

Carbon fueling complex global value chains tripled in the period 1995-2012

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Abstract

Complex global value chains are those involving more than two countries and imply that a country imports products as capital goods or intermediate inputs to the production of its exports. When tracing the life-cycle greenhouse gas (GHG) emissions of traded products, for example for border carbon adjustments, such emissions are counted at each border crossing. The prevalence and dynamics of this phenomenon have been poorly understood. This paper shows that GHG emissions associated with the production of imports used for producing exports have risen rapidly from 1995, peaking in 2012 and declining slightly to 2016. They now constitute a total of 4.4 PgCO₂equ. or 10% of global emissions. The most important exported products in terms of emissions associated with imported inputs are chemicals, vehicles, machinery, and information and communications technology (ICT). Crude petroleum, iron and steel, chemicals, and ICT components are the imported products being used for this export production. A driver analysis indicates that in industrialized countries, the declining domestic value added in exports and increasing share of exports in GDP have contributed most to this development, while in emerging economies, the growth of GDP itself has been an important driving factor, while declines in the energy intensity of export production have provided a weak counterbalance. The importance of transiting carbon raises questions of how climate policies affect industrial competitiveness and how border tax adjustment would account for such emissions.

Keywords: Emissions embodied in trade; carbon footprint; multiregional input-output analysis; EXIOBASE; trade in value added (TiVA); index decomposition; complex global value chains.

Introduction

The “common but differentiated responsibility” of rich and poor countries to address climate change led to differential policy stringency, which triggered a concern about carbon leakage undermining the effectiveness of climate policy (Aichele and Felbermayr, 2015; Babiker, 2001). Indeed, industrialized countries’ *net* imports of emissions associated with the production of internationally trade goods grew from 0 in 1970 to 1.7 PgCO₂ in 2010 (Le Quéré et al., 2016). The withdrawal of the US from the Paris agreement has revived an interest in the adjustment for carbon prices on the border (Chang, 2017). The increasing shift of resource extraction and manufacturing to developing countries raised questions about effects of domestic policies on the level of global emissions and the responsibility for emissions associated with internationally traded products (Baumert et al., 2019; Kander et al., 2015). Scientists quantified emissions and resource use associated with the production of internationally traded products (Kanemoto et al., 2014; Liddle, 2018; Peters and Hertwich, 2008), while economists and legal scholars proposed and investigated border tax adjustments or other measures targeting traded products (Ismer and Neuhoff, 2009; Trachtman, 2017).

The notion of emissions associated with traded products is based on a conception of bilateral trade, where one country produces a product and the other country consumes that product. In reality, global supply chains are complex, involving several producing countries. Companies import products as capital goods and intermediate inputs to enable the production of exports (Los et al., 2016; Meng et al., 2018; Rivoli, 2015; Zhang et al., 2017). Responding to case-study evidence of these increasingly global value chains (GVCs), economists have undertaken a systematic development of methods, indicators, and data sets as a basis for empirical analysis of all GVCs using input-output analysis, as well as approaches to study globalization at the firm level (Johnson, 2018). For example, Timmer et al. (Timmer et al., 2014) investigated the share of foreign factor added in 560 GVCs using the World Input-Output Database, showing an increase for capital and high-skilled labor but a decrease for medium- and low-skilled labor from 1995 to 2008. Koopman et al. (Koopman et al., 2014) developed a consistent system of equations to quantify four measures of GVCs using multiregional input-output (MRIO) tables:

1. a measure of vertical specialization (VS) that defines the imported content in a country’s export (Hummels et al., 2001);
2. a measure of vertical specialization (VS1) that defines the production of exports sent as intermediate inputs through third countries to final destinations;
3. the value of a country’s exported goods that are used as imported inputs by the rest of the world to produce final goods consumed domestically, (VS1*) (Daudin et al., 2011);
4. the ratio of domestic value added to export value (VAX) (Johnson and Noguera, 2017).

These measures are derived from nine components of value added associated with an economy, also covering domestic value-added. Los et al.(Los et al., 2016) showed that the imported value-added content in exports could also be derived from national input-output tables. These methods were used extensively in empirical studies to establish basic facts about value added in GVCs, which further serve analytic studies.

This paper investigates complex GVCs from a greenhouse gas (GHG) emissions perspective. In addition to value added, it quantifies primary energy, CO₂, and aggregate GHG emissions, focusing on three of the four measures described by (Koopman et al., 2014). The main focus is on the GHG emissions associated with the production of imports used to produce exported products, which we call “carbon in transit” (CiT), for want of a better name. The paper seeks to establish basic facts about GHG emissions and GVCs in parallel to equivalent studies for value added. The motivation for looking at energy and carbon emissions in GVC is that resource endowments, regulation, energy and emissions taxes, and emission trading systems can influence the location of production as well as the environmental efficiency of the global trading system. The ability to measure and distinguish factor use and emissions in GVCs will enable studies of these influences. Contrary to most previous research on energy and emissions in trade, this paper addresses only value chains that involve at least two countries in the production of products. Going beyond previous studies of GVCs, it also traces the foreign origin of capital goods used in the production of exports capitalizing on a recently developed approach and data set for the endogenization of capital consumption (Södersten et al., 2018).

Traded products that cross several borders potentially pose a challenge to the Paris agreement, which is comprised of a patchwork of national-level policies. GVCs may facilitate carbon leakage by making it easier for companies to shift energy-intensive production to countries with less stringent climate policy. Yet, basic facts need to be established first. It is hence pertinent to ask whether CiT are large enough to warrant attention? What fraction of the carbon associated with exported products has been emitted domestically? What is the dynamic of CiT, i.e. what factors drive their growth? How could they potentially be addressed by climate policies?

Environmental and social consequences of the opening of national economies to international trade have become the subject of scientific inquiry and public debate. One initial hypothesis was that the opening of trade would lead to an increase in pollution in industrialized countries specializing in manufacturing, which they could do more efficiently as owners of capital and technology(Grossman and Krueger, 1991). Yet, manufacturing did not concentrate in industrialized countries but rather was unbundled across different economies as original equipment manufacturers learned to manage supply chains over larger distances, outsourcing labor-intensive manufacturing to countries with cheap labor costs(Baldwin and Lopez-Gonzalez, 2015; Economist, 2012).

An alternative hypothesis suggested higher pollution abatement costs as a result of stricter rules would lead to the outsourcing of polluting processes to developing countries, turning these to pollution havens(Dechezleprêtre and Sato, 2017; Levinson and Taylor, 2008). There is indeed some evidence that the Kyoto Protocol has caused a modest level of strong carbon leakage, i.e. a shift of polluting production to countries with weaker climate policies as a result of those climate policies compared to what would have happened without it(Aichele and Felbermayr, 2015). Weak carbon leakage, i.e. the

increasing emissions associated with the net import of industrialized countries due to an increasing global division of labor unrelated to pollution policies(Peters and Hertwich, 2008), has played the dominant part in the divergence between the carbon footprints of nations and their territorial or production-related emissions(PEI et al., 2018; Peters et al., 2012). Both forms of carbon leakage may potentially undermine mitigation efforts; strong carbon leakage causes policy measures to increase emissions elsewhere, while weak carbon leakage reduces the relative importance of emissions targeted by domestic policy.

The issue of carbon in transit has been recognized in early assessment of CO₂ emissions associated with international trade. In their quantification of the total emissions associated with trade, Peters and Hertwich(2008) quantified only emissions in the first bilateral trade to avoid double counting , thereby terminating supply chains after one border crossing, while in their work on carbon footprints, Hertwich and Peters(2009) traced the emissions to the place of final consumption, ignoring any intermediary countries. The two approaches result in the same total trade-related emissions but different sets of destination countries. The difference between the two approaches had not been well understood. Only recently, research on carbon associated with products passing a border multiple times has emerged. Zhang et al.(2017) quantified the frequency of border crossing of carbon embodied in trade and suggested a growth of this frequency from 1.25 to 1.40 in the period 1995 – 2008. Meng et al.(2018) used the concept of backward linkage to distinguish emissions associated with import arising in the trading partner or associated with inputs from a third country. They have used the forward linkage to identify whether exports are used for final consumption or as intermediate input, and if intermediate consumption, whether the produced product is further exported to a third country or consumed by the trade partner. They showed a substantial increase in emissions transfers between industrialized and developing countries as well as the increasing centrality of China in a global network of trade-related emissions. Moran et al.(2018) showed that a 4% of US emissions occurred in the production of exports used as intermediate inputs to products sold again to the US, something they called CO₂ feedback and which is mainly due to the tight integration of Mexico and Canada in US supply chains. Other countries have rates of re-import on the order of 1%. This study is akin to the quantification of VS1* for emissions.

Here we estimate that carbon in import enabling export production increased almost threefold from 1995 to 2016, to 4.4 Pg CO₂ equivalent or 10% of global emissions, comparable to emissions from road transport(Sims et al., 2014). The most important products containing transiting emissions were chemicals, machinery and equipment, motor vehicles, and electronics. Imported products used for export production are petroleum, iron and steel, chemicals, electronics, and shipping. For the countries' most important in GVCs, we investigate the importance of factors underlying the rise in CiT; increases in imports, in exports, and developments in the energy intensity of imported products and the carbon intensity of that energy, thus taking into account both technological developments and shifts in countries of origin. We also look at the directionality of trilateral trade.

Methods

The present analysis addresses the value added, energy use, CO₂ and GHG emissions associated with global production and trade in the years 1995-2016 using version 3.6 of the EXIOBASE MRIO database (Stadler et al., 2018). CO₂ emissions included are those from the combustion of fossil fuels and industrial processes such as iron and cement production. Other GHG emissions include those of methane and nitrous oxide emissions from a wider range of activities such as fertilizer production and application, fossil fuel production and transport, and agriculture. Land-use related emissions were not included as they are more uncertain and lead to outliers in the investigated time series. GHG emissions are aggregated to CO₂ equivalents using the 100-year global warming potential.

Basic IO emissions algebra. In input-output analysis, industry balance, represented by the column of an input-output table, describes the production of a product, $x_j = \sum_i z_{ij} + \sum_k v_{kj}$. Intermediate inputs z_{ij} are required to produce production volume x_j in industry j , in addition to the inputs of the factors of production, that is, labour and capital, signified by the value added v_{kj} of type k . The market balance, represented by the row of the input-output table, describes the market for products i , which are either sold as intermediate products to industries j or as finished products to final consumer l : $x_i = \sum_j z_{ij} + \sum_l y_{il}$.

Value added, factor use and emission required for the production of products entering international trade are calculated using input-output analysis (Herendeen, 1978). Such emissions have been called indirect or embodied emissions/energy, although here we use the terms associated or trade-related emissions, as the emissions are not literally embodied in the traded products and the term can create confusion. The emissions in industry j are f_j , the cradle-to-gate emissions per unit output x_j are given by m_j . From this, we can write an emissions balance of industry j ,

$$f_j + \sum_i m_i z_{ij} = m_j x_j \quad (1a)$$

In matrix form, this can be written as

$$f + mZ = m\hat{x} \quad (1b)$$

Where small letters signify vectors and capital letters matrices. The hat indicates a diagonal matrix. Right-multiplying both equations with \hat{x}^{-1} and replacing $s = f\hat{x}^{-1}$ and $A = Z\hat{x}^{-1}$, we obtain the multiplier.

$$m = s(I - A)^{-1} = sL \quad (2)$$

Tables expressing the flow of associated energy use and emissions through the economy were obtained by multiplying the transactions (flow) and final demand tables of the MRIO with the respective multipliers indicating all upstream emissions and energy use (Hertwich and Wood, 2018).

$$\epsilon^z = \hat{m}Z \quad (3a)$$

$$\epsilon^y = \hat{m}Y \quad (3b)$$

The sum of carbon footprints of final consumption equals the sum of total emissions; the IO table is just a reallocation of those emissions ($\sum \epsilon^y = \sum f$). The calculation of ϵ^z includes counting for emissions at multiple stages along the supply chains (e.g. emissions from steel production will be included, as well as the associated emissions of the use of steel in the car). Hence $\sum \epsilon^z > \sum \epsilon^y$ (or $\sum f$). As opposed to ϵ^y or f , ϵ^z thus does not sum to the total global CO₂ emissions, but the matrix instead shows the level of emissions that each industrial and final consumer has agency over along the full upstream supply chain. The greater the difference between the sums of ϵ^y and ϵ^z , the more that multiple policy measures will have a conjoined effect.

Utilization of capital goods. Input-output tables describe the transactions in the course of a single year. Inputs to industry that are utilized over several years are accounted for as capital (Lenzen, 2001). Gross fixed capital formation (GFCF) is part of the final demand. Gross profit is often divided into two components, the consumption of fixed capital (CFC; depreciation of the capital stock) and net profit. In national accounting, the consumption of fixed capital is treated as a domestic value added, even though capital assets such as machinery, vehicles, hardware and software are among the most globally traded products. As a result, analyses of complex GVCs and VAX typically ignore the foreign origin of many capital assets. In recent years, different ways to endogenize the production of capital assets have been developed, some focusing on the longer depreciation periods and earlier-year production (Chen et al., 2018) and others offering a distinction of different capital assets (Södersten et al., 2018). Here we make use of the data on specific capital products used by various sectors, A_K , developed by (Södersten et al., 2018). It entails replacing $A \leftarrow A + A^K$. The flow table $Z = A\hat{x}$ and Leontief inverse $L = (I - A)^{-1}$ are then calculated with this new A. In addition, the GFCF column in the final demand of each county is replaced with a net fixed capital formation column

$$y_{i,j=CF} = y_{i,j=CF} - \sum_{j=d} a_{ij}^K \quad \forall j = GFCF \quad (4)$$

$$v_{i=CFC,j} = 0 \quad v_{i \neq CFC,j} = v_{i \neq CFC,j} * \frac{\sum_{i \neq CFC} v_{ij} - v_{i=CFC,j} + \sum_i a_{ij}^K}{\sum_{i \neq CFC} v_{ij}} \quad \forall j \quad (5)$$

The total amount of carbon that emitted in the production of product j consists of the sum of carbon associated with intermediate inputs and the direct emissions by the production process.

$$\sigma_j = \sum_i \epsilon_{ij} + f_j \quad (6a)$$

The embodied carbon in a product is distributed across the products in proportion to the size of the respective markets,

$$\sigma_i = \sum_j \epsilon_{ij} + \sum_l \epsilon_{il}^y \quad (6b)$$

The inflows and outflows balance, so that $\sigma_i = \sigma_j \quad \forall i = j$

GVC measures for energy and emissions. A multiregional input-output (MRIO) table contains information on the intermediate input of products by region of origin. Here the same product classification is used in each region, with m products produced in each of n regions. Individual columns and lines present the markets and production of products, respectively, in a region, called region-

products. The MRIO intermediate flow table is a square table with $m \times n$ lines and $m \times n$ columns. The corresponding final demand table has a set of $n \times o$ columns, where o is the number of final demand sectors. For each section of each table, we distinguish between domestic d and foreign inputs and markets. The domestic blocks lie along the diagonal of the matrix. For the matrix formulation, we form matrices Φ^Z and Φ^Y which have 1 when both indices are domestic and 0 otherwise, and their complement $\bar{\Phi}^Z$ and $\bar{\Phi}^Y$. These matrices act as filters for the domestic and foreign sections of the Z and Y tables, respectively.

The factors associated with imports to the production of product j that enters export can be identified as

$$\tau_j = \sum_{i \neq d} s_i l_{ij} (\sum_{k \neq d} z_{jk} + \sum_{l \neq d} y_{jl}) \quad (7a)$$

$$T = (S(\widehat{L \cdot \bar{\Phi}^Z}))((Z \cdot \bar{\Phi}^Z)i + (Y \cdot \bar{\Phi}^Y)i) \quad (7b)$$

In the matrix notation, the dot indicates an element-wise multiplication (Hadamard product) and the vector i of ones serves to add up the row elements. $S(L \cdot \bar{\Phi}^Z)$ provides the amount of foreign factor added per unit output of each production process, the sum $((Z \cdot \bar{\Phi}^Z)i + (Y \cdot \bar{\Phi}^Y)i)$ is the total export volume for each of the products. Note that in this analysis, the use of the Leontief inverse L traces the foreign factor added throughout the value chain; a use of $\sum_{i \neq d} m_i a_{ij}$ would trace the regions of origin of the intermediate inputs, not that of the factors added.

The regional total factors in transit displayed in Figs.1-2 are sums across regions r ($\sum_{j=r} \tau_j$) and the product total in Fig. 3 is the sum across products ($\sum_{j=p} \tau_j$). CiT correspond to the first measure of vertical specialization VS in (Koopman et al., 2014). Bilateral flows of factors from the region of origin to the transit region (VS1) can be identified by summing intermediate inputs i over individual regions that are the origin of those inputs (eq. 7a), and adding up the contributions of the various production processes j . If the calculation traces only one factor, a diagonalization of S in eq. (7b) can identify the region of origin. Multiplying with the bilateral trade to specific countries can identify the flow to destination countries. The domestic factors added in export as a ratio to the factors associated with exports can be calculated as $FAX_j = \sum_{i=d} s_i l_{ij} / \sum_i s_i l_{ij}$ although here we derived them as $FAX_j = 1 - \sum_{i \neq d} s_i l_{ij} / \sum_i s_i l_{ij}$.

The analysis of the directionality of the value chains by regions of origin o , transit (manufacturing) t , and consumption c .

$$\tau_{otc} = \sum_{i \in o, j \in t} s_i l_{ij} (\sum_{k \in c} z_{jk} + \sum_{l \in c} y_{jl}) \quad (8)$$

Driver analysis. The driver analysis asks the question of whether the development in the carbon in transit over time can be understood in terms of changes in macro-level variables, such as the energy intensity with which imports are products, the carbon intensity of that energy, the share of imported value added in export (1-VAX), and the share of exports in gross domestic product. It follows the general approach of presenting aggregated, indexed variables that the Intergovernmental Panel on Climate Change (IPCC) used in its analysis of drivers (Blanco et al., 2014), in which emissions are decomposed using the Kaya identity of emissions being equal to the carbon intensity of energy times the energy

intensity of GDP times the GDP per capita times the population. As a first step, we identify the carbon and energy intensities:

$$\tau^c = \sum_{j=d} \left(\sum_{i \neq d} \frac{s_i^c}{s_i^e} s_i^e l_{ij} (\sum_{k \neq d} z_{jk} + \sum_{l \neq d} y_{jl}) \right)$$

Carbon intensity of energy
Import per unit output

Energy input
Export volume

Aiming at the macro level, the driver analysis takes the energy intensity of the average import to region r .

$$\rho^{e,r} = \frac{\sum_{k=d} (\sum_{j \neq d} m_j^e z_{jk} + \sum_{j \neq d} m_j^e y_{jk})}{\sum_{k=d} (\sum_{j \neq d} z_{jk} + \sum_{j \neq d} y_{jk})} \quad (9)$$

The average carbon intensity of that energy is

$$\rho^{ce,r} = \frac{\sum_{k=d} (\sum_{j \neq d} m_j^c z_{jk} + \sum_{j \neq d} m_j^c y_{jk})}{\sum_{k=d} (\sum_{j \neq d} m_j^e z_{jk} + \sum_{j \neq d} m_j^e y_{jk})} \quad (10)$$

The foreign value added per unit export is

$$v^{mx} = \frac{\sum_{j=d} (\sum_{i \neq d} s_i^v l_{ij} (\sum_{k \neq d} z_{jk} + \sum_{l \neq d} y_{jl}))}{\sum_{j=d} (\sum_{k \neq d} z_{jk} + \sum_{l \neq d} y_{jl})} \quad (11)$$

Final factors in our driver analysis are the volume of exports as a fraction of the GDP $\omega =$

$\frac{\sum_{j=d} (\sum_{k \neq d} z_{jk} + \sum_{l \neq d} y_{jl})}{\sum_{j=d} v_j}$ and the volume of GDP $g^r = \sum_{j=d} v_j$. The use of macro-level variables leads to

potential impacts of structural change; the imports of intermediate products may have different energy and carbon multipliers from imports to final consumption; the products produced for export may be different from those produced for domestic consumption. There is a structural factor ε which describes the influence of these residual impacts.

$$\tau^r = \rho^{ce,r} \rho^{e,r} v^{mx,r} \omega^r g^r \varepsilon^r \quad (11)$$

In Figure 4, each of the variables is normalized by its 1995 value and printed on a binary logarithm scale, such that the contribution of a factor that doubles the product appears as equally large as a contribution that cuts it in half.

Choice of MRIO database. The principal MRIO databases developed to facilitate the analysis of global production, consumption, and associated environmental impacts are GTAP, WIOD, EORA, OECD-ICIO, and EXIOBASE (Tukker et al., 2018). These databases have different regional and temporal coverage, sector/product detail, and provide information on factors. Early analyses of value added in complex GVC have relied on WIOD and GTAP, while the ICIO was especially designed for the question of value added, considering differences in China and Mexico in firms producing for export and those for the domestic market. We have chosen EXIOBASE because it has a high level of detail of energy carriers, reflecting the

IEA energy statistics, and distinguishes different emissions-relevant products, such as materials and agricultural products. Recently, an approach to endogenize capital identifying different capital goods was introduced (Södersten et al., 2018). EXIOBASE distinguishes 200 products produced in 43 countries and 6 rest-of-region (Stadler et al., 2014) blocks and offers thus the highest product detail of any harmonized MRIO, but unfortunately not a very good representation of less developed countries. Given the significant issue of aggregation errors (Steen-Olsen et al., 2014), the most detailed database was preferred. Most other databases lack an identification of the consumption of fixed capital, so that emissions associated with the production of capital cannot be considered. Given the different comparative strengths of various MRIO tables, comparative results from other tables would be of interest.

Results

In 1995, about 1.6 Pg of CO₂ equivalent transited through third countries, being emitted in one country to produce intermediate products that are exported and enable production of another product that is exported again. CiT constituted 5.2% of GHG emissions. CiT nearly tripled to 4.6 Pg CO₂eq. (10.4 % of global emissions) in 2012 and then declined slightly to 4.4 Pg (Fig. 1C). This peak is reflective of a peak in trade-related emissions and general developments in trade in value added (TiVA) and associated energy use (Fig. 1A). Transferred emissions constituted 18% of total export-related emissions in 1995 rising to 27% in 2016 (Fig. 1B). At the beginning of the time period, transferred products were 13% more emissions intensive than average global trade, a gap that narrowed to 5%.

In previous analyses of emissions in bilateral trade or of the difference between production and consumption-based accounts, scientists calculated the domestic emissions that were required to produce exported products. Those are shown by the thin lines in Fig.1A. In this analysis, we focused on the emissions associated with traded products, considering each border crossing, which is shown in the thick lines. The ratio of the two factors can be interpreted as the border crossing frequency, which increased from 1.25 to 1.42 for energy and 1.25 to 1.39 for GHGs, in agreement with by Zhang et al.(2017).

For both factors exported as a fraction of the global totals (Fig. 1A) and imported factors added to export (Fig. 1B), the values are highest for energy, followed by GHGs, and lowest for value added, even though global totals include household energy consumption and associated GHG emissions but not household production. The interpretation is that traded products are more energy intensive than the average product, but that they tend to be produced with less carbon-intensive energy. Indeed, comparing the energy and carbon intensity of CiT, all exports, and total global production reveals an interesting pattern. At the beginning of the period, the energy multiplier of imported products incorporated in export production was 15% higher than that of all exports, declining to 8% at the end of the period. The energy multiplier of exports was initially 32% higher than that of average global production, increased to 51% and then fell back to around 40%. This indicates indeed that traded products are more energy intensive and that those used to produce exports are even more so. However, the carbon intensity of energy shows a countervailing picture. The energy-in-transit was 2-5% less

carbon intensive than average export production. The carbon intensity of energy used in export production fell from 96% of the global average in 1995 to 81% in 2015.

Given that imports enabling export production can be assumed to have a lower degree of fabrication (Nakamura et al., 2007), it is not surprising that those imports are even more energy intensive than the typical exports, showing the divergence between the energy added in export and the value added in export in Fig. 1B. The share of transferred factors as a fraction of global totals in Fig. 1D shows the compound effect of the differences displayed in Fig. 1A and 1B. The overall pattern in Fig.1, however, is that the different factors in trade have the same general trend.

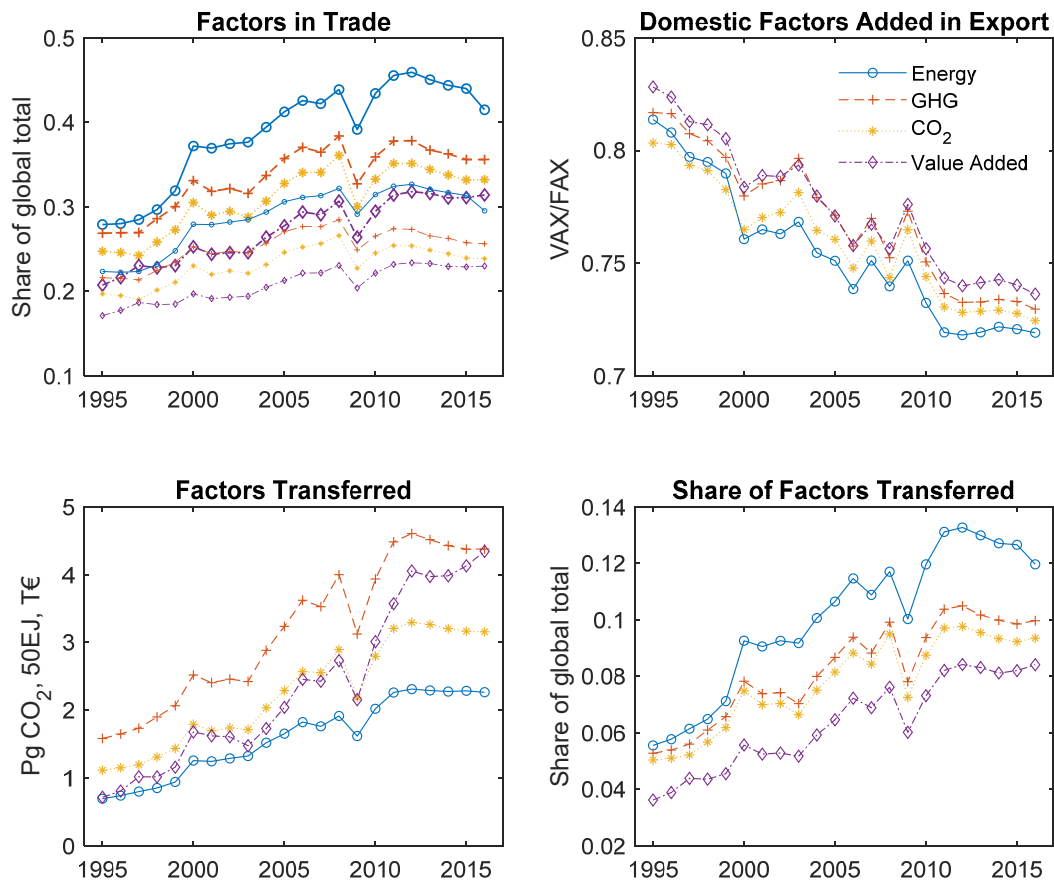


Figure 1: A global picture of the trade in value added, energy use, CO₂ and greenhouse gas emissions. A) Total trade in factors added divided by total global factor use/value added. Note that this number can be >1 when products cross borders multiple times. The thin lines quantify factors that enter international trade, i.e. count only one trade. B) Content of domestic value added/factors added in exported products/services per unit export value or factors required to produce exports. C) Energy, emissions and value added in imports that are used as intermediate inputs or capital to produce exported products, as part of complex global value chains (carbon in transit). D) Factors in imports to used produce exports as a share of global factors added.

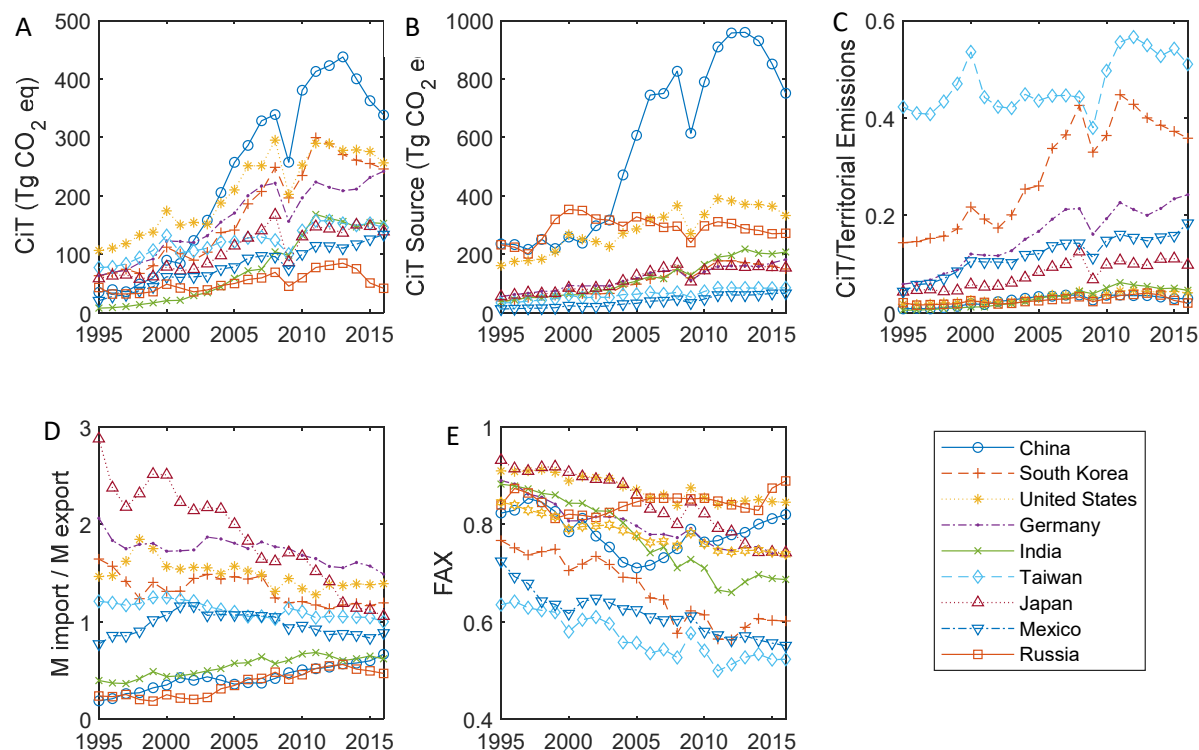


Figure 2: (A) Greenhouse gases associated with the production of imported intermediate goods that are incorporated in a country's export (carbon-in-transit), by country of transit, in 1995-2015. (B) GHG emissions in countries' exports that transit other countries, by country of origin. (C) Carbon-in-transit normalized by domestic GHG emissions. D) Emissions per unit value of imports divided by emissions per unit value of exports. E) GHG added domestically as a fraction of total GHG emissions associated with the production of exported goods from each country.

Transferred carbon reflects the economic specialization of countries participating in global supply chains. Manufacturing powerhouses such as China, the United States, South Korea, and Germany were responsible for a significant share of the global carbon in transit (Fig.2A). Remarkably, Mexico was disproportionately important, while India experienced a steep rise during the period under investigation. China was by far the most important source of emissions that became embodied in transit, peaking above 900 Tg CO₂ eq in 2013, compared to 400 Tg for the US. Russia also played an important but diminishing role as a source of carbon transiting other countries (Fig.2B), while exporting few products that were made with substantial carbon input from other countries. The resource-intensive economies of Canada, Australia, and Brazil emitted on the order of 70-80 Tg as starting points of global supply chains. On the other end of the spectrum are small, highly developed economies. The relative importance of CiT is larger in smaller, more trade-exposed economies (Fig. 2C). For Luxemburg, Malta, and Slovakia, and Switzerland, the transfer of carbon was comparable in size to domestic emissions. The implication is that for value creation in these economies, imported products play an outstanding role. The importance of CiT is tied to the ratio of multipliers (kgCO₂/EUR) of imports to exports (Fig.2D) and

the fraction of domestic value added in export, resulting in a country-specific domestic factor (GHG emissions) added to exports (FAX, Fig.2E).

The use of capital goods contributes about 20% of the CiT, starting from 25%, dropping to 17% in 2000-2001, and rising again to 22% in most of the current decade. Capital contributes in two manners. One, its inclusion increases the multiplier values of individual products through the inclusion of the emissions associated with the production of capital goods used in the production of traded goods. Two, the import of capital goods also counts in CiT when exports are produced with this capital. The share of capital is higher developed than in developing economies.

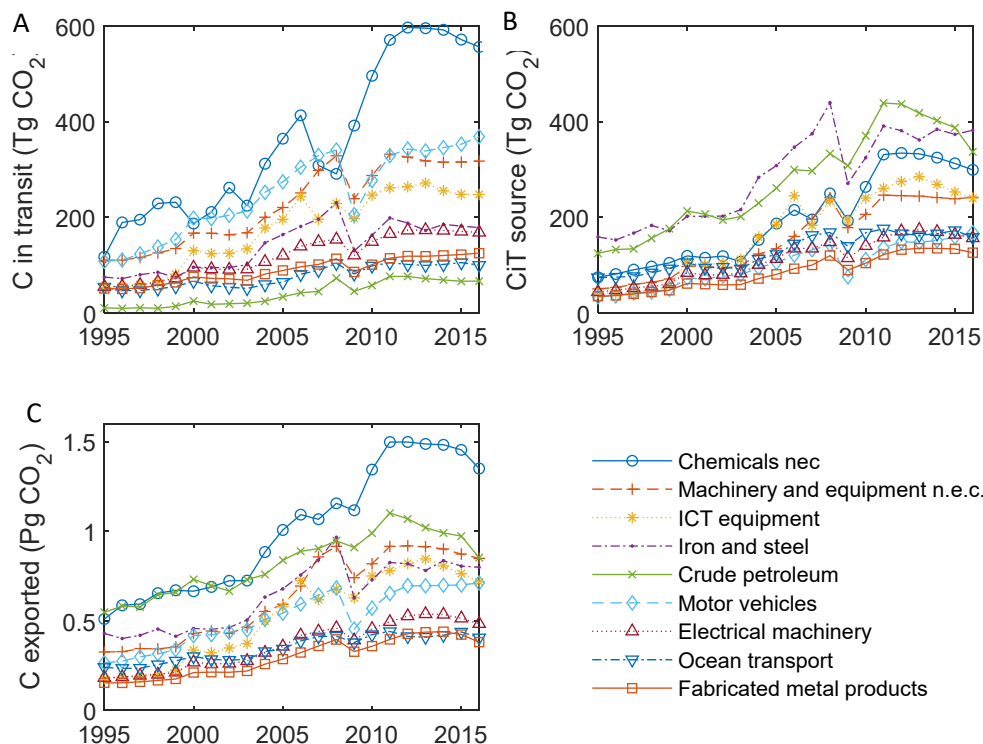


Figure 3: (A) Products that incorporate GHG transiting through countries, in terms imported GHG incorporated in exported products, in 1995-2015. (B) Imported products that become incorporated in or are used to produce products that are eventually exported. (C) GHG emissions associated with the production of various internationally traded products, provided for reference.

The production of highly manufactured products such as cars and IT relies most on carbon-intensive inputs from other countries. Measured by the cradle-to-gate emissions of their imported inputs, chemicals account for 13% of the emissions, followed by motor vehicles (7%), machinery and equipment (7%), electronics (ICT 6%, office machinery 2%), and electrical machinery and apparatus (3-4%) (Fig. 3A). Intermediate products, such as iron and steel, petroleum products, and fabricated metal products also come up as being important. For the US, medical and precision equipment and other transport equipment are also important, for South Korea and Turkey, iron and steel play a key role, and for India, refined petroleum products are most important. The contribution of products to CiT reflects several

368 factors: the general production volume, the degree to which they are traded internationally, which
 369 favors manufactured products over services, the energy intensity of manufacturing, and the
 370 specialization of countries in specific industries.

371 Logic would suggest that those products imported as intermediate inputs to the production of exports
 372 have a lower degree of fabrication. Indeed, the most important imports are crude petroleum and iron &
 373 steel (Fig.2B). The third most important product is chemicals, which is a broad class of products and one
 374 could see more basic chemicals such as ethylene or ammonia being important in this context, something
 375 the sector aggregation does not reveal. Export production also relies on imports used as capital
 376 equipment, such as machinery and ICT equipment, as well as transport equipment and services such as
 377 ocean transport.

378 Large relative increases in carbon in transit between 1995 and 2016 occurred in computer services (8x),
 379 petroleum (6x), R&D services (6x), and chemicals, ICT, medical and precision instruments (4-5x),
 380 chemicals and furniture (4x). The smallest increases occurred in textiles and hotel and restaurant
 381 services (1-2x). The increase in motor vehicles and other transport equipment, machinery, electrical
 382 machinery and apparatus, and office machinery was on the order of a factor of three, in line with the
 383 overall increase in CiT.

384 The pattern of individual countries reflects their position in the global economy. For Germany, motor
 385 vehicles and parts embodied the largest transient flow of carbon, followed by machinery and
 386 equipment, and electrical machinery. The input to production for export consisted of machinery and
 387 equipment, motor vehicles and parts, iron, steel and first products thereof, electrical machinery, and ICT
 388 equipment. The picture hence reflects the strong position of the German automotive and industrial
 389 equipment production. The case also illustrates the limited detail in the economic input-output tables
 390 used in the present modeling. Motor vehicles are grouped together with motor vehicle parts and bodies.
 391 We cannot say what part of the production process took place in Germany. CiT constituted around 40%
 392 of the emissions associated with Germany's export.

393 On the surface, the picture for Mexico is similar. Motor vehicles and parts, and ICT equipment are the
 394 most important product groups in CiT. The source of this carbon flow, the imported products that
 395 became incorporated in Mexico's exports, were ICT equipment, iron and steel, electrical machinery,
 396 motor vehicles and parts, and rubber and plastic products. Mexico exported a larger share of consumer
 397 products than Germany, and the share of transiting carbon was like that of Germany. The picture
 398 indicates that Mexico plays an important role as assembly line for its Northern neighbors. Products
 399 exported from Mexico include significant inputs from other countries. For Canada and the United States,
 400 motor vehicles and parts also constitute the most important transient flows.

401 Smaller economies often occupy specific niches in the world economy. For South Korea, ICT equipment,
 402 ocean transport, iron and steel, and chemicals are the most important products incorporating
 403 transferred carbon. The same products are also the most important source of this carbon. Like for motor
 404 vehicles and parts, the large overlap in categories indicates that the countries are part of international
 405 value chains within the same industry, with imported electronic parts being assembled to ICT products.
 406 Precious metals are important carriers of carbon transiting through Switzerland.

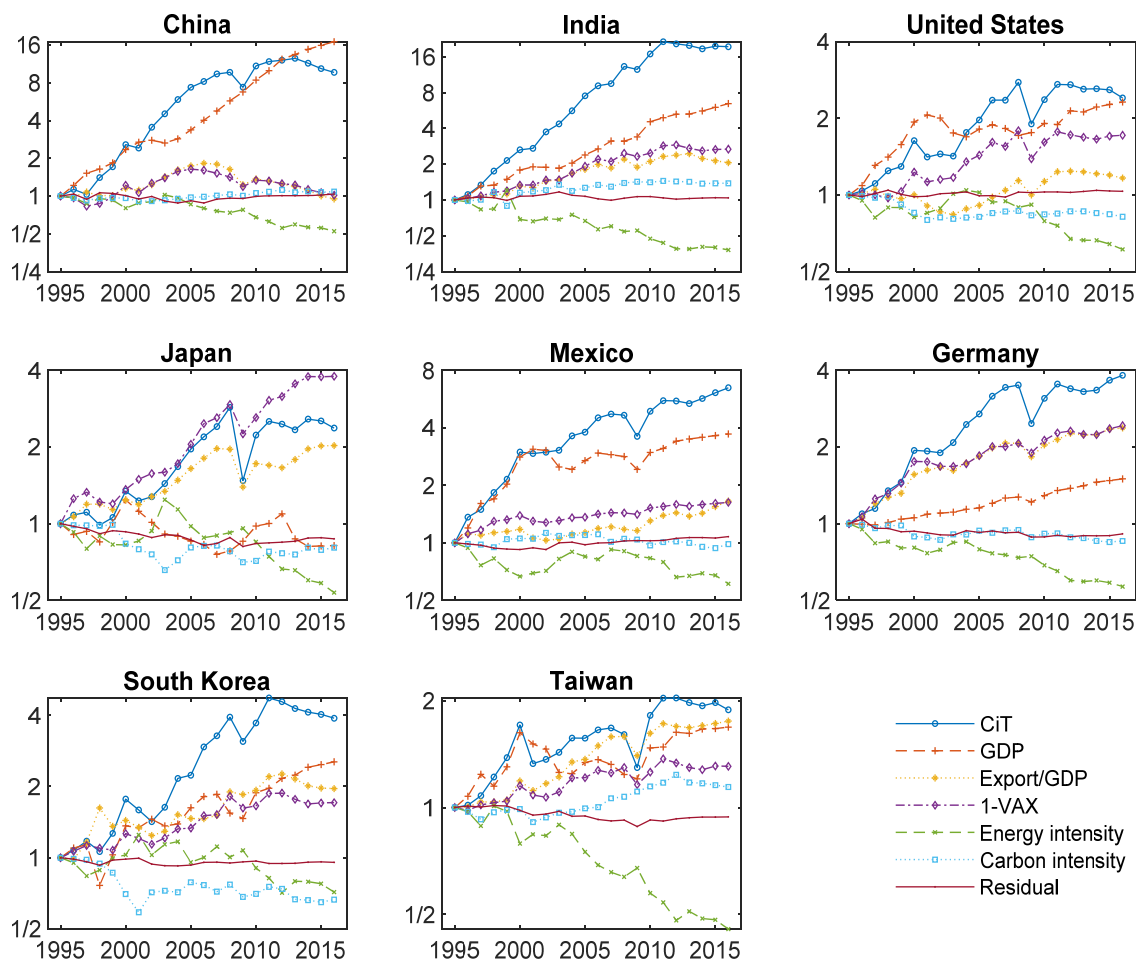


Figure 4: Explaining the rapid increase in GHGs in imports used in export production: the role of the growth of GDP, of exports as a share of GDP, and the imported value added in the production of exported goods (1-VAX), the energy intensity per value of imported products and the carbon intensity of that energy. The unexplained residual reflects differences between the average import and the import used for producing exported goods.

Growth in transferred emissions reflects growth in trade volumes. To understand the rapid growth in energy and GHG emissions in imported goods that are used to produce exports, we investigated the role of underlying developments that affect this parameter. We looked at the size of exports as a share of GDP, the total GDP, the fraction of imported value added per unit of export, the energy intensity of the imports, and the carbon intensity of that energy. Figure 4 shows that this decomposition explains the development quite well: the residual, which reflects structural differences between general imports and those used to produce exported products, is generally small. A multiple regression analysis of the logged ratios of 2011 to 1995 values (ignoring residuals) of all 43 countries shows a highly significant result

(Fstat=210, $r^2=0.97$), with the slopes of all independent variables being close to and indistinguishable from 1 and the intercept being indistinguishable from zero.

The value of export as a share of GDP and the import share of the value of exports show very similar developments in many countries. Imports are normally balanced by exports unless there are large capital inflows or outflows, but that does not mean that the two variables we look at need to be similar. The 1-VAX variable reflects the role of imports in export production; to the degree that countries specialized in specific parts of international value chains, they can diverge substantially from the importance of imports for domestic consumption. For Japan, for example, 1-VAX increased almost fourfold from 7 to 26% reflecting the outsourcing of specific production steps by Japanese multinationals. The export value as a fraction of GDP barely doubled, from 10 to 19%.

For industrialized countries, the two trade-related factors (1-VAX and export value as a share of GDP) together represent the largest driver for the increase in CiT. For the developing countries depicted in the figure, economic growth appears to be the largest driver. However, the GDP numbers used here are nominal GDP calculated with market exchange rates, so that regions that increased their competitive position may appear to gain more. Nominal GDP had to be used since the energy intensity of imported products is derived from an MRIO calculation performed in nominal prices; the construction of constant-price MRIO tables has been attempted but has not yet been successful. Similarly, the energy intensity reflects the use of energy to produce a unit of imports measured in nominal prices and hence the observed decline is in part an artefact of inflation.

China appears to present a remarkable exception to the uniform increase in the importance of the two trade related variables, because export constituted already a large share of GDP in 1995, 24%. It increased to 43% in 2006 but then fell back to its starting value at the end of the period. By contrast, the export share of Germany's GDP increased from 20 to 46%, of India's from 11 to 25%, and of Mexico's from 30 to 49%. The US increased its share of exports only from 12 to 15%.

Trilateral Trade. The analysis of directional relationships is hampered by the combinatorial complexity and size of the underlying data set. Given 49 regions in EXIOBASE, there are $49 \times 48 \times 48$ or 113000 different combinations. Excluding those involving rest-of-world regions, the largest flows of CiT in 2015 were US-Canada-US (44 MtCO_{2e}), China-Mexico-US (28), China-Korea-US (26), and US-Mexico-US (26). Additional GVC included China-Japan-China (15), China-US-Canada (11) and China-US-China (10). It is maybe not surprising that the largest economies and their closest trading partners are involved. When EU countries (plus Switzerland and Norway) are adding up, it emerges that trade within the EU accounts for 200 Mt in CiT, exceeding that of NAFTA countries, followed by China-EU-EU (110) and Russia-EU-EU (100).

Table 1 indicates the region of the emissions and the region importing the products to produce exports. It shows the importance of intra-EU trade, and the exports of China to the EU and East Asia, and of Russia to the EU. Table 2 shows the carbon associated with the foreign intermediate inputs exported from processing countries (row) to destination countries (column). Here, intra-EU trade is twice as large, indicating that the EU imports a lot of products from third countries that are then part of the production for its common market. China is also an important destination, with products imported from East Asia and the EU. The US is an important destination from exports from the EU, Canada, Mexico, East Asia, and China. Russia, which is an important source of primary production, has almost no processing trade and subsequent exports.

463 Table 1: CiT in 2015 indicating the region where the production of products and the emissions have happened (row) and the
464 region importing these products as intermediate inputs or capital goods used to produce exports (column). The East Asia region
465 includes Japan, Korea, and Taiwan, the EU+2 regions is the 27 countries of the European Union plus Norway and Switzerland. A
466 full table of all 49 regions is available in the online supporting material. Non-zero diagonal elements can occur in regions
467 comprised of more than one economy and indicate trade among economies comprising these regions.

Mt CO ₂ e	Region processing imports for export production												
Region of origin	Australia	Brazil	Canada	China	East Asia	EU+2	Indonesia	India	Mexico	Russia	Turkey	USA	Rest of World
Australia	0.0	0.2	0.6	15	17	11	0.9	6.5	0.6	0.5	0.3	2.5	27
Brazil	0.2	0.0	1.9	9.8	6.9	14	0.5	3.1	1.3	0.2	0.5	6.3	47
Canada	0.3	0.4	0.0	4.7	5.0	17	0.3	1.3	2.5	0.3	0.3	29	13
China	9.3	4.0	17	0.0	144	210	9.2	29	36	7.3	7.6	72	480
East Asia	3.6	1.0	4.6	59	50	56	2.9	6.7	8.6	1.9	2.2	21	114
EU+2	3.2	2.3	5.8	38	42	344	1.7	7.2	5.9	5.5	6.9	20	83
Indonesia	0.7	0.2	0.4	12	17	7.2	0.0	2.5	0.7	0.2	0.6	2.1	24
India	1.3	0.9	2.6	15	17	45	1.9	0.0	3.5	1.2	2.4	9.5	107
Mexico	0.2	0.4	2.4	2.3	2.7	7.6	0.1	3.9	0.0	0.1	0.2	14	11
Russia	1.2	1.0	3.0	27	32	160	1.2	3.4	3.0	0.0	8.0	10	74
Turkey	0.2	0.1	0.3	1.3	1.4	11	0.2	0.7	0.2	0.4	0.0	1.1	13
USA	1.8	2.2	57	34	39	83	1.7	10	35	1.9	2.5	0.0	80
Rest of World	16	11	14	170	190	370	16	77	12	17	16	58	260

468

469 Table 2: CiT in 2015 indicating the region where imported products are used as intermediate inputs or capital goods used to
470 produce exports (row) and the destination for the exports from the processing region (column). The numbers indicate emissions
471 that have occurred upstream in the regions of the original inputs. Region definitions and detail as for Table 1.

Mt CO ₂ e	Destination region for exports												
Processing region	Australia	Brazil	Canada	China	East Asia	EU+2	Indonesia	India	Mexico	Russia	Turkey	USA	Rest of World
Australia	0.0	0.3	0.6	5.6	5.4	6	1.0	1.2	0.2	0.4	0.2	3.4	14
Brazil	0.1	0.0	0.2	5.1	1.5	3	0.1	0.4	0.4	0.2	0.1	2.6	10
Canada	0.6	0.4	0.0	5.0	3.6	8	0.2	0.8	1.8	0.3	0.3	81	7
China	6.5	4.1	6	0.0	39	59	3.1	12	7	3.8	3.4	69	176
East Asia	10	4.7	5.4	131	58	54	6.4	16	7.9	4.0	4.3	71	196
EU+2	12	12.0	15.3	88	57	737	3.8	16	10	20	22	119	223
Indonesia	1.0	0.3	0.3	5	4.3	4.2	0.0	1.4	0.3	0.2	0.4	4.3	15
India	1.2	3.8	1.0	8	8.8	21	1.2	0.0	1.5	0.8	3.8	17.1	84
Mexico	0.5	1.2	6.4	2.8	1.9	4.6	0.0	0.3	0.0	0.1	0.2	81	12
Russia	0.3	0.4	0.4	3.4	3.0	13	0.1	0.8	0.3	0.0	1.5	2	11
Turkey	0.3	0.3	0.4	1.0	0.6	17.5	0.1	0.4	0.2	0.9	0.0	2.5	23
USA	3.5	4.5	35	30	20	44	0.6	4	30	1.6	1.6	0.0	73
Rest of World	41	27	18	209	165	338	51	70	15	24	18	164	197

472

473 Discussion

474 The investigation has revealed that emissions in imports used for export production are large and have
475 risen substantially over the past two decades, although there is a decoupling from trade volumes in the
476 most recent five years. The development can be well understood given the increase in export volumes
477 and the decreasing share of domestic value added in exported products.

478 The estimates of carbon associated with GVC are affected by several factors. Some of these can be
479 illuminated by further analysis, some of the uncertainties may require different approaches and entirely
480 new data to narrow down. We briefly mention several and highlight some significant sources.

481 **The uncertainty of MRIO results** has been the focus of recent research (Owen, 2017). For country-level
482 consumption-based carbon emissions accounts, Rodrigues et al.(2018) find a coefficient of variation (CV,
483 normalized standard deviation) of 2-16% across countries, while the product-level CV ranged from 10-
484 200%, depending on the product. In line with previous studies, they found that emissions data is an
485 important source for the overall uncertainty, thus affecting both territorial and consumption-based
486 accounts equally. However, scale of final demand, technology employed, composition of the goods
487 traded, and coefficients describing the trade of intermediate products were identified as important
488 sources of uncertainty. Contrary to an often-assumed independence of uncertainties, they found
489 correlations among coefficients of variation which lead to doubling the error of the estimated
490 uncertainty of consumption-based emissions over what independence would suggest. Estimates of CiT
491 are likely to be between the product- and the country-level.

492 **Heterogeneity and processing trade.** The specialization of countries can only in part be traced in
493 multiregional input-output tables, since the aggregation of products and sectors for accounting
494 purposes masks underlying differences in what countries produce. An important modeling assumption
495 in MRIO is the homogeneity of sectors and of products sold into different markets. The literature on
496 “processing trade” (e.g., Koopman et al., 2012) indicates that the factories participating in this
497 processing of imported goods for export - think of the Maquiladoras in Mexico or the assembly of
498 iPhones in China – are different from companies in the same industry producing for the domestic
499 market. Relaxing the assumption of homogeneity, researchers have created input-output tables that
500 described two separate economies – one for the domestic market and one for export production. Such
501 analysis shows a much lower share of domestic value added in exports (Koopman et al., 2012; Pei et al.,
502 2012). As a result, emissions associated with export are overestimated, as Liu et al. (2016) have shown
503 for China, and is underestimated. On the other hand, if Chinese exports are indeed cleaner than
504 suggested by Liu et al. (2016), the CiT of economies such as Korea, Japan and the EU would be smaller.
505 We investigated the use of the ICIO table of OECD to provide a sensitivity analysis. ICIO has been set up
506 to take into account processing trade in China and Mexico. However, the OECD does not provide
507 information on factor use other than labor and gross profit, it hence lacks information on energy use,
508 emissions, and the impact of capital.

Driver analysis. The simple decomposition presented in this paper shows that the CiT changes along with macro-variables. It does not address the role of structural changes in the economy or the trading patterns, which might affect the dependent and independent variables similarly. Given that the CiT measure is derived from a matrix equation, a structural decomposition analysis (Malik and Lan, 2016; Su and Ang, 2017) can be conducted. Another issue concerns the valuation. MRIOs are generally in current prices and the construction of constant-price tables, while known in principle, has not yielded satisfactory results. As price of different commodities vary over time in addition to the recorded variation in purchasing power and exchange rates, values of the output can be adjusted for this variation. It is, however, not clear whether the price of a traded commodity should follow that in producing or the consuming country. In principle, trade statistics recording physical in addition to monetary trade could help resolve this issue. We attempted two corrections of the GDP and energy intensity of the products, one following purchasing power parity adjustment to international 2011\$, the other based on chained price indices for the commodities constructed by the EXIOBASE team. Both results lead to unexpected jumps. Further work on constant price tables may help to resolve these issues.

Carbon-in-transit and emissions pricing. The principal policy concern with trade leakage is the divergence between consumption- and production-based emissions; reflected in the “net emissions transfer” reported by institutions such as the Global Carbon Project (Le Quéré et al., 2016). Yet, most discussed policy measures address the carbon embodied in traded goods (Böhringer et al., 2012; Branger and Quirion, 2014; Pitschas, 1994), independent of whether goods are imported for final consumption or as an intermediate input to domestic industrial production. The principal measure discussed is border tax adjustments. Calls for border tax adjustment were included in President Macron’s speech on Europe (France 24, 2017), in a climate policy proposal by elder statesmen of the US Republican Party (Baker III and Shultz, 2017), and in a call for a carbon dividend by Nobel laureates and former Federal Reserve chairs placed in the Wall Street Journal (Akerlof et al., 2019). It raises questions of whether such a regime is permitted under international trade law. Many legal experts think a border tax adjustment can be designed to be compliant with the General Agreement on Tariffs and Trade (GATT) (Monjon and Quirion, 2011; Trachtman, 2017). Such assessments presume, however, that the border tax would not undermine the intention of the GATT.

If the carbon associated with traded products was taxed, that would include a tax on CiT. If GHG emissions are taxed at a level of \$30/ton, carbon-in-transit amounts to >\$100 billion per year, surely to become a cause for contention. If processing trade and the emergence of complex global supply chains, facilitated by GATT, was indeed an important mechanism to allow developing countries participate in the world economy, an undue tax or administrative burden on GVC may contribute to a border tax adjustment be ruled as non-compliant with GATT. The literature indicates that there are different border tax schemes can be designed in different ways (Monjon and Quirion, 2011). The design of a border tax regime would need to address whether previously paid import duties are refunded upon the export of a product produced with these imports, and if so, how their magnitude is assessed and documented.

An alternative strategy that has equal effectiveness in economic models is taxing carbon emissions at the level of consumption, not production (Böhringer et al., 2017). The contribution of this paper is to quantify the potential size of the issue, to identify which products are affected, and to pinpoint the countries that will need to pay attention. Whether it is border tax adjustments or consumption-based carbon taxes, complex global value chains pose challenges for the measurement of associated emissions and hence the design of policies aiming to target trade-related emissions. If border tax adjustments do not include a tax refund for exports at the border, companies will argue against an import duty for products used for export production to ensure competitiveness on the global market; if they do, the question is how to assess the emissions associated with imported intermediates or document previously paid import duties. For a consumption tax, the challenge is how to assess the level of emissions which depends on the respective technologies of the many countries participating complex global value chains. The methods employed in this paper can give approximate answers. As indicated in other work, there are substantial uncertainties associated with the ascertainment of the carbon footprint of individual products (Owen, 2017; Rodrigues et al., 2018). While such uncertainties are not uncommon in economic or environmental policy issues, a practical implementation of a border tax adjustment will make the issue tracing the production of products and the use of quantitative methods to assess border taxes more acute. The development of international standards and product category rules for eco-labels and product environmental footprints may thus become a lot more relevant.

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