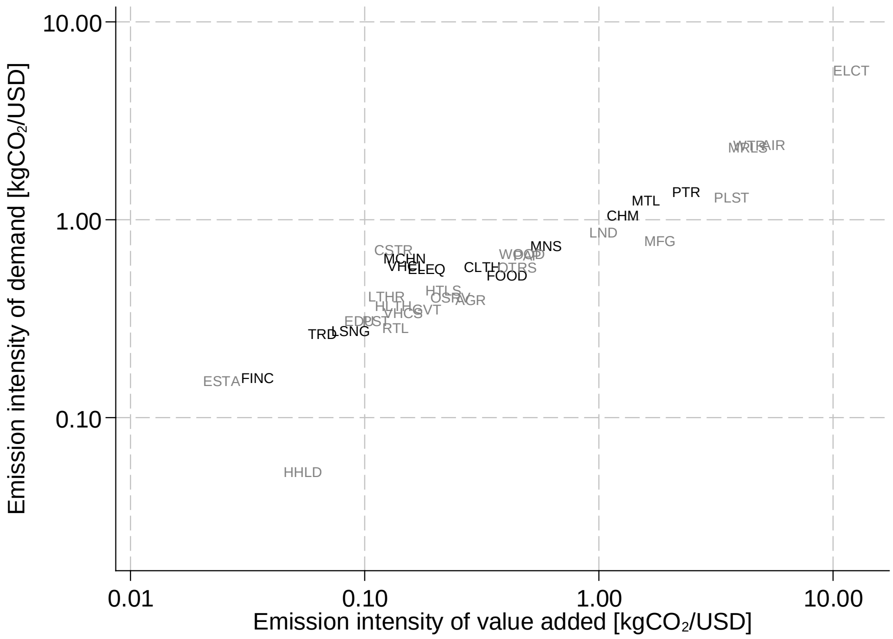

Figure 2. Emission intensities by sector, in 2009

Note: See Table 4 in the appendix for full sector names.

At first glance, this finding might seem at odd with Figure 1, which shows that exports are more emission-intensive than final demand. This apparent contradiction is explained as follows: though the most emission-intensive sectors are sheltered, they are small compared to the next group of emission-intensive traded sectors. Specifically, the top 4 sectors in terms of emission intensities (ELCT, AIR, MRLS, WTR) made up only 3.5% of total worldwide final demand in 2009, and thereby contribute a limited amount to the average emission intensity of final demand. Among the trade-intensive sectors, we find “Coke, Refined Petroleum and Nuclear Fuel” (PTR), “Basic Metals and Fabricated Metal” (MTL) and “Chemicals and Chemical Products” (CHM) to be the most emission intensive sectors, making up 19.3% of total worldwide exports. Hence these sectors are relatively exposed to trade, large and relatively emission intensive.

At the worldwide level, $T = C$ by definition, but the two measures differ when applied to individual countries and individual sectors. For each country i, net CO_2 exports ($NCO2XP$) can then be expressed as:[3]

(3)
$$\begin{aligned} NCO2XP_i &= T_i - C_i = e_i x_i - \varphi_i y_i = \varphi_i (I - A_i) x_i - \varphi_i y_i \\ &= \varphi_i [(I - A_i) x_i - y_i] = \varphi_i (XP_i - MP_i) \end{aligned}$$

where I is an identity matrix, A_i is the input-output coefficients matrix, i.e., a matrix where each column indicates the inputs from all sectors needed to produce one unit of output in a given sector, XP_i are exports from country i and MP_i are imports to country i. We decompose net CO_2 exports into economic trade balances, sector specialization, and country-specific emission intensities as follows:

(4)
$$NCO2XP_i = \bar{\varphi} u (XP_i - MP_i) + (\bar{\varphi}_s - \bar{\varphi} u)(XP_i - MP_i) + (\varphi_i - \bar{\varphi}_s)(XP_i - MP_i)$$

where φ_i is the row vector of sectoral emission intensities of demand in country i (this is also known as the Leontief multiplier or embodied emissions intensity), $\bar{\varphi}_s$ is the row vector of world average emission intensities per sector, $\bar{\varphi}$ is the average emission intensity over all sectors and all countries (i.e., a scalar), and u is a unity vector.

The first term on the right-hand-side of (4) represents the net CO_2 trade related to the economic trade balance. This term uses a world-wide average emission intensity of goods. Countries exporting much more than they import, such as China, tend to have a positive first term.

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[3] Note that sectors s have been stacked in vectors for each country i. For example: $x_i = (x_{i1} \quad \cdots \quad x_{is} \quad \cdots \quad x_{iS})'$. For the sake of conformability, vectors e_i and φ_i must be understood as row vectors.

The second term represents the net CO_2 trade position related to the sector-structure of exports and imports. The term is positive if a country exports in sectors that tend to be emission intensive and/or it imports in sectors that tend to have low associated emissions. The second term is closely related to the pollution haven debate.

The third term represents the net CO_2 trade related to differences in the emission intensities between the (exporting) country i and the countries it imports from. The term is positive if domestic emission intensities exceed the sector world average and/or if the foreign emission intensities from which the country imports are below the sector world average. This term is thus expected to be positive for countries that have a domestically 'inefficient' production, and for countries whose trade partners are emission efficient. That is, this term measures the overall production efficiency of a country *relative* to its trading partners. A country such as the US may be emission-intensive compared to the EU, but if it trades more intensely with China, then its relative performance to China matters more for its net trade in CO_2 position.

We consider the decomposition proposed in (4) over time in order to identify how the contributions of the three factors have evolved. Moreover, looking at the correlations between the different components and their evolution over time will indicate whether trade tends to increase or decrease worldwide emissions. For example, a positive correlation between sector specialization and emission intensities (second and third terms) would imply that CO_2 intensive countries specialize in CO_2 intensive sectors, and more trade is then accompanied by more emissions. Also, if emission intensive countries tend to exhibit a trade surplus, worldwide emissions would increase with trade, everything else equal.

3.3. Identification

In order to investigate if and how fuel markets, climate policies and trade opportunities drive changes in emission intensities and in trade patterns, we use the following specifications:

$$\text{(5)} \qquad \text{EIVA: } \ln(\varepsilon_{ist}) = \beta^{VA} Z_{it} + \gamma_i + \delta_{st} + \mu_{ist}$$

$$\text{(6)} \qquad \text{EID: } \ln(\varphi_{ist}) = \beta^{D} Z_{it} + \gamma_i + \delta_{st} + \mu_{ist}$$

where ε_{ist} is emission intensity of value added (EIVA) in sector s of country i at time t, φ_{ist} is emission intensity of demand inclusive of embodied emissions (EID), Z_{it} includes country variables such as income, fossil fuel income shares, and policies. The effect of these variables is identified through different trends between countries, as time fixed effects are absorbed by the sector-time fixed effects δ_{st}, and time-invariant country characteristics are absorbed through the country fixed effects γ_i, while μ_{ist} is the remaining noise. Depending on the variables included in Z_{it}, the estimated coefficients β can answer questions such as whether domestic fossil fuel abundance, Kyoto policies, and trade opportunities tend to increase or decrease emission intensities.

In addition, we test alternative measures of emission intensity that are relevant in the context of trade:

$$\text{(7)} \qquad \ln\left(\frac{\varphi_{it}XP_{it}}{\overline{\varphi}_{st}XP_{it}}\right) = \beta_1^X\, Z_{it} + \gamma_i + \delta_t + \mu_{it}$$

$$\text{(8)} \qquad \ln\left(\frac{\varphi_{it}XP_{ijt}}{\overline{\varphi}_{st}XP_{ijt}}\right) = \beta_2^X\, Z_{it} + \gamma_i + \delta_{jt} + \mu_{ijt}$$

The left-hand side variable in (7) measures emission intensity of country i exports, relative to emissions for an average country with the same sector structure of exports. The dependent variable in (8) is similar, but specified for each bilateral country-pair: XP_{ijt} represents exports from country i to country j during year t. In this case, we control for partner-country-year fixed effects. These two dependent variables are closely related to the third term of (4) and these two equations will give insights in the factors explaining country-specific emission intensities.

We then investigate sectoral structure of trade by estimating the following four equations:

$$\text{(9)} \qquad \ln\left(\frac{\overline{\varphi}_{st}XP_{it}}{\overline{\varphi}_{t}uXP_{it}}\right) = \beta_1\, Z_{it} + \gamma_i + \delta_t + \mu_{it}$$

$$\text{(10)} \qquad \ln\left(\frac{\overline{\varphi}_{st}MP_{it}}{\overline{\varphi}_{t}uMP_{it}}\right) = \beta_2\, Z_{it} + \gamma_i + \delta_t + \mu_{it}$$

$$\text{(11)} \qquad \ln\left(\frac{\overline{\varphi}_{st}XP_{ijt}}{\overline{\varphi}_{t}uXP_{ijt}}\right) = \beta_3\, Z_{it} + \beta_4 Z_{jt} + \gamma_i - \gamma_j + \delta_t + \mu_{ijt}$$

$$\text{(12)} \qquad \ln\left(\frac{\overline{\varphi}_{st}XP_{ijt}}{\overline{\varphi}uXP_{ijt}}\right) - \ln\left(\frac{\overline{\varphi}_{st}XP_{jit}}{\overline{\varphi}uXP_{jit}}\right) = \beta_5\, (Z_{it} - Z_{jt}) + (\gamma_i - \gamma_j) + \mu_{ijt}$$

All the dependent variables in these equations are measures of sector structure and are linked to the second term in (4). The dependent variable in (9) measures the sector bias of exports towards emission-intensive sectors, i.e., how the export structure of country i causes its emission intensity to differ from the average. In (10), we consider an equivalent variable for imports. In (11), the dependent variable measures the sector bias for all country-pairs of bilateral trade, considering each country-pair in both ways (i is both an exporter to j and an importer from j). In (12), we construct a symmetric equivalent that combines exports and imports into a single variable containing the net exports. We expect β_5 to be about equal to $\beta_3 - \beta_4$. Note that the country-partner fixed effects in (11) and (12) are structured so that their number is equal to the number of countries, and not to the number of country-partner pairs.

3.4. Instrumenting and weighting observations

In our analysis, we investigate whether an increase in fossil fuel rents (e.g., coal) tends to increase or decrease the emission intensity of production (5), consumption (6), exports (7)-(8), or that it changes the sector structure of trade (9)-(12). However, a correlation could also point to reverse causality: an increased demand for emission-intensive sectors leads to higher fossil fuel prices, and thus to higher fossil fuel rents. Therefore, we instrument the fuel rents.[4] For each country, we calculate the share of that country i, over the entire period, in worldwide fuel rents: s_i^c. In addition, for each year t, we calculate the global fuel rents as a share of world GDP: R_t^g. The interaction between the country share and the world fuel rents is used as an instrument for each country's fossil fuel rent:

(13) $$R_{it}^{inst} = s_i^c R_t^g$$

By construction there cannot be reverse causality if we assume that country ’s influence on total world resource rents is sufficiently small: an increase in fossil fuel demand in one country in one year will have no effect on the interaction term for that country in that year.

We also use trade openness as an independent variable in our estimations. Similarly, to avoid endogeneity, we instrument openness through the interaction between a country's average openness over the entire period and the world trade share in world GDP, for each year. In contrast to a standard instrumental variable estimation, in which all instruments would enter all first stage equations, we instrument each endogenous variable by its single instrument separately. This methodology allows avoiding cross-influences of the various instruments on the endogenous variables.

We conduct both weighted and unweighted regressions. Weighting is warranted if we expect that larger observations have better quality, in relative terms, compared to observations related to small trade flows. Another way to interpret differences between weighted and unweighted estimations is that the former indicates marginal effects for the weighted average observation, while the latter applies to the unweighted average observation. The two outcomes will differ when large countries behave systematically differently compared to smaller ones.

[4] In statistical terms, an instrument is a variable that is linked to the endogenous explanatory variable but has no independent effect on the dependent variable. The instrumental variables regression is described for example in chapter 12 in Stock and Watson (2012).

4. Results

4.1. Emission intensities

Figure 3 shows the relation between income and emission intensity of value added. It shows that production in high-income countries tends to be more emission-efficient compared to low-income countries. However, for a given income level, there is large variation in the emission intensity of production.

Figure 4 displays the evolution of emission intensities for some large countries. While emission intensities increase and then decreases over the years for Russia and Brazil, they increased continuously in India and Japan, and decreased continuously in China. The US does not show any significant change in emission intensities. The level of income is clearly negatively correlated with the level of emission intensities across countries (Figure 3), but the evolution over time is less clear (Figure 4).

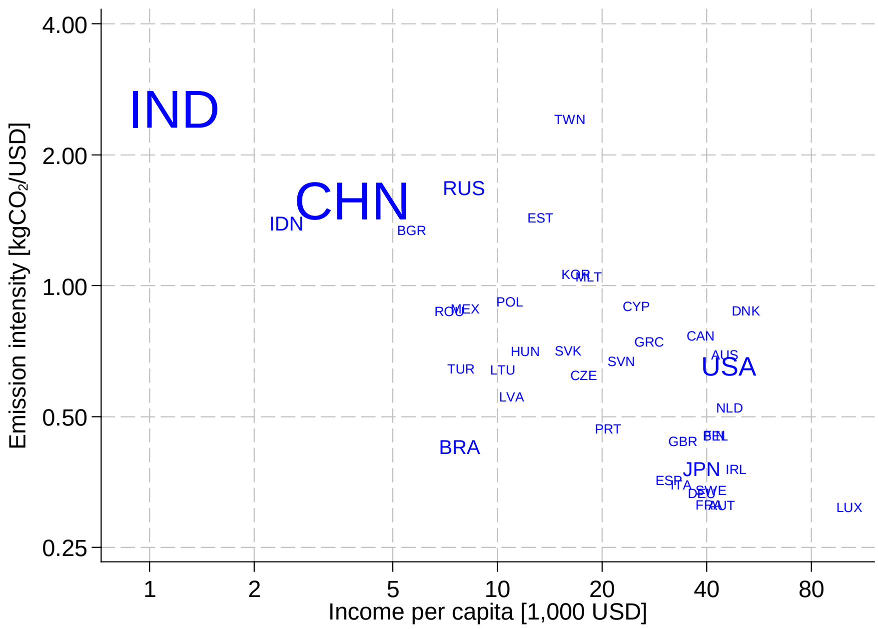

Figure 3. Emission intensity of value added versus income, 2009. Size of marker proportional to population.

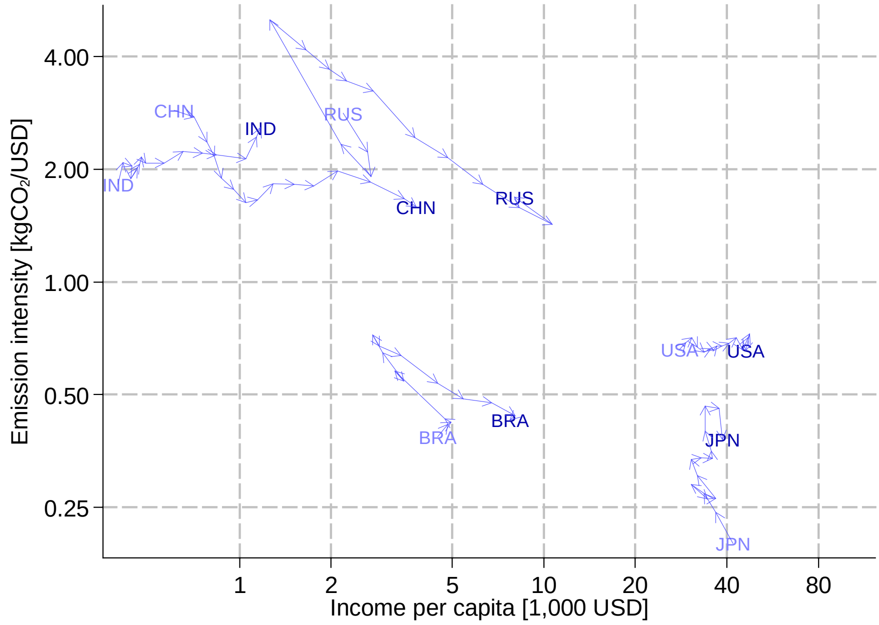

Figure 4. Emission intensity of value added versus income for some selected (largest) countries, 1995-2009. Light labels are for 1995, dark labels are for 2009, arrows indicate the annual moves between 1995 and 2009.

4.2. Decomposing CO_2 embedded in trade

In Figure 5, we implement the decomposition of net CO_2 exports presented in equation (4) and plot the sector structure (second term) effect against the efficiency effect (third term) for all countries in our sample. Two countries, the US and China, have the largest net CO_2 trade positions, as indicated by the size of their marker. But when compared to their total trade, China and Russia stand out as net CO_2 exporters because of their emission-intensive production, whereas the size of US CO_2 inflows is relatively moderate compared to the size of its domestic emissions.

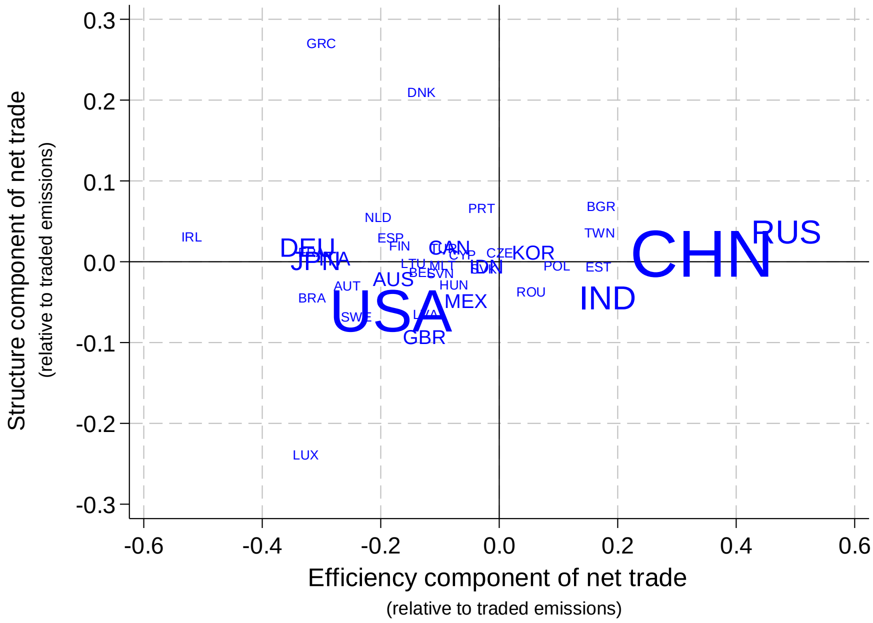

Figure 5. Contribution of domestic efficiency compared to trade partners and sector structure of trade, to net CO_2 exports, 2009. Size of marker proportional to territorial CO_2 emissions. Note the different scales on the horizontal and vertical axis.

4.3. Patterns in emission intensity and trade specialization

We next investigate how income, fossil fuel abundance, trade opportunities, and Kyoto affect emission-intensity of production and trade. While Almer and Winkler (2012) find no support for the hypothesis that Kyoto countries reduced domestic emissions, Aichele and Felbermayr (2013) obtain that higher fuel prices and a cleaner energy mix can be observed in countries that signed Kyoto. In addition to the environmental policy variable, we account for fossil fuel rents as a share of GDP and trade openness as independent variables.

Results are displayed in Table 1. The first row shows that there is a well-established substantial negative effect of income on emission intensity. The efficiency improvement, however, does not catch up with income since the elasticity is significantly smaller than one in absolute value. Thus, overall emissions robustly increase with income. The second-order effect of income is small in size, implying no sign of an environmental Kuznets curve.

Table 1. Determinants of emission intensities of value added, output and exports, controlling for sector structure

Dependent variable	EIVA	EID	EI exports	EI exports
Equation number	(5)	(6)	(7)	(8)
ln(income)	-0.768***	-0.707***	-0.637***	-0.588***
	(0.032)	(0.017)	(0.018)	(0.008)
$\ln(\text{income})^2$	0.001	-0.010*	-0.008	-
	(0.009)	(0.005)	(0.005)	
Rents coal	0.037*	0.027**	0.035***	0.039***
	(0.021)	(0.011)	(0.011)	(0.003)
Rents oil	0.022**	0.006	0.022***	0.038***
	(0.011)	(0.006)	(0.006)	(0.003)
Rents gas	-0.027*	-0.032***	-0.024***	-0.037***
	(0.016)	(0.009)	(0.009)	(0.005)
Trade	0.431**	0.271***	0.077	-0.750***
	(0.178)	(0.096)	(0.068)	(0.077)
Kyoto	0.050***	0.079***	0.020	-0.030***
	(0.019)	(0.010)	(0.013)	(0.008)
Country FE	YES	YES	YES	YES
Partner-year FE	NO	NO	NO	YES
Sector-year FE	YES	YES	NO	NO
Year FE	NO	NO	YES	NO
Weights	YES	YES	YES	YES
N	19,430	19,861	585	11,108
R^2	0.879	0.899	0.986	0.976
R^2 within	0.087	0.125	0.718	0.613

Note: Standard errors in parentheses. */**/***: significant at 10/5/1%. All regressions are estimated by IV and respectively weighted by VA, output, or exports. Each rent is instrumented by its own instrument. The first stage estimations are displayed in Appendix Table 5.

We find that coal-abundance substantially increases emission intensity. A one percentage point increase in coal rents, as a share of GDP, increases emission intensity of value added and exports by about 4%. Evidence is weaker for oil, but still significant in most estimations. For natural gas, we find a small negative effect: gas abundant countries tend to become less emission-intensive in years of high gas prices. These results reflect the relative carbon-intensity of fuels, with gas being less carbon intensive than oil and oil being less carbon intensive than coal.

Concerning trade and climate policies, we obtain mixed evidence. The signs of the coefficients are not consistent across all estimations. Also, comparing weighted against unweighted estimates, we obtain sign reversals (compare Table 7 in appendix with Table 1). The results suggest that in large countries (weighted estimations) emission intensities increase with trade and Kyoto ratification has not reduced the emission intensity, while for small countries (unweighted estimations), both trade and ratification are correlated to decreasing emission intensities. We also find a sign reversal when substituting Sauter's (2014) CO_2 stringency index for the Kyoto index (see Table 9 and Table 10 in appendix). We have not controlled for endogeneity of the Kyoto Protocol or CO_2 index. When comparing OLS and instrumental variable estimations for the Kyoto variable Aichele and Felbermayr (2012) find very similar results.

In Table 2, we consider the drivers for the sectoral composition of trade. High income countries tend to specialize in emission-intensive sectors, as exports in these sectors increase if we do not control for the trading partners (see equation (9). However, imports in emission-intensive sectors also increase (10), and when controlling for trading partners, high-income countries seem to specialize in emission-extensive sectors (11a, (12). These results are suggestive of the following pattern. High-income countries have comparative advantages in emission-extensive sectors but they also trade more with other high-income partners who demand imports from emission-intensive sectors (11b). The net effect of an income increase is then still an increase in the emission-intensity of trade, for both imports and exports (9, (10). A similar pattern is also found in unweighted estimations (Table 8 in appendix).

The estimates also provide some (weak) evidence for coal abundance leading to specialization in dirty sectors, and oil and gas abundance leading to specialization in relatively clean sectors. Increased trade leads to an unambiguous increase in the share of emission-intensive sectors. Not only are the traded goods more emission intensive, compared to the average consumption good, but increased trade amplifies the difference. This result is confirmed in unweighted estimations.

Kyoto ratification is positively correlated with an increase in imports of emission-intensive sectors ((10), both weighted and unweighted), but not when controlling for the trading partner (11b). This result suggests a shift in trading partners, following Kyoto ratification, as a potential consequence of reducing domestic emissions. However, the effect on exports, controlling for trading partners, is not robust for weighted versus unweighted estimates. There might be structural differences between large and small countries.

Table 2. Effects on sector structure

Dependent variable	Exports (separate)	Imports (separate)	Bilateral exports (joint)	Bilateral imports (joint)	Bilateral exports-imports
Equation number	(9)	(10)	(11a)	(11b)	(12)
ln(income)	0.071***	0.019**	-0.034***	0.035***	-0.070***
	(0.010)	(0.008)	(0.008)	(0.008)	(0.005)
$\ln(\text{income})^2$	0.006**	-0.001	-	-	-
	(0.003)	(0.002)			
Rents coal	-0.011*	0.004	0.022***	-0.012**	0.024***
	(0.006)	(0.005)	(0.005)	(0.005)	(0.003)
Rents oil	0.002	-0.002	-0.005*	0.015***	-0.017***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.002)
Rents gas	0.010**	0.002	-0.014***	-0.013***	-0.002
	(0.005)	(0.004)	(0.004)	(0.004)	(0.002)
Trade	0.105***	0.088***	0.240***	-0.288***	0.326***
	(0.037)	(0.029)	(0.054)	(0.052)	(0.025)
Kyoto	0.000	0.011**	0.025***	-0.013**	-0.002
	(0.007)	(0.005)	(0.006)	(0.006)	(0.003)
Country FE	YES	YES	YES	YES	JOINT
Partner FE	NO	NO	YES	YES	JOINT
Year FE	YES	YES	YES	YES	NO
Weights	YES	YES	YES	YES	YES
N	585	585	22,709	22,709	11,017
R^2	0.921	0.902	0.933	0.933	0.733
R^2 within	0.052	0.094	0.021	0.021	0.053

Note: Standard errors in parentheses. */**/***: significant at 10/5/1%. All regressions are weighted by trade flows. Each rent is instrumented by its own instrument. The first stage estimations corresponding to the IV estimations are displayed in Appendix, Table 6.

5. Conclusion

Trade must be considered when designing greenhouse gas mitigation policies. Indeed, global emissions are not reduced when countries export their emissions outside of a regulatory zone, and it is not desirable that domestic abatement policies are undermined by carbon-intensive imports. Hence, it is crucial to have good understanding of the trends and drivers of CO_2 embodied in trade.

Our findings show that more trade-exposed sectors are more emissions intensive than sheltered sectors, and that increasing trade tends to further increase the emission-intensity of traded goods. One possible mechanism underlying this positive correlation is based on fossil fuels as production factors. We find coal abundance leads both to a specialization in 'dirty' sectors, and to an increase in emissions per output when controlling for sector structure: a fossil-fuel-endowment effect.

These findings highlight the importance of considering trade, and paying due attention to fossil fuel markets, specifically coal, when designing CO_2 reduction strategies. Many of the most carbon-intensive countries are also developing economies. As their income grows, their emission intensity tends to decline, but insufficiently to compensate the direct effect of income on emissions. The net effect of an income rise is thus to increase overall emissions. Though our analysis does not offer immediate solutions to disconnect income growth and increased trade from increased emissions, it offers some insights into the drivers, and as such, is helpful to focus the search for future effective measures.

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7. Appendix 1. Data Description

Table 3: Country list (WIOD)

#	Country code	Country
1	AUS	Australia
2	AUT	Austria
3	BEL	Belgium
4	BRA	Brazil
5	BGR	Bulgaria
6	CAN	Canada
7	CHN	China
8	CYP	Cyprus
9	CZE	Czech Republic
10	DNK	Denmark
11	EST	Estonia
12	FIN	Finland
13	FRA	France
14	DEU	Germany
15	GRC	Greece
16	HUN	Hungary
17	IND	India
18	IDN	Indonesia
19	IRL	Ireland
20	ITA	Italy
21	JPN	Japan
22	LVA	Latvia
23	LTU	Lithuania
24	LUX	Luxembourg
25	MLT	Malta
26	MEX	Mexico
27	NLD	Netherlands
28	POL	Poland
29	PRT	Portugal
30	ROM	Romania
31	RUS	Russia
32	SVK	Slovakia
33	SVN	Slovenia
34	KOR	South Korea
35	ESP	Spain
36	ROW	Rest of World
37	SWE	Sweden
38	TWN	Taiwan
39	TUR	Turkey
40	GBR	UK
41	USA	USA

Table 4: Sector list (WIOD)

#	Sector code	Sector
1	AGR	Agriculture, Hunting, Forestry and Fishing
2	AIR	Air Transport
3	MTL	Basic Metals and Fabricated Metal
4	CHM	Chemicals and Chemical Products
5	PTR	Coke, Refined Petroleum and Nuclear Fuel
6	CSTR	Construction
7	EDU	Education
8	ELEQ	Electrical and Optical Equipment
9	ELCT	Electricity, Gas and Water Supply
10	FINC	Financial Intermediation
11	FOOD	Food, Beverages and Tobacco
12	HLTH	Health and Social Work
13	HTLS	Hotels and Restaurants
14	LND	Inland Transport
15	LTHR	Leather, Leather and Footwear
16	MCHN	Machinery, Nec
17	MFG	Manufacturing, Nec; Recycling
18	MNS	Mining and Quarrying
19	OSRV	Other Community, Social and Personal Services
20	MRLS	Other Non-Metallic Mineral
21	OTRS	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies
22	PST	Post and Telecommunications
23	HHLD	Private Households with Employed Persons
24	GVT	Public Admin and Defense; Compulsory Social Security
25	PAP	Pulp, Paper, Printing and Publishing
26	ESTA	Real Estate Activities
27	LSNG	Renting of M&Eq and Other Business Activities
28	RTL	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods
29	PLST	Rubber and Plastics
30	VHCS	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel
31	CLTH	Textiles and Textile Products
32	VHCL	Transport Equipment
33	WTR	Water Transport
34	TRD	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles
35	WOOD	Wood and Products of Wood and Cork

8. Appendix 2. First stage results

Table 5. First stage estimations, related to equation (5) in Table 1

Dependent variable	Rents coal	Rents oil	Rents gas	Trade
ln(income)	0.042***	-1.362***	-0.870***	-0.066***
	(0.004)	(0.022)	(0.020)	(0.002)
ln(income)^2	-0.018***	0.174***	0.001	-0.039***
	(0.001)	(0.005)	(0.005)	(0.000)
Coal s_c x R_t	0.518***	-	-	-
	(0.001)			
Oil s_c x R_t	-	0.838***	-	-
		(0.005)		
Gas s_c x R_t	-	-	0.687***	-
			(0.006)	
Trade s_c x R_t	-	-	-	0.877***
				(0.011)
Kyoto	0.023***	0.110***	-0.090***	-0.005***
	(0.002)	(0.013)	(0.013)	(0.001)
Country FE	YES	YES	YES	YES
Partner-year FE	NO	NO	NO	NO
Sector-year FE	YES	YES	YES	YES
Year FE	NO	NO	NO	NO
Weights	YES	YES	YES	YES
N	19,430	19,430	19,430	19,430
R^2	0.963	0.960	0.927	0.975
R^2 within	0.930	0.607	0.428	0.384

Note: Standard errors in parentheses. */**/***: significant at 10/5/1%.

Table 6. First stage estimations, related to equation (9) in Table 2

Dependent variable	Rents coal	Rents oil	Rents gas	Trade
ln(income)	0.045*	-1.368***	-0.911***	-0.092***
	(0.025)	(0.136)	(0.133)	(0.015)
ln(income)^2	-0.030***	0.219***	-0.017	-0.047***
	(0.006)	(0.031)	(0.031)	(0.004)
Coal s_c x R_t	0.509***	-	-	-
	(0.008)			
Oil s_c x R_t	-	0.845***	-	-
		(0.029)		
Gas s_c x R_t	-	-	0.677***	-
			(0.035)	
Trade s_c x R_t	-	-	-	1.051***
				(0.065)
Kyoto	0.041**	-0.012	-0.109	-0.009
	(0.017)	(0.098)	(0.103)	(0.012)
Country FE	YES	YES	YES	YES
Partner FE	NO	NO	NO	NO
Year FE	YES	YES	YES	YES
Weights	YES	YES	YES	YES
N	585	585	585	585
R^2	0.966	0.961	0.926	0.975
R^2 within	0.941	0.625	0.427	0.382

Note: Standard errors in parentheses. */**/***: significant at 10/5/1%.

9. Appendix 3. Robustness

Table 7. Effects on emissions per value added and output, controlling for sector structure, excluding smallest observations (unweighted)

Dependent variable	EIVA	EID	EI exports	EI exports
Equation number	(5)	(6)	(7)	(8)
ln(income)	-0.862***	-0.839***	-0.742***	-0.732***
	(0.044)	(0.020)	(0.027)	(0.013)
ln(income)^2	-0.008	0.009*	0.000	-
	(0.011)	(0.005)	(0.006)	
Rents coal	0.080**	0.071***	0.041**	0.061***
	(0.034)	(0.015)	(0.019)	(0.008)
Rents oil	0.023	0.021***	0.036***	0.059***
	(0.014)	(0.006)	(0.008)	(0.007)
Rents gas	-0.010	-0.027***	-0.028***	-0.028***
	(0.018)	(0.008)	(0.010)	(0.008)
Trade	-0.220	-0.066	-0.137***	-0.386***
	(0.139)	(0.061)	(0.048)	(0.046)
Kyoto	-0.060*	-0.042***	-0.035*	-0.030**
	(0.033)	(0.015)	(0.018)	(0.012)
Country FE	YES	YES	YES	YES
Partner-year FE	NO	NO	NO	YES
Sector-year FE	YES	YES	NO	NO
Year FE	NO	NO	YES	NO
Weights	NO	NO	NO	NO
N	14,602	14,760	420	8,070
R^2	0.818	0.889	0.980	0.958
R^2 within	0.032	0.129	0.688	0.357

Note: Standard errors in parentheses. */**/***: significant at 10/5/1%. All regressions are unweighted but the smallest 25% observations are removed. Rents are instrumented.

Table 8. Effects on sector structure, excluding smallest observations (unweighted)

Dependent variable	Exports (separate)	Imports (separate)	Bilateral exports (joint)	Bilateral imports (joint)	Bilateral exports-imports
Equation number	(9)	(10)	(11a)	(11b)	(12)
ln(income)	0.071***	0.044***	-0.111***	-0.050***	-0.072***
	(0.015)	(0.011)	(0.009)	(0.009)	(0.008)
$\ln(\text{income})^2$	0.002	-0.008***	-	-	-
	(0.003)	(0.002)			
Rents coal	0.015	-0.000	0.015**	-0.008	0.024***
	(0.010)	(0.007)	(0.007)	(0.007)	(0.006)
Rents oil	0.004	-0.007**	-0.013***	0.001	-0.012***
	(0.004)	(0.003)	(0.003)	(0.003)	(0.003)
Rents gas	0.004	0.006*	-0.003	-0.005	-0.001
	(0.005)	(0.004)	(0.004)	(0.004)	(0.004)
Trade	0.190***	-0.057	0.287***	-0.136***	0.409***
	(0.027)	(0.056)	(0.027)	(0.030)	(0.026)
Kyoto	0.014	0.021***	-0.021***	-0.004	-0.018***
	(0.010)	(0.007)	(0.008)	(0.007)	(0.007)
Country FE	YES	YES	YES	YES	JOINT
Partner FE	NO	NO	YES	YES	JOINT
Year FE	YES	YES	YES	YES	NO
Weights	NO	NO	NO	NO	NO
N	420	420	16,815	16,815	8,070
R^2	0.932	0.909	0.625	0.625	0.669
R^2 within	0.163	0.083	0.024	0.024	0.047

Note: Standard errors in parentheses. */**/***: significant at 10/5/1%. All regressions are unweighted, but the smallest 25% observations are removed. Rents are instrumented.

Table 9 and Table 10 provide a robustness test for the results in Table 1. In Table 9, we substitute Sauter's (2014) CO_2 index for the Kyoto index used in the main text. However, we note that Sauter's index is not available for major economies (US, China, Brazil and Indonesia; see the number of observations). Therefore, we repeat the estimations from Table 1 for the restricted country sample and report them in Table 10. We find that the change in country sample affects the Kyoto coefficients significantly. This is in line with the findings presented in Table 7, where major economies also received equal weight as small economies.

We proceed similarly to provide a robustness check for the results in Table 2. We repeat the estimations from Table 2 in Table 11 using Sauter's index, and in Table 12 for the same restricted sample but with the Kyoto index.

Table 9. Effects on emissions per value added and output, controlling for sector structure, using CO_2 index instead of Kyoto

Dependent variable	EIVA	EID	EI exports	EI exports
Equation number	(5)	(6)	(7)	(8)
ln(income)	-0.766***	-0.788***	-0.747***	-0.729***
	(0.049)	(0.024)	(0.024)	(0.012)
$\ln(\text{income})^2$	-0.023*	-0.002	0.021***	-
	(0.012)	(0.006)	(0.006)	
Rents coal	0.004	0.004	0.054**	0.023*
	(0.044)	(0.022)	(0.025)	(0.012)
Rents oil	0.007	0.003	0.016***	0.026***
	(0.011)	(0.006)	(0.005)	(0.005)
Rents gas	-0.011	-0.017**	-0.012*	-0.025***
	(0.015)	(0.008)	(0.007)	(0.007)
Trade	-0.260	-0.140	-0.093	-0.420***
	(0.178)	(0.089)	(0.058)	(0.038)
CO_2 index	0.238***	-0.008	-0.010	0.069***
	(0.091)	(0.045)	(0.045)	(0.019)
Country FE	YES	YES	YES	YES
Partner-year FE	NO	NO	NO	YES
Sector-year FE	YES	YES	NO	NO
Year FE	NO	NO	YES	NO
Weights	YES	YES	YES	YES
N	17,420	17,851	525	8,922
R^2	0.852	0.889	0.985	0.972
R^2 within	0.145	0.214	0.766	0.668

Note: Standard errors in parentheses. */**/***: significant at 10/5/1%. All regressions are estimated by IV and respectively weighted by VA, output, or exports. Each rent is instrumented by its own instrument.

Table 10. Effects on emissions per value added and output, controlling for sector structure, using Kyoto but same sample as if CO_2 index was used

Dependent variable	EIVA	EID	EI exports	EI exports
Equation number	(5)	(6)	(7)	(8)
ln(income)	-0.741***	-0.794***	-0.751***	-0.720***
	(0.048)	(0.024)	(0.023)	(0.011)
$\ln(\text{income})^2$	-0.017	-0.001	0.023***	-
	(0.012)	(0.006)	(0.006)	
Rents coal	0.001	0.011	0.063**	0.017
	(0.044)	(0.022)	(0.025)	(0.012)
Rents oil	0.008	0.004	0.018***	0.023***
	(0.011)	(0.006)	(0.005)	(0.005)
Rents gas	-0.014	-0.017**	-0.013**	-0.025***
	(0.015)	(0.008)	(0.007)	(0.007)
Trade	-0.265	-0.142	-0.087	-0.416***
	(0.178)	(0.089)	(0.058)	(0.039)
Kyoto	-0.095***	-0.077***	-0.064***	-0.053***
	(0.032)	(0.016)	(0.015)	(0.010)
Country FE	YES	YES	YES	YES
Partner-year FE	NO	NO	NO	YES
Sector-year FE	YES	YES	NO	NO
Year FE	NO	NO	YES	NO
Weights	YES	YES	YES	YES
N	17,420	17,851	525	8,922
R^2	0.852	0.889	0.986	0.972
R^2 within	0.145	0.216	0.773	0.668

Note: Standard errors in parentheses. */**/***: significant at 10/5/1%. All regressions are estimated by IV and respectively weighted by VA, output, or exports. Each rent is instrumented by its own instrument.

Table 11. Effects on sector structure, using CO_2 index instead of Kyoto

Dependent variable	Exports (separate)	Imports (separate)	Bilateral exports (joint)	Bilateral imports (joint)	Bilateral exports-imports
Equation number	(9)	(10)	(11a)	(11b)	(12)
ln(income)	0.113***	0.043***	-0.048***	0.013	-0.056***
	(0.016)	(0.012)	(0.012)	(0.012)	(0.007)
ln(income)^2	0.002	-0.003	-	-	-
	(0.004)	(0.003)			
Rents coal	0.071***	0.022*	-0.026*	0.001	-0.044***
	(0.016)	(0.013)	(0.016)	(0.016)	(0.009)
Rents oil	-0.004	-0.005*	-0.018***	0.014***	-0.028***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.002)
Rents gas	0.006	0.003	0.009**	-0.016***	0.018***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.003)
Trade	0.111***	0.060*	0.190***	-0.226***	0.270***
	(0.038)	(0.031)	(0.049)	(0.047)	(0.020)
CO_2 index	-0.088***	-0.043**	0.052**	-0.033	0.120***
	(0.029)	(0.022)	(0.025)	(0.025)	(0.014)
Country FE	YES	YES	YES	YES	JOINT
Partner FE	NO	NO	YES	YES	JOINT
Year FE	YES	YES	YES	YES	NO
Weights	YES	YES	YES	YES	YES
N	525	525	18,309	18,309	8,864
R^2	0.906	0.905	0.911	0.911	0.727
R^2 within	0.175	0.063	0.078	0.078	0.110

Note: Standard errors in parentheses. */**/***: significant at 10/5/1%. All regressions are weighted by trade flows. Each rent is instrumented by its own instrument.

Table 12. Effects on sector structure, using Kyoto but same sample as if CO_2 index was used

Dependent variable	Exports (separate)	Imports (separate)	Bilateral exports (joint)	Bilateral imports (joint)	Bilateral exports-imports
Equation number	(9)	(10)	(11a)	(11b)	(12)
ln(income)	0.104***	0.039***	-0.043***	0.012	-0.048***
	(0.015)	(0.012)	(0.012)	(0.012)	(0.007)
ln(income)^2	0.002	-0.003	-	-	-
	(0.004)	(0.003)			
Rents coal	0.076***	0.023*	-0.028*	0.004	-0.050***
	(0.016)	(0.013)	(0.016)	(0.016)	(0.009)
Rents oil	-0.003	-0.005*	-0.018***	0.014***	-0.028***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.002)
Rents gas	0.006	0.004	0.008*	-0.016***	0.017***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.003)
Trade	0.110***	0.061**	0.186***	-0.218***	0.259***
	(0.038)	(0.031)	(0.048)	(0.047)	(0.020)
Kyoto	0.007	0.018**	-0.013	-0.026***	0.004
	(0.010)	(0.008)	(0.010)	(0.010)	(0.006)
Country FE	YES	YES	YES	YES	JOINT
Partner FE	NO	NO	YES	YES	JOINT
Year FE	YES	YES	YES	YES	NO
Weights	YES	YES	YES	YES	YES
N	525	525	18,309	18,309	8,864
R^2	0.904	0.905	0.912	0.912	0.725
R^2 within	0.161	0.064	0.084	0.084	0.103

Note: Standard errors in parentheses. */**/***: significant at 10/5/1%. All regressions are weighted by trade flows. Each rent is instrumented by its own instrument.