The global CO_2 emissions growth after international crisis and the role of international trade

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Abstract:

In this paper, we decompose the driving forces of global CO_2 emissions for the post-crisis era 2008–2011 from both production-based and consumption-based aspects. The results suggest that non-OECD economies have become the major drivers for the rapid global growth of CO_2 emissions after the crisis. More specifically, the increasing consumption and investment of non-OECD economies, as well as stagnation of their emission intensity reductions, have largely contributed to global growth of CO_2 emissions after 2009. On the contrary, OECD economies have a less carbon-intensive life style. Coupled with a decrease in investment and stagnation of consumption, the OECD economies have successfully reduced both their production-based and consumption-based emissions. However, the magnitude of their reduction is much lower than the increase led by non-OECD economies. In addition, both OECD and non-OECD economies have started to increase their purchases of intermediate and final products from non-OECD economies. Such changes of international trade caused an additional 673 Mt of global emissions from 2008 to 2011. The results of our decomposition provide both worries about and insights into future global climate change mitigation.

Key words: Global CO_2 emissions; structural decomposition; consumption-based accounting; international financial crisis; OECD and non-OECD economies

1. Introduction

Despite the global efforts toward climate change mitigation, the global CO_2 emissions from fossil-fuel combustion and cement production have been growing for decades. While previous crises, such as the oil crisis in 1973, the US savings and loan crisis in 1979, the collapse of the Former Soviet Union in 1990, and the Asian Financial Crisis in 1997, seriously slowed down the global growth of CO_2 emissions for several years, the impact of the 2008 financial crisis on emissions has been very short-lived (Peters et al., 2012). The global CO_2 emissions from fossil-fuel combustion only decreased by 1.90%, from 28.87 Gt (Gigatonnes) in 2008 to 28.32 Gt in 2009 and then sharply increased to 29.84 Gt in 2010 -- a 5.36% increase -- reaching the highest annual growth rate recorded since 2004. Ever since then, the emissions have continued to grow, reaching 32.30 Gt in 2014 (IEA, 2015). Such persistent growth and the potential for even higher future growth of CO_2 emissions has led to extensive worries about the target for limiting global warming to less than 2°C (see also, Peters et al., 2013; Friedlingstein et al., 2014; Raupach et al., 2014; Rozenberg et al., 2015).

It is interesting to explore what drives the persistent growth of global CO_2 emissions, especially after the financial crisis. In this domain, structural decomposition analysis (SDA) based on input-output tables has been widely employed (see, e.g. Su and Ang (2012), Wang et al. (2017) for explicit reviews). SDA can break down the changes in CO_2 emissions (or any other variable) over time into its determinants, such as energy intensity, production recipe, final demand structure, affluence, and population growth. Based on a single-region input-output database, for example, the literature reveals extensive use of SDA to identify the drivers behind the changes of CO_2 emissions of a range of countries/regions, such as the USA (Feng et al., 2015), China (Guan et al., 2008; Gui et al., 2014), Norway (Yamakawa and Peters, 2011), the Baltic States (Brizga et al., 2014), Taiwan (Chang et al., 2008), Spain (Cansino et al., 2016), and Brazil (Perobelli et al., 2015), etc.

In addition, there is a growing literature that explores the drivers behind global CO_2 emissions growth by introducing SDA on global multi-regional input-output tables (GMRIO): e.g.

Baiocchi and Minx, 2010; Arto and Dietzenbacher, 2014; Owen et al., 2014; Malik and Lan, 2016; Jiang and Guan, 2016; and Hoekstra et al., 2016. The SDA based on GMRIO can not only capture the drivers behind CO_2 emissions growth as single-regional IO table captures, such as emission intensity, production recipe, and final demand, but can also trace the changes in international trade patterns of both intermediate and final products (see also Wiedmann, 2009; Arto and Dietzenbacher, 2014; Malik and Lan, 2016). The international trade has not only caused a separation of production and consumption of products and embodied emissions (Peters et al., 2011) but has also led to significant net growth of global CO_2 emissions (Arto and Dietzenbacher, 2014; Hoekstra et al., 2016; Malik and Lan, 2016).

Despite such extensive literature, the growth of CO_2 emissions after the financial crisis in 2008–2009 is barely discussed. The current literature has either analyzed the annual growth of growth of CO_2 emissions before the crisis (see, e.g. Arto and Dietzenabcher, 2014; Hoekstra et al., 2016; Jiang and Guan, 2016), or analyzed the growth from 1990 to 2010 into several sub-periods (Malik and Lan, 2016; Malik et al., 2016). One pioneering work focusing on growth of CO_2 emissions after the financial crisis might be Peters et al. (2012). They estimated both the production-based and consumption-based CO_2 emissions after the global financial crisis, and found that, from the consumption-based aspect, economic activities, including large government investment and growing consumptions in emerging countries, were the major drivers for the rapid rebound of global CO_2 emissions from 2008 to 2010. From the production-based aspect, the researchers found that developed countries became temporarily less dependent on imports, hence slowing down the emissions embodied in international trade, and increased their production/territorial-based emissions.

In this study, we employed SDA based on a global inter-country input-output table that compiled by OECD and decomposed the global growth of CO_2 emissions, with a special focus on the post-crisis era 2008–2011. One of the advantages of the OECD-ICIO table over the other available databases[1] is that it distinguishes processing exports and normal productions for China and Mexico. Based on single-country input-output tables, the literatures have widely

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[1] Some other popular GMRIO databases include Eora, EXIOBASE, OECD-ICIO, GTAP-MRIO. Please refer to Tukker and Dietzenbacher (2013) for an explicit review.

acknowledged that the production recipes and emission intensity of processing exports and normal productions are highly different in China (see, e.g. Dietzenbacher et al., 2012; Su et al., 2013; Jiang et al., 2016; Su and Thomson, 2016). By employing the OECD-ICIO table, our paper thus differs from the literatures that use either single-country input-output table or other GMRIO databases, in that it focuses on the impact of different trends of processing exports, with normal production in China and Mexico, on the global CO_2 emissions. In addition, we adopt Hoekstra et al.'s (2016) decomposition idea, and isolate the impact of the changing pattern of international trade on CO_2 emissions by income group in the decomposition process. As found by Peter et al. (2012), developed countries turned to support domestic activities, with the result that international trade experienced a serious drop during the 2008–2009 financial crisis. Besides, there are signs of a further geographic shift of trade to less-developed countries in South Asia and Africa after the financial crisis, to seek lower labor costs (see also, Lehmann, 2012; Stratfor, 2013; AfDB, OECD and UNDP, 2014). It is also interesting to explore the extent to which such a change of international trade patterns influenced the global CO_2 emissions after the crisis.

Our article is organized as follows. In section 2 we introduce our methods and data sources; in section 3 we present our decompositions' results, at both aggregate and individual region/industry level. Some policy-related implications of our findings are discussed in section 4.

2. **Methodology and Data**

2.1. Global Multi-Regional Input-Output (GMRIO) framework and data source

The GMRIO has been widely accepted in tracing the CO_2 emissions footprint along global production chains (see Wiedmann (2009) and Minx et al. (2010) for reviews). Table 1 presents the GMRIO framework employed in this paper. The diagonal matrices of intermediate use give the intra-regional intermediate deliveries, that is, the elements z_{ij}^{rr} of matrix $\mathbf{Z}^{rr}$ give the intermediate deliveries from industry i in region r to industry j in region r, with $i, j = 1,\ldots,m$, where m is the number of industries, and $r = 1,\ldots,n$, where n is the number of regions. The non-diagonal matrices indicate inter-regional intermediate deliveries, that is, the elements z_{ij}^{rs} of matrix $\mathbf{Z}^{rs}$ indicate the deliveries of products from industry *i* (=1,..,m) in region *r* (=1,..,n) for input use in industry *j* (=1,..,m) in region *s* (=1,..,n; ≠ *r*). The matrices of final demand $\mathbf{F}^{\mathrm{rs}}$(*r*, *s*=1,...,n) are divided into consumption $\mathbf{F}^{\mathrm{rs}}_{\mathrm{cons}}$ (*r*, *s*=1,...,n) (including consumption by households, governments, and non-government organizations), and investment $\mathbf{F}^{\mathrm{rs}}_{\mathrm{inv}}$ (*r*, =1,...,n) (i.e. fixed capital formation). $\mathbf{X}^{\mathrm{r}}$ (*r* =1,...,n) represents the total output in region *r* (=1,..,n).

INSERT TABLE 1 ABOUT HERE

According to Table 1, we have row equilibrium in matrix notation as follows:

$$\begin{bmatrix} \mathbf{Z}^{11} & \cdots & \mathbf{Z}^{1\mathrm{n}} \\ \vdots & \ddots & \vdots \\ \mathbf{Z}^{\mathrm{n}1} & \cdots & \mathbf{Z}^{\mathrm{nn}} \end{bmatrix} + \begin{bmatrix} \mathbf{F}^{11} + \cdots + \mathbf{F}^{1\mathrm{n}} \\ \cdots \\ \mathbf{F}^{\mathrm{n}1} + \cdots + \mathbf{F}^{\mathrm{nn}} \end{bmatrix} = \begin{bmatrix} \mathbf{X}^{1} \\ \vdots \\ \mathbf{X}^{\mathrm{n}} \end{bmatrix} \tag{1}$$

The direct input coefficients can then be obtained by normalizing the columns in the IO table; that is:

$$\mathbf{A}^{\mathrm{rs}} = \mathbf{Z}^{\mathrm{rs}}(\widehat{\mathbf{X}^{\mathrm{s}}})^{-1} \tag{2}$$

where *r*, *s*=1,...,n, and $(\widehat{\mathbf{X}^{\mathrm{s}}})^{-1}$ denotes the inverse of a diagonal matrix of total outputs in region *s*.

Define the input coefficients matrix $\mathbf{A} = \begin{bmatrix} \mathbf{A}^{11} & \cdots & \mathbf{A}^{1\mathrm{n}} \\ \vdots & \ddots & \vdots \\ \mathbf{A}^{\mathrm{n}1} & \cdots & \mathbf{A}^{\mathrm{nn}} \end{bmatrix}$, where $\mathbf{A}^{\mathrm{rs}}$ is the input coefficient from region *r* to region *s*. Then, the Leontief inverse can be calculated as $\mathbf{B} = (\mathbf{I} - \mathbf{A})^{-1}$; that is, $\mathbf{B} = \begin{bmatrix} \mathbf{B}^{11} & \cdots & \mathbf{B}^{1\mathrm{n}} \\ \vdots & \ddots & \vdots \\ \mathbf{B}^{\mathrm{n}1} & \cdots & \mathbf{B}^{\mathrm{nn}} \end{bmatrix} = \begin{bmatrix} \mathbf{I} - \mathbf{A}^{11} & \cdots & -\mathbf{A}^{1\mathrm{n}} \\ \vdots & \ddots & \vdots \\ -\mathbf{A}^{\mathrm{n}1} & \cdots & \mathbf{I} - \mathbf{A}^{\mathrm{nn}} \end{bmatrix}^{-1}$, where **I** is the identity matrix, with diagonal elements as ones and non-diagonal elements as zeros. The Leontief inverse describes both the direct and indirect linkages across regions and industries.

Using $\mathbf{Q}^{\mathrm{r}}_{\mathrm{carbon}}$ to denote the matrix of production-based CO_2 emissions by industry group in region *r* and $\mathbf{EI}^{\mathrm{r}} = \mathbf{Q}^{\mathrm{r}}_{\mathrm{carbon}}(\widehat{\mathbf{X}^{\mathrm{r}}})^{-1}$ to denote the matrix of carbon emissions intensity per unit of output by industry group in region *r*, the CO_2 emissions generated along global production chains can be traced as follows:

$$\begin{bmatrix} \mathbf{Q}^{11} & \cdots & \mathbf{Q}^{1n} \\ \vdots & \ddots & \vdots \\ \mathbf{Q}^{n1} & \cdots & \mathbf{Q}^{nn} \end{bmatrix} = \begin{bmatrix} \widehat{\mathbf{EI}}^{1} & 0 & 0 \\ 0 & \cdots & 0 \\ 0 & 0 & \widehat{\mathbf{EI}}^{n} \end{bmatrix} \begin{bmatrix} \mathbf{B}^{11} & \cdots & \mathbf{B}^{1n} \\ \vdots & \ddots & \vdots \\ \mathbf{B}^{n1} & \cdots & \mathbf{B}^{nn} \end{bmatrix} \begin{bmatrix} \mathbf{F}^{11} & \cdots & \mathbf{F}^{1n} \\ \vdots & \ddots & \vdots \\ \mathbf{F}^{n1} & \cdots & \mathbf{F}^{nn} \end{bmatrix} \tag{4}$$

where the elements Q_{io}^{rs} of matrix $\mathbf{Q}^{\mathrm{rs}}$ indicate the production-based emissions of industry *i* (=1,..,m) in region *r* (=1,..,n) led by the final demand type o (=cons, inv) in region *s* (=1,..,n). The summation of $\mathbf{Q}^{\mathrm{rs}}$, $\sum_{\mathrm{s}} \mathbf{Q}^{\mathrm{rs}}$ and $\sum_{\mathrm{r}} \mathbf{Q}^{\mathrm{rs}}$ will give the production-based emissions of region *r* and consumption-based emissions of region *s*, respectively.

Recent years have seen a proliferation of GMRIO tables that are available to analyze the global energy use and emissions issues, such as Eora, WIOD, EXIOBASE, OECD-ICIO, GTAP-MRIO (see Tukker and Dietzenbacher (2013) for a review). Despite difference recipes to construct the data, the insights from different GMRIO tables are similar. Moran and Wood (2014), for example, compared the results of consumption-based carbon accounts based on four GMRIOs: Eora, WIOD, EXIOBASE, and the GTAP-based OpenEU databases. They found that carbon footprint results for most major economies disagree by <10% between GMRIOs, and the results for the temporal change across models appear to agree. As mentioned, our GMRIO database is an inter-country input-output database compiled by OECD. It covers 62 regions (34 OECD regions and 28 non-OECD regions) and 34 industries, and 1995, 2000, 2005, 2008, 2009, 2010, and 2011. In particular, it distinguishes the production of Mexico into global manufacturing (serving as processing production) and non-global manufacturing (serving as domestic production), and that of China into domestic demand, processing exports, and normal exports, because their production recipes and emission intensities are highly different. Therefore, we would have n=65 and m=34 for the intermediate deliveries, and $\mathbf{Q}_{\mathrm{carbon}}^{\mathrm{r}}$ and $\mathbf{EI}^{\mathrm{r}}$ (*r* =1,...,65) as a 1*34 vector, $\mathbf{A}^{\mathrm{rs}}$ and $\mathbf{B}^{\mathrm{rs}}$ (*r*,*s* =1,..,65) as 34*34 matrix, **A** and **B** as 2210*2210 matrix. For the final use, after we aggregate the consumptions and investment, $\mathbf{F}^{\mathrm{rs}}$ (*r* =1,..,65; *s* = 1,...,62) is a 34*1 vector and **F** is a 2210*62 matrix. Unlike the other GMRIO database, the OECD-ICIO are only released in current prices. To convert them into constant prices for our SDA study of the period t0-t1, we followed Lan et al.’s (2016) procedure, i.e. the “convert-first then deflate” procedure (see also Fremdling et al. 2007). That is, after converting the monetary data for each country into U.S. dollars, we used the double-deflation method with sectoral Producer Price Indexes for the US economy and deflated the GMRIO table at year t1 from current price into a constant price of year t0[2]. To avoid uncertainty of deflation over a long period, the base year of constant prices is set at year t0, depending on the period t0-t1. For example, in the process of decomposition over period 2008-2009, the GMRIO table of 2009 is deflated into constant prices of 2008 while the GMRIO table of 2008 is directly adopted.

Regarding CO_2 emissions, we mainly rely on IEA's statistics on CO_2 emissions from fuel combustion and reconcile them into the classification of OECD-ICIO table (IEA, 2014).[3] With respect to the CO_2 emissions by production type for China and Mexico, we adopted the method of Jiang *et al.* (2016) to use intermediate energy in the OECD-ICIO table to proportionally decompose the CO_2 emissions of China (and Mexico) by three (and two) production types for each industry. China's (and Mexico's) disaggregations by production type are calibrated to ensure that a re-aggregation would result in an official release of IEA at the sectoral level. There are two primary-energy-related industries exhibited in the OECD-ICIO table: industry 2, mining and quarrying (C10T14); and industry 7, coke, refined petroleum products and nuclear fuel (C23). The intermediate use of these two industries by production type is used to proportionally separate the corresponding CO_2 emissions in industry *i*. Let (i) θ_{lj}^{s} indicate the intermediate use of energy industries in industry group *j* for the production type *l* in country *s* (= China or Mexico); and (ii) e_j^s indicate the CO_2 emissions in industry group *j* of country *s* (= China or Mexico) taken from IEA, then we can estimate the CO_2 emissions in production type *l* and industry group *j* of country s (= China or Mexico) as $e_{lj}^{s} = \frac{\theta_{lj}^{s}}{\sum_l \theta_{lj}^{s}} \cdot e_j^s \ (s = \text{China or Mexico})$.[4] In a similar vein, the emissions of the Rest of the World (RoW) by industry group can be estimated as well, by disaggregating the total emissions of RoW proportionally according to their intermediate energy

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[2] Please refer to appendix B for our procedure of estimating OECD-ICIO tables in constant prices. For more detail and explanations, please refer to appendix A of Lan et al. (2016).

[3] That means, in this paper we only focus on the CO_2 emissions generated in the productions of goods and services. The CO_2 emissions from land use, forestry, and household activities by combustions of fossil fuels (e.g. driving cars or cooking) are excluded.

[4] Note that our estimations on CO_2 emissions by production type follow the lines of Dietzenbacher et al. (2012) and Jiang et al. (2016), by taking full advantage of intermediate deliveries. One alternative method is proposed by Su et al. (2013) and followed by Su & Thomson (2016), that assumes emission intensities for processing exports would be the same as the representative processing trade regions (such as Guangdong, Fujian and Jiangsu provinces) in China. Comparing with the 2007 estimates reported in Su and Thomson (2016),our emission intensity of processing exports is 0.094 ton CO_2/1000 RMB for year 2008 (vs. 0.089 ton CO_2/1000 RMB for year 2007 in Su and Thomson, 2016), while that of non-processing exports is 0.256 ton CO_2/1000 RMB for year 2008 (vs. 0.232 ton CO_2/1000 RMB in Su and Thomson, 2016).

use by industry group.

2.2. The structural decompositions of global growth of CO_2 emissions in production processes

In this paper, we follow the line of Xu and Dietzenbacher (2014), Arto and Dietzenbacher (2014), and Hoekstra et al. (2016), and decompose the **A**-matrix into technical coefficients and pattern of international source. That is, we define the total technical input coefficients of industry *j* (=1,...,34) in region *s* (=1,...,65) from industry *i* (*i*-input, *i* = 1,...,34) as $a_{ij}^{*s} = \sum_r a_{ij}^{rs}$. In matrix form, the technical input coefficients of region s would be $\mathbf{A}^{*\mathrm{s}} = \begin{bmatrix} a_{11}^{*s} & \cdots & a_{1m}^{*s} \\ \vdots & \ddots & \vdots \\ a_{m1}^{*s} & \cdots & z_{mm}^{*s} \end{bmatrix}$ as a 34*34 matrix. Then, after we horizontally stack the $\mathbf{A}^{*\mathrm{s}}$ matrices and further vertically stack the result 65 times, we would have $\mathbf{A}^{*} = \begin{bmatrix} \mathbf{A}^{*1} & \cdots & \mathbf{A}^{*\mathrm{n}} \\ \vdots & \ddots & \vdots \\ \mathbf{A}^{*1} & \cdots & \mathbf{A}^{*\mathrm{n}} \end{bmatrix}$ as a 2210*2210 matrix. Let $\mathbf{A}^{\mathrm{s}} = \begin{bmatrix} 0 & \cdots & \mathbf{A}^{*\mathrm{s}} & \cdots & 0 \\ \vdots & \ddots & \vdots & & \vdots \\ 0 & & \mathbf{A}^{*\mathrm{s}} & & 0 \\ \vdots & & \vdots & \ddots & \vdots \\ 0 & \cdots & \mathbf{A}^{*\mathrm{s}} & \cdots & 0 \end{bmatrix}$, $\mathbf{A}^{*} = \sum_{\mathrm{s}} \mathbf{A}^{\mathrm{s}}$ is the technical intermediate input coefficients irrespective of the sourcing region.

Let $c_{ij}^{rs} = a_{ij}^{rs} / a_{ij}^{*s}$ indicate the share sourced from region *r* (=1,...,65) in the input a_{ij}^{*s} in region *s* (=1,...,65); then in the matrix form, we would have $\mathbf{C}^{\mathrm{rs}} = \begin{bmatrix} c_{11}^{rs} & \cdots & c_{1m}^{rs} \\ \vdots & \ddots & \vdots \\ c_{m1}^{rs} & \cdots & c_{mm}^{rs} \end{bmatrix}$ as a 34*34 matrix (where $\sum_r c_{ij}^{rs} = 1$), and $\mathbf{C} = \begin{bmatrix} \mathbf{C}^{11} & \cdots & \mathbf{C}^{1\mathrm{n}} \\ \vdots & \ddots & \vdots \\ \mathbf{C}^{\mathrm{n}1} & \cdots & \mathbf{C}^{\mathrm{nn}} \end{bmatrix}$ as a 2210*2210 matrix, to reflect the pattern of international sourcing. Then the A-matrix can be decomposed as

$$\mathbf{A} = \mathbf{C} \otimes \left(\sum\nolimits_{\mathrm{s}} \mathbf{A}^{\mathrm{s}}\right) \tag{5}$$

where $\otimes$ stands for the Hadamard product.

Moreover, we can split the **C**-matrix into sub-matrices for each region s (=1,...,65). Let $\mathbf{C}^{\mathrm{S}} = \begin{bmatrix} 0 & \cdots & \mathbf{C}^{1\mathrm{s}} & \cdots & 0 \\ \vdots & \ddots & \vdots & & \vdots \\ 0 & & \mathbf{C}^{\mathrm{ss}} & & 0 \\ \vdots & & \vdots & \ddots & \vdots \\ 0 & \cdots & \mathbf{C}^{65,\mathrm{s}} & \cdots & 0 \end{bmatrix}$, we would have $\mathbf{C} = \sum_{\mathrm{s}} \mathbf{C}^{\mathrm{S}}$. As a further step, the $\mathbf{C}^{\mathrm{s}}$-matrices can be subdivided by source country, i.e. according to the origin of the intermediate inputs. We firstly separate the domestic shares of regions s as $\mathbf{C}^{\mathrm{s}}_{\mathrm{dom}} = \begin{bmatrix} 0 & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & & & \vdots \\ 0 & & \mathbf{C}^{\mathrm{ss}} & & 0 \\ \vdots & & & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & 0 \end{bmatrix}$, then we classify other countries according to OECD definition, i.e. OECD (also known as high-income) and non-OECD (also known as low-income) countries. That is, $\mathbf{C}^{\mathrm{s}}_{\mathrm{oecd}} = \begin{bmatrix} 0 & \cdots & \mathbf{C}^{\mathrm{1s}} & \cdots & 0 \\ \vdots & \ddots & \vdots & & \vdots \\ 0 & & \mathbf{C}^{\mathrm{35,s}} & & 0 \\ \vdots & & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & 0 \end{bmatrix}$ and $\mathbf{C}^{\mathrm{s}}_{\mathrm{noecd}} = \begin{bmatrix} 0 & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & & \vdots \\ 0 & & \mathbf{C}^{\mathrm{36,s}} & & 0 \\ \vdots & & \vdots & \ddots & \vdots \\ 0 & \cdots & \mathbf{C}^{\mathrm{65,s}} & \cdots & 0 \end{bmatrix}$, in which the sub-matrix $\mathbf{C}^{\mathrm{ss}}$ is replaced by zeros. These three submatrices by type of source country can be summed such that $\mathbf{C}^{\mathrm{s}}_{\mathrm{dom}} + \mathbf{C}^{\mathrm{s}}_{\mathrm{oecd}} + \mathbf{C}^{\mathrm{s}}_{\mathrm{noecd}} = \mathbf{C}^{\mathrm{s}}$. Overall, the submatrices sum to $\mathbf{C}$:

$$\textstyle\sum_{\mathrm{s}}(\mathbf{C}^{\mathrm{s}}_{\mathrm{dom}} + \mathbf{C}^{\mathrm{s}}_{\mathrm{oecd}} + \mathbf{C}^{\mathrm{s}}_{\mathrm{noecd}}) = \mathbf{C} \tag{6}$$

The Leontief inverse can be rewritten as:

$$\mathbf{B} = [\mathbf{I} - \textstyle\sum_{\mathrm{s}}(\mathbf{C}^{\mathrm{s}}_{\mathrm{dom}} + \mathbf{C}^{\mathrm{s}}_{\mathrm{oecd}} + \mathbf{C}^{\mathrm{s}}_{\mathrm{noecd}}) \otimes (\sum_{\mathrm{s}} \mathbf{A}^{\mathrm{s}})]^{-1} \tag{7}$$

In a similar fashion, the final demand can be decomposed into the determinants of total final demand and the pattern of sourcing. Let $y_i^{*s} = \sum_r y_i^{rs}$ indicate the total final demand in region *s* for output of industry *i* from all source regions, $h_i^{rs} = y_i^{rs}/y_i^{*s}$ indicate the share sourced from region *r* (=1,...,65, including the exports-oriented production types of China and Mexico) in the final demand of region *s* (=1,...,62) for output in industry *i* (=1,...,34), and define the matrices $\mathbf{H}^{\mathrm{s}}_{\mathrm{dom}}$, $\mathbf{H}^{\mathrm{s}}_{\mathrm{oecd}}$and $\mathbf{H}^{\mathrm{s}}_{\mathrm{noecd}}$. Correspondingly, the final demand can be decomposed as

$$\mathbf{F} = \textstyle\sum_{\mathrm{s}}(\mathbf{H}^{\mathrm{s}}_{\mathrm{dom}} + \mathbf{H}^{\mathrm{s}}_{\mathrm{oecd}} + \mathbf{H}^{\mathrm{s}}_{\mathrm{noecd}}) \otimes \mathbf{Y}^{*} \tag{8}$$

Furthermore, the $\mathbf{Y}^{*}$ matrix can be written as the product of $\mathbf{V}$ and $\mathbf{Y}$. Let $\mathbf{Y} = \begin{bmatrix} y^{*1} \\ \vdots \\ y^{*s} \\ \vdots \\ y^{*n} \end{bmatrix}$ with y^{*s} is the region s' final demand, $\mathbf{V} = \begin{bmatrix} \mathbf{V}^{11} & \cdots & \mathbf{V}^{1\mathrm{n}} \\ \vdots & \ddots & \vdots \\ \mathbf{V}^{\mathrm{n}1} & \cdots & \mathbf{V}^{\mathrm{nn}} \end{bmatrix}$ with $\mathbf{V}^{\mathrm{s}} = \begin{bmatrix} v_1^s \\ \vdots \\ v_i^s \\ \vdots \\ v_n^s \end{bmatrix}$ and $v_i^s = y_i^{*s}/y^{*s}$.

Then we would have

$$\mathbf{Y}^{*} = \mathbf{V} \cdot \mathbf{Y} = \left(\sum\nolimits_{s} \mathbf{V}^{s}\right)\left(\sum\nolimits_{s} \mathbf{Y}^{s}\right) \tag{9}$$

The CO_2 emissions across regions in time t1 then can be traced as:

$$\begin{bmatrix} \mathbf{Q}_{t1}^{11} & \cdots & \mathbf{Q}_{t1}^{1n} \\ \vdots & \ddots & \vdots \\ \mathbf{Q}_{t1}^{n1} & \cdots & \mathbf{Q}_{t1}^{nn} \end{bmatrix} = \begin{bmatrix} \widehat{\mathbf{EI}}_{t1}^{1} & 0 & 0 \\ 0 & \cdots & 0 \\ 0 & 0 & \widehat{\mathbf{EI}}_{t1}^{n} \end{bmatrix} \cdot \left[\mathbf{I} - \sum\nolimits_{s}\left(\mathbf{C}_{\mathrm{dom}}^{s,t1} + \mathbf{C}_{\mathrm{oecd}}^{s,t1} + \mathbf{C}_{\mathrm{noecd}}^{s,t1}\right) \otimes \left(\sum\nolimits_{s} \mathbf{A}_{t1}^{s}\right)\right]^{-1} \cdot$$

$$\sum\nolimits_{s}\left(\mathbf{H}_{\mathrm{dom}}^{s,t1} + \mathbf{H}_{\mathrm{oecd}}^{s,t1} + \mathbf{F}_{\mathrm{noecd}}^{s,t1}\right) \otimes \left(\sum\nolimits_{s} \mathbf{V}_{t1}^{s}\right)\left(\sum\nolimits_{s} \mathbf{Y}_{t1}^{s}\right) \tag{10}$$

$$= f\left(\mathbf{EI}, \mathbf{C}_{\mathrm{dom}}, \mathbf{C}_{\mathrm{oecd}}, \mathbf{C}_{\mathrm{noecd}}, \mathbf{A}, \mathbf{H}_{\mathrm{dom}}, \mathbf{H}_{\mathrm{oecd}}, \mathbf{H}_{\mathrm{noecd}}, \mathbf{V}, \mathbf{Y}\right)$$

where the summations $\sum_{s} \mathbf{Q}^{rs}$ and $\sum_{r} \mathbf{Q}^{rs}$ give the production-based emissions of region *r* and consumption-based emissions of region *s*, respectively. Given *n* factors, there would be *n*! types of decompositions. In this paper, we adopt the recommendation of Dietzenbacher and Bart (1998), and employ the average of two polar decomposition formulae to decompose the global growth of CO_2 emission into each determinant. In addition, it is possible to isolate the impact of changes of any factor in country *s* on global/regional CO_2 emissions based on the decompositions. Please refer to appendix A for the detailed formula.

3. Empirical Results

3.1 Decomposition results of global growth of CO_2 emissions

As aforementioned, we mainly focused on the growth of CO_2 emissions after the financial crisis. That is, we decomposed the growth of CO_2 emissions for the sub-period 2008–2009, 2009–2010, and 2010–2011. For comparison, the decompositions of emissions growth from 2000 to 2008, before the crisis, are included. Figure 1a presents the impacts of 6 factors that are related to the international trade patterns, including the share of intermediates from domestically produced, OECD and non-OECD countries, $\mathbf{D}_{\mathbf{C}_{\mathrm{dom}}}$, $\mathbf{D}_{\mathbf{C}_{\mathrm{oecd}}}$ and $\mathbf{D}_{\mathbf{C}_{\mathrm{noecd}}}$; and the share of final demand from domestically produced, OECD and non-OECD countries, $\mathbf{D}_{\mathbf{H}_{\mathrm{dom}}}$, $\mathbf{D}_{\mathbf{H}_{\mathrm{oecd}}}$ and $\mathbf{D}_{\mathbf{H}_{\mathrm{noecd}}}$. Their respective totals, i.e. the impact due to change in purchase of intermediate $\mathbf{D}_{\mathbf{C}} = \mathbf{D}_{\mathbf{C}_{\mathrm{dom}}} + \mathbf{D}_{\mathbf{C}_{\mathrm{oecd}}} + \mathbf{D}_{\mathbf{C}_{\mathrm{noecd}}}$ and the impact due to change in purchase of final demand $\mathbf{D}_{\mathbf{H}} = \mathbf{D}_{\mathbf{H}_{\mathrm{dom}}} + \mathbf{D}_{\mathbf{H}_{\mathrm{oecd}}} + \mathbf{D}_{\mathbf{H}_{\mathrm{noecd}}}$, are also included. Figure 1b presents the impact of changes in the remaining 4 factors, including the emission intensity $\mathbf{D}_{\mathrm{EI}}$, production recipe indicated by technical input coefficients matrix $\mathbf{D}_{\mathrm{A}}$, structure of final demand $\mathbf{D}_{\mathrm{V}}$, and volume of total final demand $\mathbf{D}_{\mathrm{Y}}$. The net global growth of CO_2 emissions is also included.

INSERT FIGURE 1 ABOUT HERE

The global CO_2 emissions from production processes dropped by 206 Mt from 2008 to 2009, and then skyrocketed by 1711 and 1213 Mt from 2009 to 2010 and from 2010 to 2011, respectively. The degree of annual emissions growth from 2009 to 2011 is much higher than is that before the crisis, i.e., from 2000 to 2008. Even considering the drop from 2008 to 2009, the net annual emissions growth from 2008 to 2011 is still larger than is that before the crisis.

Further decompositions show that the difference before and after the crisis mainly lies in the changes of emission intensity and trade pattern of intermediates. Changes of emission intensity dominated the decrease of CO_2 emissions from 2000 to 2008, leading to reductions of 1781 and 2631 Mt of global emissions for the periods 2000-2005 and 2005-2008, respectively, which largely offset the increase driven by growth of final demand. Ever since 2009, however, changes in emission intensity have led to increases of CO_2 emissions by 180 and 319 Mt for the periods 2009–2010 and 2010–2011, respectively. Together with the growth of final demand, they jointly led to the total net emissions growth. This finding is in line with other SDA literatures that cover the period before and after crisis, such as Malik and Lan (2016), Jiang and Guan (2016).

Another factor showing a different effect before and after the crisis is the domestic share of intermediates and final products. Before the international crisis, the change of domestic share of intermediates led to decreases of CO_2 emissions by 524 Mt and 388 Mt for the periods 2000–2005, and 2005–2008, respectively. This suggests that either high-intensive countries (often non-OECD countries) decreased their domestic share of intermediate usage, or low-intensive countries (often OECD countries) increased their domestic share of intermediate usage. On the contrary, during the crisis of 2008–2009, the change of domestic share of intermediate ($\mathbf{C}_{\mathrm{dom}}$) led to an increase of CO_2 emissions by 887 Mt. Although this reverted to negative after 2009, the overall effect for the period 2008–2011 was positive, leading to an increase by 283 Mt from 2008 to 2011. The change of domestic share of final products $(\mathbf{H}_{\mathrm{dom}})$ also shows different signs of effects on the change of CO_2 emissions. Before the crisis, from 2000 to 2008, the change of $\mathbf{H}_{\mathrm{dom}}$ led to 184 and 133 Mt decreases of CO_2 emissions from 2000 to 2005, and from 2005 to 2008, respectively. After the crisis, from 2008 to 2011, the change of $\mathbf{H}_{\mathrm{dom}}$ led to an increase of 64 Mt CO_2 emissions. This suggested that, after the crisis either non-OECD countries turned to purchase intermediates and final products domestically, or OECD countries turned to outsource their intermediates and final demand (see also Peters et al., 2012).

The remaining factors contributed to the overall changes of CO_2 emissions very similarly, with some minor differences in magnitude before and after the crisis. For example, non-OECD countries expanded their share of exports in both intermediate and final products (WTO, 2015). Consequently, the change of the share of intermediates from non-OECD countries has always led to increases of CO_2 emissions, of 862 Mt, 711 Mt, and 21 Mt for the sub-periods 2000–2005, 2005–2008, and 2008–2011, respectively (see also Hoekstra et al., 2016). The intermediate trade has long been dominated by production fragmentation and the resultant intermediate exports across countries (WTO, 2013). Such decrease in share of intermediates from non-OECD countries implies that the international fragmentation that was mainly led by developed OECD countries has seriously slowed down after the crisis. On the contrary, the change of share of final demand from non-OECD countries has continuously led to increases of CO_2 emissions of 420 Mt, 348 Mt, and 238 Mt, respectively, for the same sub-periods of 2000–2011. Unlike intermediate trade, the source of final demand is mainly influenced by consumer preference. Thus, there is barely change in the share of final products by country and it shows similar effects both before and after the crisis.

3.2 The decomposition results of regional production-based growth of CO_2 emissions, 2008–2011

In this section, we further decomposed the production-based growth of CO_2 emissions by region for the period 2008–2011. The idea is to isolate the effects of each factor on different countries/regions. As final demand is the major driving force of increase in emissions growth, we separate the final demand and its structure into four categories, consumptions by OECD and non-OECD countries, and investment by OECD and non-OECD countries. In this way, the regional growth of CO_2 emissions has been decomposed into 19 factors. For simplicity, we only list the regions for which production-based CO_2 emissions' changes are larger than 10 Mt from 2008 to 2011.

INSERT FIGURE 2 ABOUT HERE

The first observation of fig. 2 is that regions with positive growth of CO_2 emissions in production process from 2008 to 2011 are mostly non-OECD economies, and the regions with negative emissions growths are mostly OECD economies (see also Jiang and Guan, 2016). Among them, the domestic productions of China dominated the global growth of CO_2 emissions, by contributing a 1453 Mt of net growth, while it is followed by India, Korea, Russia, and Saudi Arabia. On the contrary, USA dominated the global CO_2 emissions reduction, by contributing a 271 Mt of net reduction, while it is followed by UK, Spain, Italy, and non-processing exports of China.

The major driving forces behind the growth of CO_2 emissions for most non-OECD economies are their own domestic consumption and investment need, indicated as green and purple shaded bars in fig. 2a-2b. Among these, investment demand surpassed consumption demand as the largest driving force of China's domestic production-led growth of CO_2 emissions (China-D). China launched a 4 trillion RMB stimulus package against the economic downtown at the end of 2008. Over half of the money was spent on general and rural infrastructure construction. The investment demand of China alone caused China's own CO_2 emissions to increase by 1841 Mt from 2008 to 2011. In contrast, for most other non-OECD economies, consumption demand by themselves and other non-OECD economies was still the dominant driving force of their emissions' growth. One exception is the non-global manufacturing production of Mexico

(Mexico-NGM), for which the consumptions of OECD economies increased its emissions. Although the NGM productions of Mexico do not directly serve as the final demand of OECD economies, they provide intermediates indirectly for its production chains. This suggested that the demand on intermediates produced by Mexico did not be influenced by the international financial crisis, as a result the emissions increased.

Except for the final demand, the changes in production recipe (i.e. technical input matrix A) also led to considerable growth of CO_2 emissions in a few non-OECD economies, such as Russia, South Africa, and Turkey, and in most OECD economies (fig. 2a-2c). In general, the intermediate input ratio would experience an inverse U-shape of change with the economic development from the transition from labor-intensive economy, to industrialized economy, and further to service-based economy (Shishido et al., 2000). The positive contributions of technical input matrix on growth of CO_2 emissions imply that for these economies, the intermediate inputs per output have started to decrease with the transition of service-based economy. Conversely, most non-OECD economies, such as South Arabia, Indonesia, Brazil, and Thailand, in addition to China's domestic production, are still at the first stage of a U-shape, experiencing an increase of intermediate input ratios and the consequent positive contributions from input ratios on growth of CO_2 emissions.

With respect to emission intensity, as mentioned earlier, the overall decrease has been slowed down after the crisis. The decompositions also verified such a trend, as the negative contributions from emission intensity (D_{CA}) are much smaller than are the positive contributions driven by changes in consumption and investment. In some countries, such as the US and France, the changes in emission intensity even led to a weak increase of CO_2 emissions. This is in line with Feng et al. (2015), who found that rising energy intensity, together with increasing population and consumption volume, has driven an increase in the US's CO_2 emissions between 2009 and 2011.[5]

Conversely, the change of domestic share in intermediate trade led to a 283 Mt increase from 2008 to 2011. Figs. 2d-2f suggest that such change mainly happened in some non-OECD economies, such as China, Saudi Arabia, and South Africa. Among these, the domestic sales

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[5] Note that Feng et al. (2015) decomposed the US CO2 emissions from 1997 to 2013 and found that the decrease of energy intensity and changes in fuel mix (mainly driven by affluent shale gas) decreased the emissions significantly from 2011 to 2013. Our period, however, only covered 2000–2011.

production of China (China-D) has significantly shifted its intermediates from imports to domestic products. Given the high-energy intensity and high dependency on coal as primary energy inputs of China, such change alone has led to a 305 Mt increase in China's CO_2 emissions (see also Su and Thomson, 2016). Most OECD and non-OECD economies have been continuously decreasing their requirement share on domestic intermediates. However, the magnitude of this change is relatively minor and only partly offsets the increase driven by growing final demand worldwide.

The shares of OECD and non-OECD economies in the global trade market have also changed. Figs. 2d-2f suggest that changes in shares of intermediate and consumptions purchased from non-OECD economies has considerably increased the CO_2 emissions in most economies. This is in line with the trend that non-OECD economies have continuously expanded their share in international trade, even after the crisis (see also WTO, 2013). Note that the non-processing export productions of China (China-NP) show a quite different trend. The production-based CO_2 emissions from China's non-processing production experienced a decrease, which is mainly attributable to the decrease in share of intermediates of non-OECD economies ('share of intermediates from non-OECD economies', i.e. $\mathbf{D}_{\mathbf{C}_{\mathrm{noecd}}}$ as shown in fig. 2f). While most non-OECD economies, such as India, Indonesia, South Africa, Vietnam, Thailand, and Malaysia have expanded their shares in the global intermediate trade by showing positive in $\mathbf{D}_{\mathbf{C}_{\mathrm{noecd}}}$, China seems to have lost its share by showing negative in $\mathbf{D}_{\mathbf{C}_{\mathrm{noecd}}}$. As mentioned earlier, with increasing labor and land costs China is becoming less attractive to inflow of foreign direct investment. There are signs that the global value chain is shifting to less developing areas, such as South Asia and Africa (see also, Lehmann, 2012; Stratfor, 2013; AfDB, OECD, and UNDP, 2014). Such change has decreased China's emissions, but it has increased emissions in the corresponding regions that undertook the shares. In sum, the changes of share of intermediate and final products of non-OECD economies have increased global CO_2 emissions by 259 Mt.

3.3 The decomposition results of consumption-based growth of CO_2 emissions, by source region, 2008–2011

In section 3.2 we decomposed the impact of global changes in 19 factors such as demand, trade pattern, and emission intensity on the regional production-based CO_2 emissions. The literature have revealed considerable carbon leakage from OECD economies to non-OECD economies via international trade (see, e.g. Douglas & Nishioka, 2009; Davis and Caldrin, 2011; Peters et al., 2011; Malik and Lan, 2016). Therefore, in this section, we decompose the consumption-based CO_2 emissions by region, that is, analyzing the global CO_2 emissions' change due to changes of each factor in one specific region. Thus, the factors have a different meaning to that under production-based accounting. For example, the impact due to changes in total consumption of China under production-based accounting explains the impact of changes of *global* consumption demand on *China*'s emissions within its own territory; under consumption-based accounting it explains the impact of changes of *China*'s consumption demand on *global* emissions. In addition, only the final demand of region *s* would influence its consumption-based CO_2 emissions. As a result, the final demand and its structure can only be separated into two categories, i.e., consumption and investment, rather than four categories under production-based accounting. Consequently the regional growth of CO_2 emissions under consumption-based accounting would be decomposed into 15 factors, rather than 19 factors under production-based accounting. For simplification, we only consider the regions for which the total emissions changes are larger than 10 Mt for 2008–2011, as was done in section 3.2.

Figure 3 present our results. The first observation of fig. 3 is that regions that dominated the global growth of CO_2 emissions/reductions are similar under consumption-based and production-based accounting. As in consumption-based accounting, regions with positive growth of CO_2 emissions from 2008 to 2011 are mostly non-OECD economies (figs. 3a-3b, 3d-3e), and the regions with negative emissions growths are mostly OECD economies (figs. 3c and 3f). Among these, the increasing demand of China still dominated the global consumption-based growth of CO_2 emissions, contributing 1310 Mt of net CO_2 growth, while the change of demand from the US still dominated the CO_2 emissions reduction, contributing 282 Mt of net reduction. Even when carbon leakage is taken into account, the global CO_2 emissions after the crisis in 2008 are largely attributable to non-OECD economies.

INSERT FIGURE 3 ABOUT HERE

However, the decomposition results provide some new insights. Regarding final demand, while the changes in consumption in most OECD and non-OECD economies have been the major driving force increasing their consumption-based CO_2 emissions, the changes in investment have caused different effects across economies. In all OECD economies for which consumption-based CO_2 emissions reductions are larger than 10 Mt, e.g., USA, Spain, UK, Italy, France, Germany, and Denmark, investment shrank after the crisis and, consequently, reduced their consumption-based CO_2 emissions. Conversely, the change in investment has been the major driving force in consumption-based growth of CO_2 emissions of most non-OECD economies. In some countries, such as China and India, investment even surpassed consumption as the leading driving force behind their growth of CO_2 emissions (see also Jiang and Guan, 2016).

The structure of demand also plays different roles among OECD and non-OECD economies. The changes in structure of consumption in OECD economies have led to considerable reductions for their consumption-based CO_2 emissions (fig. 3c). The changes have also led to reductions of consumption CO_2 emissions in some non-OECD economies, such as China and India, but the magnitudes are negligible. In most non-OECD economies, such as South Africa, Vietnam, Turkey, Russia, Saudi Arabia and Thailand, the change in structure of consumption has still led to net growth of CO_2 emissions worldwide. The changes in production recipe (technical inputs matrix A) show similar results. These have led to considerable reductions in consumption-based CO_2 emissions for most OECD economies, whereas they have led to growth in most non-OECD economies. In general, OECD economies have a less carbon-intensive life style, with higher shares of services expenditure, while non-OECD economies are still obsessed by basic living needs, with higher shares of goods expenditure. Given the fact that the decreases in emission intensity of most non-OECD economies are not significant enough to offset the effect of growing demand on emissions growth, it is reasonable to deduce that non-OECD economies have been the leading force for global growth of CO_2 emissions after the crisis.

With respect to trade patterns, compared with production basis, we argue that the effects of trade patterns under consumption basis (as shown in figs. 3c-3f) reflect better the changes of trade led by specific economies. The change of shares in intermediate trade from OECD ($\mathbf{D}_{\mathbf{C}_{\mathrm{oecd}}}$) in China under a production basis, for example, reflects the effects of changes in the share of all OECD economies on China's intermediates on emissions, while the change under a consumption basis reflects the effects of changes in the share of China's demand on OECD's intermediates on emissions.

More specifically, fig. 3f suggested that most OECD economies have tended to increase their domestic shares and shares from non-OECD economies in both intermediate and final products after the crisis. Such changes have been indicated as positive contributions of the domestic share in the international trade of both intermediate and final products' trade and negative contributions of non-OECD share in the international trade of both intermediate and final products. This is because OECD economies have generally lower emission intensity than non-OECD economies. Consequently, the increasing share of domestic products, rather than imports, has decreased the consumption-based emissions for most OECD economies, and the increasing share of non-OECD's products has increased these economies' consumption-based emissions.

The non-OECD economies show a different trend. Some of them, such as China, Saudi Arabia, and South Africa, have significantly increased their domestic shares in intermediate and final products. Such changes have been indicated as positive contributions of domestic shares in increasing these economies' consumption-based emissions. Most remaining non-OECD economies, such as India, Brazil, Turkey, Thailand, and Mexico, have significantly decreased their domestic shares but increased their shares of intermediate and final products from other non-OECD economies. Such changes have been indicated as negative contributions of domestic shares and positive contributions of non-OECD shares in increasing these economies' consumption-based emissions.

4. Conclusion and Policy Implications

In this paper, we employed structural decomposition analysis to explore the forces driving rapid increases in global CO_2 emissions from both production-based and consumption-based aspects for the post-crisis era, 2008–2011. The results suggest that emerging non-OECD economies are the major driving forces of global growth of CO_2 emissions. More specifically, the increasing consumptions and investment need, as well as stagnation of emission intensity reductions, of emerging non-OECD economies have largely contributed to global growth of CO_2 emissions. On the contrary, advanced OECD economies have a lower carbon-intensive life style. Coupled with decreases in investment need and stagnation of consumption need, the advanced economies have successfully reduced both their production-based and their consumption-based emissions.

In the process, the new trend of international trade has also considerably shaped global growth of CO_2 emissions. Most OECD economies, and some non-OECD economies (such as China and South Africa), have started to increase their domestic shares in intermediates and final products after the crisis. In particular, the increasing domestic share of non-OECD economies has led to a 413 Mt increase of global production-based CO_2 emissions from 2008 to 2011. In addition, most non-OECD economies have increased their shares of non-OECD's productions of intermediate and final products, with the result that global production-based CO_2 emissions have increased by 260 Mt for the same period. The international trade has apparently experienced a geographic shift from OECD economies to non-OECD economies such as China with lower labor costs (see also Jiang and Chris, 2017). Furthermore, there are signs of a further geographic shift to even less-developed countries in South Asia and Africa (see also, Lehmann, 2012; Stratfor, 2013; AfDB, OECD and UNDP, 2014). In spite of rapid improvement, the emission intensity of non-OECD economies is still much higher than that of OECD economies (Jiang and Guan, 2016). In this context, such change of geographic shift in international trade may loom the climate change mitigation seriously.

Although our decompositions are only for the period 2008–2011, we argue that our results can be extended for the near future. Very recently, there has been evidence of stagnation of the global growth of CO_2 emissions, which increased by only 36 Mt from 2014 to 2015 (BP, 2016). The OECD economies have *reduced* their production-based emissions by 146 Mt, while the non-OECD economies *increased* theirs by 182 Mt. The leading role of non-OECD economies in global growth of CO_2 emissions has been sustained (BP, 2016).

More importantly, it is highly probable that the driving force leading to the global growth of CO_2 emissions will be sustained. On one hand, the factors that have led to growth of CO_2 emissions, such as increased purchase of goods from emerging non-OECD economies, driven mainly by lower costs and higher profits, or increased investment and consumption demand in non-OECD economies, which are crucial for improving the living standard in these emerging countries, are unlikely to undergo any changeover in the near future. Moreover, as recently China established the Asian Infrastructure Investment Bank (AIIB), in addition to current World Bank and Asian Development Bank (ADB), that are dedicated to infrastructure investment support for underdevelopment regions, there might be some additional growth of CO_2 emissions caused by the construction of operation of these infrastructures. On the other hand, the further changes of factors that lead to reductions of CO_2 emissions, such as a decrease in emission intensity, become more difficult to maintain. Emission intensity is determined by both fuel mix and energy intensity. For fuel mix, BP statistics (BP, 2016) shows that the share of fossil fuels (i.e. coal, oil and gas) in global primary energy consumptions remained almost unchanged in past decades, fluctuated from 86.97% in 2001 to 86.02% in 2015. Feng et al. (2015) also found that the shift from coal to natural gas has played a very limited role in decreasing the USA's CO_2 emissions in recent years. With respect to energy intensity, although the aspirations of technology transfer from advanced OECD economies to emerging non-OECD economies have been apparent for years, the gap has remained.

These observations suggest that, instead of focusing on emission reduction commitments, global climate change mitigation efforts should focus much more on commitments to both technology transfer and the successful development of new, scalable low-carbon energy sources and technologies, without which any international agreement to reduce global emissions will not be credible.

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Appendix A. The decomposition formula

A.1 The decomposition formula of global CO_2 emissions change

The global CO_2 emissions change for the period t0-t1 can be decomposed into impact by 10 factors. Let $\mathbf{D}_{\mathrm{EI}}$ represent the impact of changes in emissions intensity, $\mathbf{D}_{\mathbf{C}_{\mathrm{dom}}}$ represent the impact of changes in domestic shares in intermediate inputs, $\mathbf{D}_{\mathbf{C}_{\mathrm{oecd}}}$ represent the impact of changes in shares of OECD countries in providing intermediate inputs (excl. domestically provided), $\mathbf{D}_{\mathbf{C}_{\mathrm{noecd}}}$ represent the impact of changes in shares of non-OECD countries in providing intermediate inputs (excl. domestically provided), $\mathbf{D}_{\mathrm{A}}$ represent the impact of changes in technical intermediate input coefficients, $\mathbf{D}_{\mathbf{H}_{\mathrm{dom}}}$ represent the impact of changes in domestic share of final products, $\mathbf{D}_{\mathbf{H}_{\mathrm{oecd}}}$ represent the impact of changes in share of OECD countries in providing final products (excl. domestically provided), $\mathbf{D}_{\mathbf{H}_{\mathrm{noecd}}}$ represent the impact of changes in share of non-OECD countries in providing final products (excl. domestically provided), $\mathbf{D}_{\mathrm{V}}$ represent the impact of structural change of final demand by 34 industries, $\mathbf{D}_{\mathrm{Y}}$ represent the impact of changes in total volumes of final demand. The effects of each of the 10 factors on global CO_2 emissions change for the period t0-t1 can be calculated as follows:

$$\mathbf{D}_{\mathrm{EI}} = \frac{1}{2}(\mathbf{EI}_{\mathrm{t1}} - \mathbf{EI}_{\mathrm{t0}}) \cdot [(\mathbf{I} - \mathbf{C}_{\mathrm{t1}} \otimes \mathbf{A}^{*}_{\mathrm{t1}})^{-1} \cdot \mathbf{H}_{\mathrm{t1}} \otimes \mathbf{V}_{\mathrm{t1}} \cdot \mathbf{Y}_{\mathrm{t1}} + (\mathbf{I} - \mathbf{C}_{\mathrm{t0}} \otimes \mathbf{A}^{*}_{\mathrm{t0}})^{-1} \cdot \mathbf{H}_{\mathrm{t0}} \otimes \mathbf{V}_{\mathrm{t0}} \cdot \mathbf{Y}_{\mathrm{t0}}] \qquad \text{(A.1)}$$

$$\mathbf{D}_{\mathbf{C}_{\mathrm{dom}}} = \frac{1}{2}\mathbf{EI}_{\mathrm{t0}} \cdot \begin{bmatrix} \left(\mathbf{I} - \sum_{\mathrm{s}}\left(\mathbf{C}^{\mathrm{s,t1}}_{\mathrm{dom}} + \mathbf{C}^{\mathrm{s,t1}}_{\mathrm{oecd}} + \mathbf{C}^{\mathrm{s,t1}}_{\mathrm{noecd}}\right) \otimes \mathbf{A}^{*}_{\mathrm{t1}}\right)^{-1} \\ -\left(\mathbf{I} - \sum_{\mathrm{s}}\left(\mathbf{C}^{\mathrm{s,t0}}_{\mathrm{dom}} + \mathbf{C}^{\mathrm{s,t1}}_{\mathrm{oecd}} + \mathbf{C}^{\mathrm{s,t1}}_{\mathrm{noecd}}\right) \otimes \mathbf{A}^{*}_{\mathrm{t1}}\right)^{-1} \end{bmatrix} \cdot \mathbf{H}_{\mathrm{t1}} \otimes \mathbf{V}_{\mathrm{t1}} \cdot \mathbf{Y}_{\mathrm{t1}} \qquad \text{(A.2)}$$

$$+\frac{1}{2}\mathbf{EI}_{\mathrm{t1}} \cdot \begin{bmatrix} \left(\mathbf{I} - \sum_{\mathrm{s}}\left(\mathbf{C}^{\mathrm{s,t1}}_{\mathrm{dom}} + \mathbf{C}^{\mathrm{s,t0}}_{\mathrm{oecd}} + \mathbf{C}^{\mathrm{s,t0}}_{\mathrm{noecd}}\right) \otimes \mathbf{A}^{*}_{\mathrm{t0}}\right)^{-1} \\ -(\mathbf{I} - \sum_{\mathrm{s}}\left(\mathbf{C}^{\mathrm{s,t0}}_{\mathrm{dom}} + \mathbf{C}^{\mathrm{s,t0}}_{\mathrm{oecd}} + \mathbf{C}^{\mathrm{s,t0}}_{\mathrm{noecd}}\right) \otimes \mathbf{A}^{*}_{\mathrm{t0}})^{-1} \end{bmatrix} \cdot \mathbf{H}_{\mathrm{t0}} \otimes \mathbf{V}_{\mathrm{t0}} \cdot \mathbf{Y}_{\mathrm{t0}}$$

$$\mathbf{D}_{\mathbf{C}_{\mathrm{oecd}}} = \frac{1}{2}\mathbf{EI}_{\mathrm{t0}} \cdot \begin{bmatrix} \left(\mathbf{I} - \sum_{\mathrm{s}}\left(\mathbf{C}^{\mathrm{s,t0}}_{\mathrm{dom}} + \mathbf{C}^{\mathrm{s,t1}}_{\mathrm{oecd}} + \mathbf{C}^{\mathrm{s,t1}}_{\mathrm{noecd}}\right) \otimes \mathbf{A}^{*}_{\mathrm{t1}}\right)^{-1} \\ -\left(\mathbf{I} - \sum_{\mathrm{s}}\left(\mathbf{C}^{\mathrm{s,t0}}_{\mathrm{dom}} + \mathbf{C}^{\mathrm{s,t0}}_{\mathrm{oecd}} + \mathbf{C}^{\mathrm{s,t1}}_{\mathrm{noecd}}\right) \otimes \mathbf{A}^{*}_{\mathrm{t1}}\right)^{-1} \end{bmatrix} \cdot \mathbf{H}_{\mathrm{t1}} \otimes \mathbf{V}_{\mathrm{t1}} \cdot \mathbf{Y}_{\mathrm{t1}} \qquad \text{(A.3)}$$

$$+\frac{1}{2}\mathbf{EI}_{\mathrm{t1}} \cdot \begin{bmatrix} \left(\mathbf{I} - \sum_{\mathrm{s}}\left(\mathbf{C}^{\mathrm{s,t1}}_{\mathrm{dom}} + \mathbf{C}^{\mathrm{s,t1}}_{\mathrm{oecd}} + \mathbf{C}^{\mathrm{s,t0}}_{\mathrm{noecd}}\right) \otimes \mathbf{A}^{*}_{\mathrm{t0}}\right)^{-1} \\ -(\mathbf{I} - \sum_{\mathrm{s}}\left(\mathbf{C}^{\mathrm{s,t1}}_{\mathrm{dom}} + \mathbf{C}^{\mathrm{s,t0}}_{\mathrm{oecd}} + \mathbf{C}^{\mathrm{s,t0}}_{\mathrm{noecd}}\right) \otimes \mathbf{A}^{*}_{\mathrm{t0}})^{-1} \end{bmatrix} \cdot \mathbf{H}_{\mathrm{t0}} \otimes \mathbf{V}_{\mathrm{t0}} \cdot \mathbf{Y}_{\mathrm{t0}}$$

$$\mathbf{D}_{\mathbf{C}_{\mathrm{noecd}}} = \frac{1}{2}\mathbf{EI}_{\mathrm{t0}} \cdot \begin{bmatrix} \left(\mathbf{I} - \sum_{\mathrm{s}}\left(\mathbf{C}_{\mathrm{dom}}^{\mathrm{s,t0}} + \mathbf{C}_{\mathrm{oecd}}^{\mathrm{s,t0}} + \mathbf{C}_{\mathrm{noecd}}^{\mathrm{s,t1}}\right) \otimes \mathbf{A}_{\mathrm{t1}}^{*}\right)^{-1} \\ -\left(\mathbf{I} - \sum_{\mathrm{s}}\left(\mathbf{C}_{\mathrm{dom}}^{\mathrm{s,t0}} + \mathbf{C}_{\mathrm{oecd}}^{\mathrm{s,t0}} + \mathbf{C}_{\mathrm{noecd}}^{\mathrm{s,t0}}\right) \otimes \mathbf{A}_{\mathrm{t1}}^{*}\right)^{-1} \end{bmatrix} \cdot \mathbf{H}_{\mathrm{t1}} \otimes \mathbf{V}_{\mathrm{t1}} \cdot \mathbf{Y}_{\mathrm{t1}} \quad \text{(A.4)}$$

$$+\frac{1}{2}\mathbf{CA}_{\mathrm{t1}} \cdot \begin{bmatrix} \left(\mathbf{I} - \sum_{\mathrm{s}}\left(\mathbf{C}_{\mathrm{dom}}^{\mathrm{s,t1}} + \mathbf{C}_{\mathrm{oecd}}^{\mathrm{s,t1}} + \mathbf{C}_{\mathrm{noecd}}^{\mathrm{s,t1}}\right) \otimes \mathbf{A}_{\mathrm{t0}}^{*}\right)^{-1} \\ -(\mathbf{I} - \sum_{\mathrm{s}}\left(\mathbf{C}_{\mathrm{dom}}^{\mathrm{s,t1}} + \mathbf{C}_{\mathrm{oecd}}^{\mathrm{s,t1}} + \mathbf{C}_{\mathrm{noecd}}^{\mathrm{s,t0}}\right) \otimes \mathbf{A}_{\mathrm{t0}}^{*})^{-1} \end{bmatrix} \cdot \mathbf{H}_{\mathrm{t0}} \otimes \mathbf{V}_{\mathrm{t0}} \cdot \mathbf{Y}_{\mathrm{t0}}$$

$$\mathbf{D}_{\mathrm{A}} = \frac{1}{2}\mathbf{EI}_{\mathrm{t0}} \cdot \begin{bmatrix} (\mathbf{I} - \mathbf{C}_{\mathrm{t0}} \otimes \mathbf{A}_{\mathrm{t1}}^{*})^{-1} \\ -(\mathbf{I} - \mathbf{C}_{\mathrm{t0}} \otimes \mathbf{A}_{\mathrm{t0}}^{*})^{-1} \end{bmatrix} \cdot \mathbf{H}_{\mathrm{t1}} \otimes \mathbf{V}_{\mathrm{t1}} \cdot \mathbf{Y}_{\mathrm{t1}} \quad \text{(A.5)}$$

$$+\frac{1}{2}\mathbf{EI}_{\mathrm{t1}} \cdot \begin{bmatrix} (\mathbf{I} - \mathbf{C}_{\mathrm{t1}} \otimes \mathbf{A}_{\mathrm{t1}}^{*})^{-1} \\ -(\mathbf{I} - \mathbf{C}_{\mathrm{t1}} \otimes \mathbf{A}_{\mathrm{t0}}^{*})^{-1} \end{bmatrix} \cdot \mathbf{H}_{\mathrm{t0}} \otimes \mathbf{V}_{\mathrm{t0}} \cdot \mathbf{Y}_{\mathrm{t0}}$$

$$\mathbf{D}_{\mathbf{H}_{\mathrm{dom}}} = \frac{1}{2}\mathbf{EI}_{\mathrm{t0}} \cdot (\mathbf{I} - \mathbf{C}_{\mathrm{t0}} \otimes \mathbf{A}_{\mathrm{t0}}^{*})^{-1} \cdot (\textstyle\sum_{\mathrm{s}} \mathbf{H}_{\mathrm{dom}}^{\mathrm{s,t1}} - \sum_{\mathrm{s}} \mathbf{H}_{\mathrm{dom}}^{\mathrm{s,t0}}) \otimes \mathbf{V}_{\mathrm{t1}} \cdot \mathbf{Y}_{\mathrm{t1}} \quad \text{(A.6)}$$

$$+\frac{1}{2}\mathbf{EI}_{\mathrm{t1}} \cdot (\mathbf{I} - \mathbf{C}_{\mathrm{t1}} \otimes \mathbf{A}_{\mathrm{t1}}^{*})^{-1} \cdot (\textstyle\sum_{\mathrm{s}} \mathbf{H}_{\mathrm{dom}}^{\mathrm{s,t1}} - \sum_{\mathrm{s}} \mathbf{H}_{\mathrm{dom}}^{\mathrm{s,t0}}) \otimes \mathbf{V}_{\mathrm{t0}} \cdot \mathbf{Y}_{\mathrm{t0}}$$

$$\mathbf{D}_{\mathbf{H}_{\mathrm{oecd}}} = \frac{1}{2}\mathbf{EI}_{\mathrm{t0}} \cdot (\mathbf{I} - \mathbf{C}_{\mathrm{t0}} \otimes \mathbf{A}_{\mathrm{t0}}^{*})^{-1} \cdot (\textstyle\sum_{\mathrm{s}} \mathbf{H}_{\mathrm{oecd}}^{\mathrm{s,t1}} - \sum_{\mathrm{s}} \mathbf{H}_{\mathrm{oecd}}^{\mathrm{s,t0}}) \otimes \mathbf{V}_{\mathrm{t1}} \cdot \mathbf{Y}_{\mathrm{t1}} \quad \text{(A.7)}$$

$$+\frac{1}{2}\mathbf{EI}_{\mathrm{t1}} \cdot (\mathbf{I} - \mathbf{C}_{\mathrm{t1}} \otimes \mathbf{A}_{\mathrm{t1}}^{*})^{-1} \cdot (\textstyle\sum_{\mathrm{s}} \mathbf{H}_{\mathrm{oecd}}^{\mathrm{s,t1}} - \sum_{\mathrm{s}} \mathbf{H}_{\mathrm{oecd}}^{\mathrm{s,t0}}) \otimes \mathbf{V}_{\mathrm{t0}} \cdot \mathbf{Y}_{\mathrm{t0}}$$

$$\mathbf{D}_{\mathbf{H}_{\mathrm{noecd}}} = \frac{1}{2}\mathbf{EI}_{\mathrm{t0}} \cdot (\mathbf{I} - \mathbf{C}_{\mathrm{t0}} \otimes \mathbf{A}_{\mathrm{t0}}^{*})^{-1} \cdot (\textstyle\sum_{\mathrm{s}} \mathbf{H}_{\mathrm{noecd}}^{\mathrm{s,t1}} - \sum_{\mathrm{s}} \mathbf{H}_{\mathrm{noecd}}^{\mathrm{s,t0}}) \otimes \mathbf{V}_{\mathrm{t1}} \cdot \mathbf{Y}_{\mathrm{t1}} \quad \text{(A.8)}$$

$$+\frac{1}{2}\mathbf{EI}_{\mathrm{t1}} \cdot (\mathbf{I} - \mathbf{C}_{\mathrm{t1}} \otimes \mathbf{A}_{\mathrm{t1}}^{*})^{-1} \cdot (\textstyle\sum_{\mathrm{s}} \mathbf{H}_{\mathrm{noecd}}^{\mathrm{s,t1}} - \sum_{\mathrm{s}} \mathbf{H}_{\mathrm{noecd}}^{\mathrm{s,t0}}) \otimes \mathbf{V}_{\mathrm{t0}} \cdot \mathbf{Y}_{\mathrm{t0}}$$

$$\mathbf{D}_{\mathrm{V}} = \frac{1}{2}\mathbf{EI}_{\mathrm{t0}} \cdot (\mathbf{I} - \mathbf{C}_{\mathrm{t0}} \otimes \mathbf{A}_{\mathrm{t0}}^{*})^{-1} \cdot \mathbf{H}_{\mathrm{t0}} \otimes (\mathbf{V}_{\mathrm{t1}} - \mathbf{V}_{\mathrm{t0}}) \cdot \mathbf{Y}_{\mathrm{t1}} \quad \text{(A.9)}$$

$$+\frac{1}{2}\mathbf{EI}_{\mathrm{t1}} \cdot (\mathbf{I} - \mathbf{C}_{\mathrm{t1}} \otimes \mathbf{A}_{\mathrm{t1}}^{*})^{-1} \cdot \mathbf{H}_{\mathrm{t1}} \otimes (\mathbf{V}_{\mathrm{t1}} - \mathbf{V}_{\mathrm{t0}}) \cdot \mathbf{Y}_{\mathrm{t0}}$$

$$\mathbf{D}_{\mathrm{Y}} = \frac{1}{2}\mathbf{EI}_{\mathrm{t0}} \cdot (\mathbf{I} - \mathbf{C}_{\mathrm{t0}} \otimes \mathbf{A}_{\mathrm{t0}}^{*})^{-1} \cdot \mathbf{H}_{\mathrm{t0}} \otimes \mathbf{V}_{\mathrm{t0}} \cdot (\mathbf{Y}_{\mathrm{t1}} - \mathbf{Y}_{\mathrm{t0}}) \quad \text{(A.10)}$$

$$+\frac{1}{2}\mathbf{EI}_{\mathrm{t1}} \cdot (\mathbf{I} - \mathbf{C}_{\mathrm{t1}} \otimes \mathbf{A}_{\mathrm{t1}}^{*})^{-1} \cdot \mathbf{H}_{\mathrm{t1}} \otimes \mathbf{V}_{\mathrm{t1}} \cdot (\mathbf{Y}_{\mathrm{t1}} - \mathbf{Y}_{\mathrm{t0}})$$

Note that the effects of changes in final demand can be further separated into the changes in consumptions and fixed capital formation, by separating $\mathbf{H}_{\mathrm{dom}}, \mathbf{H}_{\mathrm{oecd}}, \mathbf{H}_{\mathrm{noecd}}, \mathbf{V}$ and $\mathbf{Y}$ for consumptions or fixed capital formation only.

A.2 The decomposition formula of regional production-based and consumption-based CO_2 emissions change

The above formulate can be extended to the decomposition of regional CO_2 emissions change. Note that, however, the accounting system matters when we discuss the regional CO_2 emissions change. More specifically, the production-based and consumption-based CO_2 emissions of region *s* in time t1 can be traced as:

$$\mathbf{Q}^{s}\_\mathrm{p} = \widehat{\mathbf{EI}}_{t1}^{s} \cdot \left[\mathbf{I} - \textstyle\sum_{s}\left(\mathbf{C}_{dom}^{s,t1} + \mathbf{C}_{oecd}^{s,t1} + \mathbf{C}_{noecd}^{s,t1}\right) \otimes \left(\sum_{s} \mathbf{A}_{t1}^{s}\right)\right]^{-1} \cdot \textstyle\sum_{s}\left(\mathbf{H}_{dom}^{s,t1} + \mathbf{H}_{oecd}^{s,t1} + \mathbf{H}_{noecd}^{s,t1}\right) \otimes \left(\sum_{s} \mathbf{V}_{t1}^{s}\right)\left(\sum_{s} \mathbf{Y}_{t1}^{s}\right) \quad \text{(A.11a)}$$

$$\mathbf{Q}^{s}\_\mathrm{c} = \mathbf{EI}_{t1} \cdot \left[\mathbf{I} - \textstyle\sum_{s}\left(\mathbf{C}_{dom}^{s,t1} + \mathbf{C}_{oecd}^{s,t1} + \mathbf{C}_{noecd}^{s,t1}\right) \otimes \left(\sum_{s} \mathbf{A}_{t1}^{s}\right)\right]^{-1} \cdot \textstyle\sum_{s}\left(\mathbf{H}_{dom}^{s,t1} + \mathbf{H}_{oecd}^{s,t1} + \mathbf{H}_{noecd}^{s,t1}\right) \otimes \left(\sum_{s} \mathbf{V}_{t1}^{s}\right)\left(\mathbf{Y}_{t1}^{s}\right) \quad \text{(A.11b)}$$

where $\mathbf{EI}_{t1}$ is the global emission intensity, $\widehat{\mathbf{EI}}_{t1}^{s}$ is a diagonal emission intensity filled with the emission intensity of region *s* at year t1 and others with zeros; $\sum_{s} \mathbf{Y}_{t1}^{s}$ is the global final demand, $\mathbf{Y}_{t1}^{s}$ is the final demand of region s. Equation 11a gives the production-based emissions of region *s*, i.e., emissions in region *s* due to global final demand; and equation 11b gives the consumption-based emissions of region *s*, i.e., global emissions due to final demand of region *s*. It can be found that the difference of production-based and consumption-based emissions decompositions mainly lies in the way how emission intensity multiply with output.

In a similar way, assume that only the emission intensity of region *s* change and other factors remain unchanged, its impact on regional production-based and consumption-based CO_2 emissions would be:

$$\mathbf{D}_{EI\_}^{s}\mathrm{p} = \frac{1}{2}\left(\widehat{\mathbf{EI}}_{t1}^{s} - \widehat{\mathbf{EI}}_{t0}^{s}\right) \cdot \begin{bmatrix} (\mathbf{I} - \mathbf{C}_{t1} \otimes \mathbf{A}_{t1}^{*})^{-1} \cdot \mathbf{H}_{t1} \otimes \mathbf{V}_{t1} \cdot \mathbf{Y}_{t1} \\ +(\mathbf{I} - \mathbf{C}_{t0} \otimes \mathbf{A}_{t0}^{*})^{-1} \cdot \mathbf{H}_{t0} \otimes \mathbf{V}_{t0} \cdot \mathbf{Y}_{t0} \end{bmatrix} \quad \text{(A.12a)}$$

$$\mathbf{D}_{EI\_}^{s}\mathrm{c} = \frac{1}{2}\left(\widehat{\mathbf{EI}}_{t1}^{s} - \widehat{\mathbf{EI}}_{t1}^{s}\right) \cdot \begin{bmatrix} (\mathbf{I} - \mathbf{C}_{t1} \otimes \mathbf{A}_{t1}^{*})^{-1} \cdot \mathbf{H}_{t1} \otimes \mathbf{V}_{t1} \cdot \mathbf{Y}_{t1}^{s} \\ +(\mathbf{I} - \mathbf{C}_{t0} \otimes \mathbf{A}_{t0}^{*})^{-1} \cdot \mathbf{H}_{t0} \otimes \mathbf{V}_{t0} \cdot \mathbf{Y}_{t0}^{s} \end{bmatrix} \quad \text{(A.12b)}$$

where $\widehat{\mathbf{EI}}_{t1}^{s}$ and $\widehat{\mathbf{EI}}_{t0}^{s}$ are the diagonal emission intensity matrix filled with the emission intensity of region *s* at year t0 and t1 and others with zeros, $\mathbf{Y}_{t1}^{s}$ and $\mathbf{Y}_{t0}^{s}$ are final demand of region *s* at year t0 and t1. Equation 12a gives the decomposition for production-based emissions, equation 12b gives the decomposition for consumption-based emissions.

The impact of changes of structure of final demand in region s (**V**^{s}) then can be quantified as:

$$\mathbf{D}_{V-p}^{s} = \quad \text{(A.13a)}$$

$$\frac{1}{2}\widehat{\mathbf{EI}}_{t0}^{s} \cdot (\mathbf{I} - \mathbf{C}_{t0} \otimes \mathbf{A}_{t0}^{*})^{-1} \cdot \mathbf{H}_{t0} \otimes \left[\left(\mathbf{V}_{t1}^{s} + \textstyle\sum_{k,k\neq s} \mathbf{V}_{t1}^{k}\right) - \left(\mathbf{V}_{t0}^{s} + \textstyle\sum_{k,k\neq s} \mathbf{V}_{t1}^{k}\right)\right] \cdot \mathbf{Y}_{t1} + \frac{1}{2}\widehat{\mathbf{EI}}_{t1}^{s} \cdot$$

$$(\mathbf{I}-\mathbf{C}_{\mathrm{t1}}\otimes\mathbf{A}^{*}_{\mathrm{t1}})^{-1}\cdot\mathbf{H}_{\mathrm{t1}}\otimes\left[(\mathbf{V}^{\mathrm{s}}_{\mathrm{t1}}+\textstyle\sum_{\mathrm{k,k\neq s}}\mathbf{V}^{\mathrm{k}}_{\mathrm{t0}})-(\mathbf{V}^{\mathrm{s}}_{\mathrm{t0}}+\textstyle\sum_{\mathrm{k,k\neq s}}\mathbf{V}^{\mathrm{k}}_{\mathrm{t0}})\right]\cdot\mathbf{Y}_{\mathrm{t0}}$$

$$\mathbf{D}^{\mathrm{s}}_{\mathrm{V\_c}}= \qquad \text{(A.13b)}$$

$$\tfrac{1}{2}\mathbf{EI}_{\mathrm{t0}}\cdot(\mathbf{I}-\mathbf{C}_{\mathrm{t0}}\otimes\mathbf{A}^{*}_{\mathrm{t0}})^{-1}\cdot\mathbf{H}_{\mathrm{t0}}\otimes\left[(\mathbf{V}^{\mathrm{s}}_{\mathrm{t1}}+\textstyle\sum_{\mathrm{k,k\neq s}}\mathbf{V}^{\mathrm{k}}_{\mathrm{t1}})-(\mathbf{V}^{\mathrm{s}}_{\mathrm{t0}}+\textstyle\sum_{\mathrm{k,k\neq s}}\mathbf{V}^{\mathrm{k}}_{\mathrm{t1}})\right]\cdot\mathbf{Y}^{\mathrm{s}}_{\mathrm{t1}}+\tfrac{1}{2}\mathbf{CA}_{\mathrm{t1}}\cdot$$

$$(\mathbf{I}-\mathbf{C}_{\mathrm{t1}}\otimes\mathbf{A}^{*}_{\mathrm{t1}})^{-1}\cdot\mathbf{H}_{\mathrm{t1}}\otimes\left[(\mathbf{V}^{\mathrm{s}}_{\mathrm{t1}}+\textstyle\sum_{\mathrm{k,k\neq s}}\mathbf{V}^{\mathrm{k}}_{\mathrm{t0}})-(\mathbf{V}^{\mathrm{s}}_{\mathrm{t0}}+\textstyle\sum_{\mathrm{k,k\neq s}}\mathbf{V}^{\mathrm{k}}_{\mathrm{t0}})\right]\cdot\mathbf{Y}^{\mathrm{s}}_{\mathrm{t0}}$$

where equation 13a gives the decomposition for production-based emissions, equation 13b gives the decomposition for consumption-based emissions.

And the impact of the changes of total final demand in region *s* ($\mathbf{Y}^{\mathrm{s}}$) can be quantified as:

$$\mathbf{D}^{\mathrm{s}}_{\mathrm{Y\_}}\mathrm{p}=\tfrac{1}{2}\widehat{\mathbf{EI}}^{\mathrm{s}}_{\mathrm{t0}}\cdot(\mathbf{I}-\mathbf{C}_{\mathrm{t0}}\otimes\mathbf{A}^{*}_{\mathrm{t0}})^{-1}\cdot\mathbf{H}_{\mathrm{t0}}\otimes\mathbf{V}_{\mathrm{t0}}\cdot(\mathbf{Y}^{\mathrm{s}}_{\mathrm{t1}}-\mathbf{Y}^{\mathrm{s}}_{\mathrm{t0}}) \qquad \text{(A.14a)}$$

$$+\tfrac{1}{2}\widehat{\mathbf{EI}}^{\mathrm{s}}_{\mathrm{t1}}\cdot(\mathbf{I}-\mathbf{C}_{\mathrm{t1}}\otimes\mathbf{A}^{*}_{\mathrm{t1}})^{-1}\cdot\mathbf{H}_{\mathrm{t1}}\otimes\mathbf{V}_{\mathrm{t1}}\cdot(\mathbf{Y}^{\mathrm{s}}_{\mathrm{t1}}-\mathbf{Y}^{\mathrm{s}}_{\mathrm{t0}})$$

$$\mathbf{D}^{\mathrm{s}}_{\mathrm{Y\_}}\mathrm{c}=\tfrac{1}{2}\mathbf{EI}_{\mathrm{t0}}\cdot(\mathbf{I}-\mathbf{C}_{\mathrm{t0}}\otimes\mathbf{A}^{*}_{\mathrm{t0}})^{-1}\cdot\mathbf{H}_{\mathrm{t0}}\otimes\mathbf{V}_{\mathrm{t0}}\cdot(\mathbf{Y}^{\mathrm{s}}_{\mathrm{t1}}-\mathbf{Y}^{\mathrm{s}}_{\mathrm{t0}}) \qquad \text{(A.14b)}$$

$$+\tfrac{1}{2}\mathbf{EI}_{\mathrm{t1}}\cdot(\mathbf{I}-\mathbf{C}_{\mathrm{t1}}\otimes\mathbf{A}^{*}_{\mathrm{t1}})^{-1}\cdot\mathbf{H}_{\mathrm{t1}}\otimes\mathbf{V}_{\mathrm{t1}}\cdot(\mathbf{Y}^{\mathrm{s}}_{\mathrm{t1}}-\mathbf{Y}^{\mathrm{s}}_{\mathrm{t0}})$$

where equation 14a gives the decomposition for production-based emissions, equation 14b gives the decomposition for consumption-based emissions.

The impact of changes in outsourcing shares and technical inputs are slightly different because the Leontief inverse is involved. Take an example of the changes in domestic share of intermediate. Assume that only the domestic share of intermediate inputs in region *s* changed, its impact on $\mathrm{CO_2}$ emissions can be quantified as:

$$\mathbf{D}_{\mathbf{C}^{\mathrm{s}}_{\mathrm{dom}}}\mathrm{\_p}=\tfrac{1}{2}\widehat{\mathbf{EI}}^{\mathrm{s}}_{\mathrm{t0}}\cdot$$

$$\left\{\begin{array}{l}\left[\mathbf{I}-\textstyle\sum_{\mathrm{s}}\left(\mathbf{C}^{\mathrm{s,t1}}_{\mathrm{dom}}+\mathbf{C}^{\mathrm{s,t1}}_{\mathrm{oecd}}+\mathbf{C}^{\mathrm{s,t1}}_{\mathrm{noecd}}\right)\otimes\mathbf{A}^{*}_{\mathrm{t1}}-\textstyle\sum_{\mathrm{k,k\neq s}}\left(\mathbf{C}^{\mathrm{k,t1}}_{\mathrm{dom}}+\mathbf{C}^{\mathrm{k,t1}}_{\mathrm{oecd}}+\mathbf{C}^{\mathrm{k,t1}}_{\mathrm{noecd}}\right)\otimes\mathbf{A}^{*}_{\mathrm{t1}}\right]^{-1}\\-\left[\mathbf{I}-\textstyle\sum_{\mathrm{s}}\left(\mathbf{C}^{\mathrm{s,t0}}_{\mathrm{dom}}+\mathbf{C}^{\mathrm{s,t1}}_{\mathrm{oecd}}+\mathbf{C}^{\mathrm{s,t1}}_{\mathrm{noecd}}\right)\otimes\mathbf{A}^{*}_{\mathrm{t1}}-\textstyle\sum_{\mathrm{k,k\neq s}}\left(\mathbf{C}^{\mathrm{s,t1}}_{\mathrm{dom}}+\mathbf{C}^{\mathrm{s,t1}}_{\mathrm{oecd}}+\mathbf{C}^{\mathrm{s,t1}}_{\mathrm{noecd}}\right)\otimes\mathbf{A}^{*}_{\mathrm{t1}}\right]^{-1}\end{array}\right\}\cdot$$

$$\mathbf{H}_{\mathrm{t1}}\otimes\mathbf{V}_{\mathrm{t1}}\cdot\mathbf{Y}_{\mathrm{t1}} \qquad \text{(A.15a)}$$

$$+\frac{1}{2}\widehat{\mathbf{EI}}^{\mathrm{s}}_{\mathrm{t1}}$$

$$\cdot\left\{\begin{array}{l}\left[\mathbf{I}-\sum_{\mathrm{s}}\left(\mathbf{C}^{\mathrm{s,t1}}_{\mathrm{dom}}+\mathbf{C}^{\mathrm{s,t0}}_{\mathrm{oecd}}+\mathbf{C}^{\mathrm{s,t0}}_{\mathrm{noecd}}\right)\otimes\mathbf{A}^{*}_{\mathrm{t0}}-\sum_{\mathrm{k,k\neq s}}\left(\mathbf{C}^{\mathrm{k,t0}}_{\mathrm{dom}}+\mathbf{C}^{\mathrm{k,t0}}_{\mathrm{oecd}}+\mathbf{C}^{\mathrm{k,t0}}_{\mathrm{noecd}}\right)\otimes\mathbf{A}^{*}_{\mathrm{t0}}\right]^{-1}\\-\left[\mathbf{I}-\sum_{\mathrm{s}}\left(\mathbf{C}^{\mathrm{s,t0}}_{\mathrm{dom}}+\mathbf{C}^{\mathrm{s,t0}}_{\mathrm{oecd}}+\mathbf{C}^{\mathrm{s,t0}}_{\mathrm{noecd}}\right)\otimes\mathbf{A}^{*}_{\mathrm{t0}}-\sum_{\mathrm{k,k\neq s}}\left(\mathbf{C}^{\mathrm{k,t0}}_{\mathrm{dom}}+\mathbf{C}^{\mathrm{k,t0}}_{\mathrm{oecd}}+\mathbf{C}^{\mathrm{k,t0}}_{\mathrm{noecd}}\right)\otimes\mathbf{A}^{*}_{\mathrm{t0}}\right]^{-1}\end{array}\right\}\cdot\mathbf{H}_{\mathrm{t0}}$$

$$\otimes\mathbf{V}_{\mathrm{t0}}\cdot\mathbf{Y}_{\mathrm{t0}}$$

$$\mathbf{D}_{\mathbf{C}^{\mathrm{s}}_{\mathrm{dom}}\_}\mathrm{c} = \tfrac{1}{2}\mathbf{EI}_{\mathrm{t0}} \cdot$$

$$\begin{Bmatrix} \left[\mathbf{I} - \sum_{\mathrm{s}}\left(\mathbf{C}^{\mathrm{s,t1}}_{\mathrm{dom}} + \mathbf{C}^{\mathrm{s,t1}}_{\mathrm{oecd}} + \mathbf{C}^{\mathrm{s,t1}}_{\mathrm{noecd}}\right) \otimes \mathbf{A}^{*}_{\mathrm{t1}} - \sum_{\mathrm{k,k\neq s}}\left(\mathbf{C}^{\mathrm{k,t1}}_{\mathrm{dom}} + \mathbf{C}^{\mathrm{k,t1}}_{\mathrm{oecd}} + \mathbf{C}^{\mathrm{k,t1}}_{\mathrm{noecd}}\right) \otimes \mathbf{A}^{*}_{\mathrm{t1}}\right]^{-1} \\ -\left[\mathbf{I} - \sum_{\mathrm{s}}\left(\mathbf{C}^{\mathrm{s,t0}}_{\mathrm{dom}} + \mathbf{C}^{\mathrm{s,t1}}_{\mathrm{oecd}} + \mathbf{C}^{\mathrm{s,t1}}_{\mathrm{noecd}}\right) \otimes \mathbf{A}^{*}_{\mathrm{t1}} - \sum_{\mathrm{k,k\neq s}}\left(\mathbf{C}^{\mathrm{s,t1}}_{\mathrm{dom}} + \mathbf{C}^{\mathrm{s,t1}}_{\mathrm{oecd}} + \mathbf{C}^{\mathrm{s,t1}}_{\mathrm{noecd}}\right) \otimes \mathbf{A}^{*}_{\mathrm{t1}}\right]^{-1} \end{Bmatrix} \cdot$$

$$\mathbf{H}_{\mathrm{t1}} \otimes \mathbf{V}_{\mathrm{t1}} \cdot \mathbf{Y}^{\mathrm{s}}_{\mathrm{t1}} \tag{A.15b}$$

$$+\frac{1}{2}\mathbf{EI}_{\mathrm{t1}}$$

$$\cdot \begin{Bmatrix} \left[\mathbf{I} - \sum_{\mathrm{s}}\left(\mathbf{C}^{\mathrm{s,t1}}_{\mathrm{dom}} + \mathbf{C}^{\mathrm{s,t0}}_{\mathrm{oecd}} + \mathbf{C}^{\mathrm{s,t0}}_{\mathrm{noecd}}\right) \otimes \mathbf{A}^{*}_{\mathrm{t0}} - \sum_{\mathrm{k,k\neq s}}\left(\mathbf{C}^{\mathrm{k,t0}}_{\mathrm{dom}} + \mathbf{C}^{\mathrm{k,t0}}_{\mathrm{oecd}} + \mathbf{C}^{\mathrm{k,t0}}_{\mathrm{noecd}}\right) \otimes \mathbf{A}^{*}_{\mathrm{t0}}\right]^{-1} \\ -\left[\mathbf{I} - \sum_{\mathrm{s}}\left(\mathbf{C}^{\mathrm{s,t0}}_{\mathrm{dom}} + \mathbf{C}^{\mathrm{s,t0}}_{\mathrm{oecd}} + \mathbf{C}^{\mathrm{s,t0}}_{\mathrm{noecd}}\right) \otimes \mathbf{A}^{*}_{\mathrm{t0}} - \sum_{\mathrm{k,k\neq s}}\left(\mathbf{C}^{\mathrm{k,t0}}_{\mathrm{dom}} + \mathbf{C}^{\mathrm{k,t0}}_{\mathrm{oecd}} + \mathbf{C}^{\mathrm{k,t0}}_{\mathrm{noecd}}\right) \otimes \mathbf{A}^{*}_{\mathrm{t0}}\right]^{-1} \end{Bmatrix} \cdot \mathbf{H}_{\mathrm{t0}}$$

$$\otimes \mathbf{V}_{\mathrm{t0}} \cdot \mathbf{Y}^{\mathrm{s}}_{\mathrm{t0}}$$

where the intermediate inputs columns of other region *k* (*k*≠*s*) remain unchanged, only the intermediate inputs columns of region *s* experienced changes regarding the domestic share of region *s* in intermediates. The equation 15a gives the decomposition for production-based emissions, equation 15b gives the decomposition for consumption-based emissions. In a similar way, the impact of changes in other shares $\mathbf{C}^{\mathrm{s}}_{\mathrm{oecd}}$, $\mathbf{C}^{\mathrm{s}}_{\mathrm{noecd}}$, $\mathbf{H}^{\mathrm{s}}_{\mathrm{dom}}$,$\mathbf{H}^{\mathrm{s}}_{\mathrm{oecd}}$ and $\mathbf{H}^{\mathrm{s}}_{\mathrm{noecd}}$ can be calculated.

At the end, the impact of the changes in technical input coefficients (i.e. production recipe A) can be quantified as:

$$\mathbf{D}^{\mathrm{s}}_{\mathrm{A}\_}\mathrm{p} = \tfrac{1}{2}\widehat{\mathbf{EI}}^{\mathrm{s}}_{\mathrm{t0}} \cdot \begin{Bmatrix} \left[\mathbf{I} - \mathbf{C}_{\mathrm{t0}} \otimes (\mathbf{A}^{\mathrm{s}}_{\mathrm{t1}} + \sum_{\mathrm{k,k\neq s}} \mathbf{A}^{\mathrm{k}}_{\mathrm{t1}})\right]^{-1} \\ -\left[\mathbf{I} - \mathbf{C}_{\mathrm{t0}} \otimes (\mathbf{A}^{\mathrm{s}}_{\mathrm{t0}} + \sum_{\mathrm{k,k\neq s}} \mathbf{A}^{\mathrm{k}}_{\mathrm{t1}})\right]^{-1} \end{Bmatrix} \cdot \mathbf{H}_{\mathrm{t1}} \otimes \mathbf{V}_{\mathrm{t1}} \cdot \mathbf{Y}_{\mathrm{t1}} \tag{A.16a}$$

$$+\tfrac{1}{2}\widehat{\mathbf{EI}}^{\mathrm{s}}_{\mathrm{t1}} \cdot \begin{Bmatrix} \left[\mathbf{I} - \mathbf{C}_{\mathrm{t1}} \otimes (\mathbf{A}^{\mathrm{s}}_{\mathrm{t1}} + \sum_{\mathrm{k,k\neq s}} \mathbf{A}^{\mathrm{k}}_{\mathrm{t0}})\right]^{-1} \\ -\left[\mathbf{I} - \mathbf{C}_{\mathrm{t1}} \otimes (\mathbf{A}^{\mathrm{s}}_{\mathrm{t0}} + \sum_{\mathrm{k,k\neq s}} \mathbf{A}^{\mathrm{k}}_{\mathrm{t0}})\right]^{-1} \end{Bmatrix} \cdot \mathbf{H}_{\mathrm{t0}} \otimes \mathbf{V}_{\mathrm{t0}} \cdot \mathbf{Y}_{\mathrm{t0}}$$

$$\mathbf{D}^{\mathrm{s}}_{\mathrm{A}\_}\mathrm{c} = \tfrac{1}{2}\mathbf{EI}_{\mathrm{t0}} \cdot \begin{Bmatrix} \left[\mathbf{I} - \mathbf{C}_{\mathrm{t0}} \otimes (\mathbf{A}^{\mathrm{s}}_{\mathrm{t1}} + \sum_{\mathrm{k,k\neq s}} \mathbf{A}^{\mathrm{k}}_{\mathrm{t1}})\right]^{-1} \\ -\left[\mathbf{I} - \mathbf{C}_{\mathrm{t0}} \otimes (\mathbf{A}^{\mathrm{s}}_{\mathrm{t0}} + \sum_{\mathrm{k,k\neq s}} \mathbf{A}^{\mathrm{k}}_{\mathrm{t1}})\right]^{-1} \end{Bmatrix} \cdot \mathbf{H}_{\mathrm{t1}} \otimes \mathbf{V}_{\mathrm{t1}} \cdot \mathbf{Y}^{\mathrm{s}}_{\mathrm{t1}} \tag{A.16b}$$

$$+\tfrac{1}{2}\mathbf{EI}_{\mathrm{t1}} \cdot \begin{Bmatrix} \left[\mathbf{I} - \mathbf{C}_{\mathrm{t1}} \otimes (\mathbf{A}^{\mathrm{s}}_{\mathrm{t1}} + \sum_{\mathrm{k,k\neq s}} \mathbf{A}^{\mathrm{k}}_{\mathrm{t0}})\right]^{-1} \\ -\left[\mathbf{I} - \mathbf{C}_{\mathrm{t1}} \otimes (\mathbf{A}^{\mathrm{s}}_{\mathrm{t0}} + \sum_{\mathrm{k,k\neq s}} \mathbf{A}^{\mathrm{k}}_{\mathrm{t0}})\right]^{-1} \end{Bmatrix} \cdot \mathbf{H}_{\mathrm{t0}} \otimes \mathbf{V}_{\mathrm{t0}} \cdot \mathbf{Y}^{\mathrm{s}}_{\mathrm{t1}}$$

where the equation 16a gives the decomposition for production-based emissions, equation 16b gives the decomposition for consumption-based emissions.

Appendix B. Construction procedures of constant-price IO tables

There are two prevailing procedures for constructing constant-price IO tables: (i) first converting national currency values into a common currency (by using convertors), typically U.S. dollars, and then applying appropriate U.S. price indexes (deflators), which account for price level variability, to express the data in constant prices; or (ii) first deflating national currency values by using appropriate price indexes (deflators) for the national currency, which account for temporal variability in local price levels, and then converting them to a common currency (by using convertors), say, U.S. dollars (see Lan et al., 2016 for a review). As the OECD-ICIO has been converted into a unified U.S. dollars based on market exchange rate, we adopted the first approach of ‘‘convert-first then deflate” in this study to construct GMRIO tables in constant prices.

With respect to price deflators, there are three series of deflators: gross output deflators, final demand deflators and cell-specific deflators. Dietzenbacher and Temurshoev (2012) used Denmark data and found that the results of IO impact analysis are very similar as long as one of the three series of deflators is available. For the U.S. economy, only gross output deflators are available at sectoral level, from U.S. Bureau of Labor Statistics. Therefore in this study, we have employed the gross output deflator of U.S. economy to deflate the entire GMRIO table from year t1 to year t0. It should be noted, that we also used a double-deflation method to derive value added in the process, to achieve the table balance in constant prices.

Reference:

Dietzenbacher, E. and Temurshoev, U. (2012) Input–output impact analysis in current or constant prices: does it matter? Journal of Economic Structure,1(1): 4-10.

Lan, J., Malik, A., Lenzen, M., McBain, D. and Kanemoto, K. (2016) A structural decomposition analysis of global energy footprints, Applied Energy, 163(3): 436–451.