Revisit the global net CO_2 emissions transfers: The impact of heterogeneity of trade mode

Xuemei Jiang, Quanrun Chen, Kunfu Zhu, Cuihong Yang(chyang@iss.ac.cn)
Academy of Mathematics and Systems Science, CAS

Abstract

This paper employs a new world-wide multi-regional input-output table where China's productions are distinguished into domestic use, processing exports and non-processing exports, to revisit the global net CO_2 emissions transfers for year 2007. The results show that processing exports in China involve relatively less CO_2 emissions than other production types for the same amount of outputs. As a result, without appropriate distinction of processing exports, the net CO_2 emission exports from China to other regions have been distorted, and in some cases the relative bias reached 15%. The net emissions transfers of regions other than China are distorted as well, especially for the regions that use considerable processing exports of China as intermediates, such as USA, Europe and East Asia. Given the fact that processing exports are prevailing in quite a number of developing countries, such as Mexico and Vietnam, it should be careful to interpret the measurements of net emissions transfers under the ordinary world-wide multi-regional input-output model.

Keywords: Multi-regional input-output table, net emissions transfers, processing trade, China

1. Introduction

In today's globalized world, production processes increasingly fragment across countries. As a result, the local consumption in one country is increasingly met by global supply chains (Hubacek et al., 2014). In the climate front, this phenomenon has attracted extensive scholarly and policy debates on the allocation of greenhouse gases (GHG) emission – especially CO_2 emission – responsibilities linked to international trade, because international trade causes a net emissions transfers (see, e.g. Ahmad and Wyckoff, 2003; Liu and Ma, 2011; Wiedmann, 2009; Peters et al., 2011).

Due to detailed description on production chains, environmental input-output (EIO) model has been widely accepted to trace the net CO_2 emissions transfers and environmental footprints from consumption across global supply chains (Hubacek et al., 2014). Note there are two kinds of models: single-region input-output model (SRIO, see, e.g. Su and Ang, 2010; Su et al., 2013; Liu et al., 2013) and multi-region input-output model (MRIO, see, e.g. Peters et al., 2011; Feng et al., 2013). Most single-country emission studies adopt SRIO model because its data requirement is low. Along with wider availability of global MRIO databases[1], MRIO model has gradually become mainstream, as it records the flows of goods and services along the global production chain across countries and thus can trace the emissions to final consumptions in any specific country (See Wiedmann et al.

[1] Please refer to Tukker and Dietzenbacher (2013) for a through outlook of available global MRIO databases.

(2007) for reviews, and Peters et al. (2011) and Feng et al. (2013) for some recent applications). Peters et al. (2011), for example, employed a MRIO model to quantify the net CO_2 emissions transfers embodied in international trade across 113 countries from 1990 to 2008.

Among all countries, China and its trade-linked emissions have received a great deal of interest, as its dual role of world's largest exporter as well as the world's largest CO_2 emitter. One feature of Chinese international trade, however, is the prevalence of processing exports, for which firms import parts and components from abroad under favorable tariff treatment, and assemble them for export. Thus there is significant heterogeneity between the productions of processing exports and non-processing exports. Generally speaking, processing exports have much lower CO_2 emission intensities than the production of non-processing exports, and it has been proved that without appropriate distinction of processing exports, the exports-linked CO_2 emissions of China would be seriously overestimated (Dietzenbacher et al., 2012; Su et al. 2013; Weitzel and Ma, 2014).

All of these discussions however are based on SRIO model (see, e.g., Dietzenbacher et al., 2012; Su et al., 2013; Weitzel and Ma, 2014). There is no literature – as far as we know – to discuss the impact of heterogeneity of trade mode (i.e. processing vs. non-processing trade) on the measurements of net emissions transfers in trade based on a MRIO model. In addition to the CO_2 emissions embodied in China's exports that can be well captured by a SRIO model, the heterogeneity of trade would also influence the measurements of CO_2 emissions embodied in China's imports. In fact, the productions of same amount of processing exports require more imports rather than domestic products as intermediates, while that of domestic use and non-processing exports require more domestic products rather than imports as intermediates (Ma *et al.*, 2014). As a result, if the processing trade is not distinguished, the linkage between production for domestic use (D) and abroad sectors will be overestimated, leading to an overestimation of CO_2 emissions of other countries generated by China's final consumptions, that are China's imports of CO_2 emissions. Moreover, many countries rely on China's exports as intermediate inputs, the overestimation of China's exports-linked emissions may lead to a subsequent overestimation of embodied CO_2 emissions in the related final products of other countries. All of these may distort the picture of embodied global net CO_2 emissions transfers and the link between local consumption and global emissions.

In this paper, we employed a new world-wide MRIO table that distinguishes China's production types into domestic use (D), processing exports (P) and non-processing exports (N) (abbreviated as WIOD-DPN table hereafter, Chen et al., 2014), to revisit the net CO_2 emissions transfers embodied in international trade. We also compared the biases of measurements in global net CO_2 emissions transfers, to evaluate the impact of a failure of consideration of heterogeneity in terms of trade mode in China. In addition to China, there are a series of countries such as Mexico, Indonesia and Vietnam, that have considerable processing exports (WTO, 2011). By using China as a case, we would also like to shed some light on the issues of the extent to which the heterogeneity of trade mode influences the measurement of global net CO_2 emissions transfers.

2. Materials and Methods

In this paper we selected World Input−Output Database (WIOD) as our starting point to further disaggregate China's productions into domestic use (D), processing exports (P) and non-processing exports (N). Although the WIOD is not the most detailed in terms of numbers of countries and products, it has a unique feature that is necessary for our study: it includes inter-country supply-use tables that can be transformed into symmetric global MRIO table by product*product type. Note the Chinese SRIO table that distinguishes production type D, P and N is by product*product type (also known as DPN table, see e.g. Lau et al., 2006; Chen et al., 2012)[2]. The same product*product type allows a link between global MRIO table and Chinese DPN table, generating a "new" WIOD-DPN table. This WIOD-DPN table covers 59 products in 40 countries and the Rest of the World (RoW), while China's productions are distinguished into three types. As for CO_2 emissions, we first transformed the CO_2 emissions data in WIOD from industry*industry type into product*product type, then we adopted the idea of Jiang *et al.* (2015), that is using intermediate energy use in input-output table to proportionally decompose the CO_2 emissions of China by three production type. Note all disaggregation of IO tables and CO_2 emissions are calibrated so that a re-aggregation would result in an official WIOD release for year 2007[3].

With respect to measurements, we followed Peters et al. (2011)'s methods and defined the difference between the production-based and consumption-based emissions of a given country *r* as a "net emission transfer", i.e. $E\_T^r = E\_P^r - E\_C^r$, where E_P^r are the production-based emissions of country *r* and E_C^r are the consumption-based emissions of country *r*. The net emissions transfers of country *r* can be expressed equivalently in terms of "emissions embodied in international trade," i.e. $E\_T^r = E\_ex^r - E\_im^r$, where E_ex^r are the emissions generated in country *r* due to all final demands of other countries and E_im^r are the emissions generated in other countries due to final demands of country *r*. Note the net emissions transfers can be measured at bilateral level as well. Let $E\_ex(F^{rk})$ indicates the emissions exports from country *r* to country *k* (i.e. the emissions generated in country r due to all final demands of country k), $E\_im(F^{rk})$ indicates the emissions imports of country *r* from country *k* (i.e. the emissions generated in country *k* due to all final demands of country *r*), the net emissions transfers between country *r* and country *k* can be measured as $E\_T(F^{rk}) = E\_ex(F^{rk}) - E\_im(F^{rk})$.

For a full description of the data compilations and measurements methods see the Supporting Information (SI).

3. Results

3.1 Net CO2 emissions transfers based on the new WIOD-DPN table

For the sake of simplicity, we aggregated the detailed country results into 13 regions: the USA, the European Union (27 member states, EU-27), East Asia (Japan, South Korea and Taiwan), Australia, Canada, China, Brazil, Russia, India, Indonesia, Mexico and Turkey, and the RoW. Figure 1 gives the comparisons between production-based and consumption-based CO_2 emissions based on our WIOD-DPN table in 2007. Similar with the literatures about global net CO_2 emission transfers, such as Peters et al. (2011), Davis and Caldeira (2010) and Kanemoto et al. (2014), our results also show that developed countries have net imports of emissions and developing countries have net exports of emissions.

[2] China custom statistics by trade mode are conducted at the product level, therefore the Chinese DPN is compiled at product level. Please refer to Lau et al. (2006) and Chen et al. (2012) for the details of framework and compilations.
[3] See www.wiod.org. The most recent Chinese DPN table until the end of 2014 is for year 2007, thus in this paper we only compiled the WIOD-DPN table for year 2007.

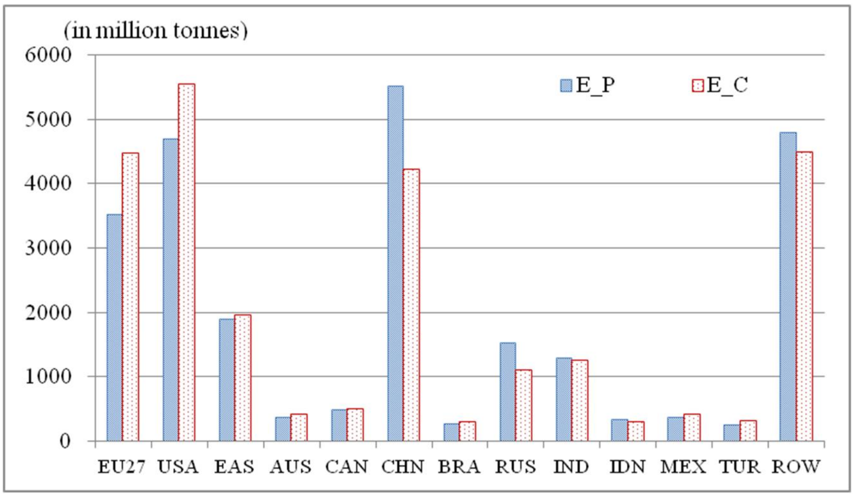

Figure 1. Production-based and Consumption-based CO_2 emissions, by region, 2007. Region codes: AUS: Australia; BRA: Brazil; CAN: Canada; CHN: China; EAS: East Asia (Japan, South Korea and Taiwan); EU-27: European Union 27 Member States; IND: India; IDN: Indonesia; MEX: Mexico; RUS: Russia; TUR: Turkey; USA: United States of America; RoW: Rest of the World.

As aforementioned, the differences between production-based and consumption-based CO_2 emissions lie in net emissions transfers embodied in trade, i.e. $E\_T^r = E\_ex^r - E\_im^r$. One of advantages of our WIOD-DPN table is that it can trace China's exported emissions into different production types. As Figure 2a indicated, the productions for domestic use, processing and non-processing exports accounted for 59.5%, 4.2% and 36.3% of China's exported CO_2 emissions, respectively, for year 2007. Although productions for domestic use (D) do not serve directly as final products of other countries, they provide intermediates for the productions of final products consumed in other countries. According to the WIOD-DPN table, 7.4 trillion USD of Chinese products are used as intermediates worldwide in 2007, among them the production type D, P and N contributed 5.5, 0.3 and 1.6 trillion USD, respectively. It is therefore not surprising that production type D dominated the driving force of China's exported CO_2 emissions in Figure 2a.

The emissions embodied in processing exports (P) and non-processing exports (N) are caused by the exports of intermediates as well as final goods. According to the WIOD-DPN table, respective 283 and 326 trillion USD of Chinese processing exports are sold as intermediates and final goods of other countries in 2007; much smaller than that of non-processing exports: 1608 trillion USD as intermediates and 548 trillion USD as final goods.[4] Therefore we found that non-processing exports (N) accounted for a larger share of China's exported CO_2 emissions than processing exports (P) in Figure 2a.

For the sake of contrast, we also include the pattern of China's imported CO_2 emissions in Figure 2b. By subtracting imported emissions from exported emissions, it is found that China has net exports of CO_2 emissions to all the other regions, in particularly with USA, EU27 and East Asia. In 2007, the net CO_2 exports from China to these three regions are 847 million tonnes, accounted

[4] Custom statistics show processing exports accounted for about half of Chinese merchandise exports in 2007. Our results show that Chinese processing exports are much lower than non-processing exports in 2007. This is mainly because that our results include service exports that only non-processing trade can provide. In addition, custom statistics are in FOB (Free on Board) prices, and our results are in basic prices where transportation, whole sale and retail margins are excluded. As a result, the margins of processing exports are allocated to service exports (non-processing) in our WIOD-DPN table.

for 65.4% of China's total exported CO_2 emissions.

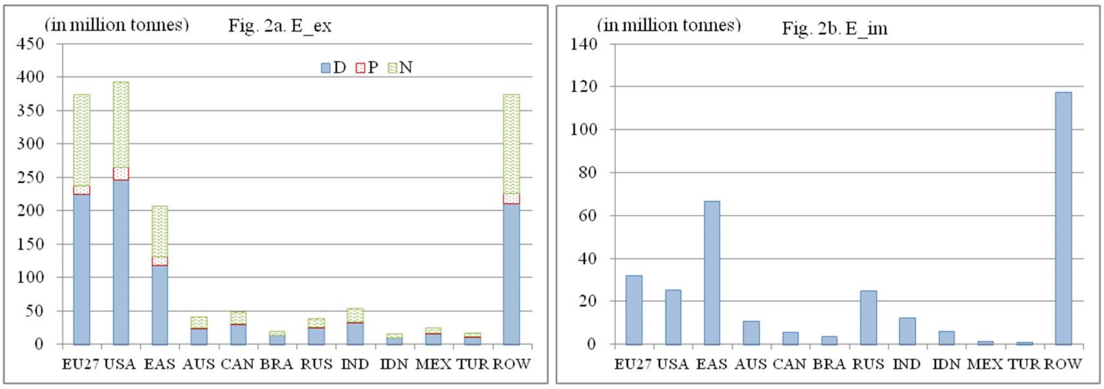

Figure 2. (a) China's exported CO_2 emissions, by production type and by region, 2007. (b) China's imported CO_2 emissions, by region, 2007. Region codes are as same as Figure 1. Same as below.

3.2 The biases of measurements of net CO2 emissions transfers when the heterogeneity of trade in China is not considered

In most cases, the WIOD-DPN table is not available and we have to rely on an ordinary WIOD table to obtain our estimations on net CO_2 emissions transfers embodied in trade. In this section we explored the extent to which the distinction of production types in China influences our estimations, i.e. the results based on ordinary WIOD table minus the results based on WIOD-DPN table. In Figure 3a we firstly compared the estimation biases for the exported and imported CO_2 emissions for the regions other than China, where the bars represent the overestimation (positive) or underestimation (negative) degrees in million tonnes. It can be found that both the exports and imports of emissions have been overestimated for most regions (except India and Indonesia), shown as positive bars in Figure 3a. The distortion extents of exported emissions are much lower than that of imported emissions. As a result, we found overestimations of net CO_2 emissions transfers based on an ordinary WIOD table for most regions (Figure 3b). More specifically, the highest bias of net imported CO_2 emission is found for USA, amounting to 34.7 million tonnes, while it is followed by EU27 (16.5 million tonnes) and East Asia (11.4 million tonnes). This is reasonable because these three regions are exact the top three trading partners with China in terms of processing trade. According to the custom releases of China, the USA, EU27 and East Asia accounted for 19.2%, 30.6%, 17.2% of China's processing exports in 2007, respectively.

In contrary, India and Indonesia are found with overestimations of the exported emissions and underestimations of the imported emissions (Figure 3a). As a result, the ordinary WIOD overestimated the net exported emissions of India and Indonesia, at 2.7 million tonnes and 0.2 million tonnes, respectively (Figure 3b). Note that the global sum of exported CO_2 emissions should equal to the sum of global imported CO_2 emissions, regardless of WIOD or WIOD-DPN table. Therefore, the sum of global biases in net CO_2 emission transfers should equal to zero, and we omitted the results for China in Figure 3. In contrary of most other regions, we found an overestimation of net CO_2 exported emission for China at 83 million tonnes. More specifically, China's exports and imports of CO_2 emissions are overestimated, but the exported emissions have been seriously overestimated at 149 million tonnes, much higher than that of the imported emissions at 66 million tonnes.

In relative terms, we calculated the results by using WIOD-DPN table as the denominators, and the biases that results based on ordinary WIOD table minus the results based on WIOD-DPN table as the numerators. China's trade-linked CO_2 emissions have been distorted the most: the estimation biases of exported and imported emissions reached 9.3% and 21.7%, respectively. For the remaining regions, the estimation biases of exported emissions ranged from 0.01%-0.4% across regions, while the biases of imported emissions ranged from 0.3-2.7%. With respect to net emissions transfers, we found even larger biases: the average bias of net emission transfers reached 5% of the total net emissions transfers (Figure 3b). In some regions, such as East Asia and Canada, the relative biases of net emission transfers even reached 20.6% and 14.9%, respectively.

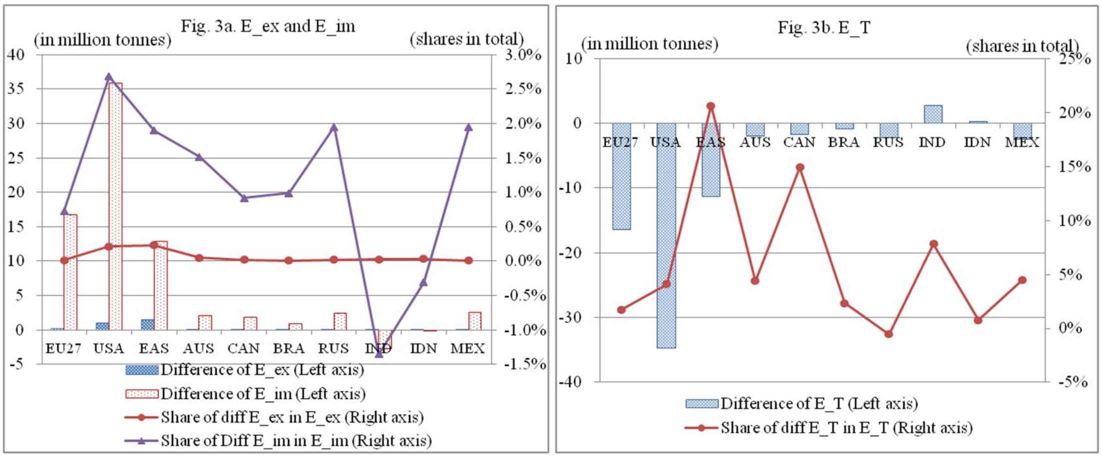

Figure 3. (a) The estimation biases of CO_2 emissions embodied in exports and imports (WIOD-DPN table vs. ordinary WIOD table) and their shares in totals, by region, 2007; (b) The estimation biases of net CO_2 emission transfers embodied in trade (WIOD-DPN table vs. ordinary WIOD table) and their shares in totals, by region, 2007..

Figure 4 further describes the biases of net CO_2 emissions transfers at the bilateral level, where the bars represent the distorted degrees in million tonnes. Note the sums of net overestimation/underestimation degrees in Figure 4 equal to the degrees shown in Figure 3b. For example, the net transfer of CO_2 emissions of USA with China and Mexico have been underestimated at 45.8 million tonnes, while the net transfer of CO_2 emissions of USA with East Asia have been overestimated at 5.4 million tonnes (Figure 4). To sum over all regions, we found the net imported CO_2 emissions of USA have been underestimated at 34.7 million tonnes in total, equivalent to the results in Figure 3b.

Since our results are symmetric for any pair of regions, we omitted the results for China in Figure 4 as well. Among all bilateral net CO_2 emissions transfers with China, the net imported CO_2 emissions of USA from China has been overestimated the most (at 45.8 million tonnes), while it is followed by EU27 (18.5 million tonnes), RoW (4.5 million tonnes), Mexico (3.3 million tonnes), Canada (2.3 million tonnes) and Australia (2.2 million tonnes). The net imported emission of India from China has been seriously underestimated at 3.4 million tonnes.

The failure of distinction of China's trade mode also distorts the net CO_2 emission transfers embodied in the trade of countries other than China. The net imported CO_2 emissions of East Asia from USA and EU27, for example, are overestimated at 5.4 and 2.8 million tonnes, respectively. This is not a surprising results, however, in the light of the fact that USA, EU27 and East Asia are the top three trading partners of China in terms of processing trade in 2007.

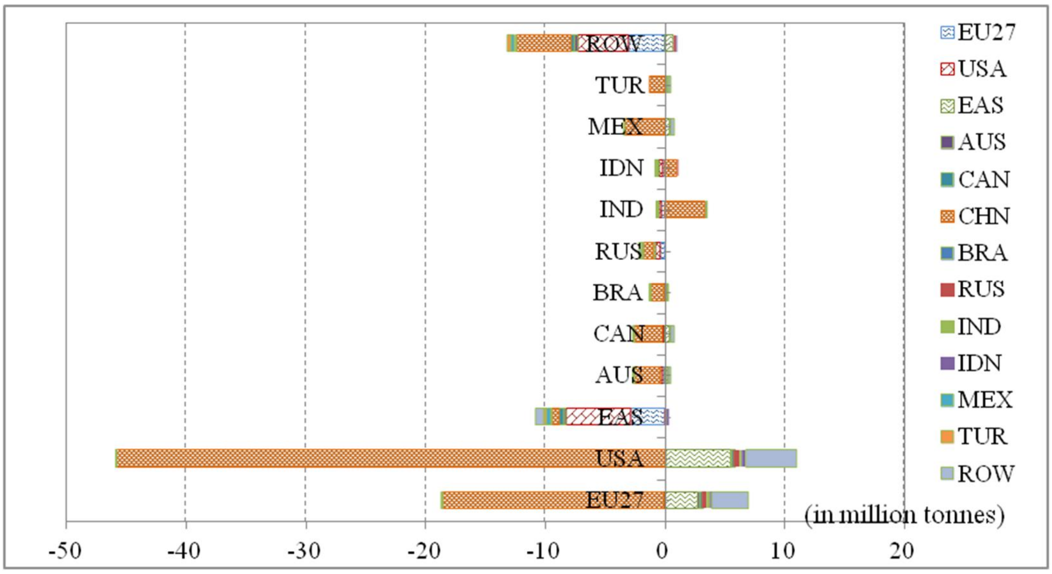

Figure 4. The biases of net CO_2 emission transfers embodied in bilateral trade (WIOD-DPN table vs. ordinary WIOD table), 2007.

3.3 Discussions: What if the processing exports of China were conducted in other countries?

In sum, Chinese processing exports generated (directly and indirectly) 68.7 million tonnes of CO_2 emissions (Figure 2a). In spite of small proportion in China's total, this emission is equivalent to the entire CO_2 emission of a medium-scaled countries in 2007, such as Austria (69.7 million tonnes), Finland (64.4 million tonnes), Philippians (71.8 million tonnes) or Vietnam (93.6 million tonnes).[5] Unlike the other production types, the processing exports mainly involve assembly and packaging activities, where firms import parts and components from abroad and then assemble them for exports. One of the consequences is that processing exports mainly require electricity instead of fossil fuels as energy inputs. One well known fact about China is that it relies to a great degree on coal-fired power for its electricity generation (over 80% in 2007). As a result, its electricity generation is much more carbon-intensive than the world average. Assuming that processing exports only require electricity as energy inputs, in this section we simulated the changes of global CO_2 emissions under the scenarios that the processing activities of China were conducted in country i other than China. That is, let φ_i indicate the CO_2 emissions per kWh from electricity in region i, μ_{CHN} indicate the total CO_2 emissions of China generated by processing exports activities, the "new" global CO_2 emissions if country i replaces China can be calculated as $\mu_i = (\varphi_i/\varphi_{CHN}) * \mu_{CHN}$. In table 1 we summarize our simulation results.

Table 1. The CO_2 emissions if the processing exports of China were conducted in other countries

[5] The CO2 emissions by country are taken from IEA (2010).

Target Country	CO_2 emissions per kWh from electricity generation (in grammes CO_2)*	CO_2 emissions if the processing exports of China were conducted in the target country (in million tonnes)	Processing imports from China (in billion USD)
China	758	68.67	
EU27	362	32.81	116.73
USA	549	49.77	186.25
East Asia	455	41.22	105.11
Australia	907	82.17	10.89
Canada	205	18.57	15.72
Brazil	73	6.61	7.28
Russia	323	29.26	6.83
India	928	84.07	8.37
Indonesia	692	62.69	2.06
Mexico	547	49.56	17.32
Turkey	478	43.31	4.99
RoW	642	58.16	127.78

* The CO_2 emissions data per kWh from electricity by country generation is taken from IEA (www.iea.org), among them the data of East Asia is the average of Korea and Japan, the data of Row is that of Non-Annex I Parties. The processing exports from China to each region are also listed as reference.

One observation of Table 1 is that most regions have lower CO_2 emission intensity per kWh of electricity generation than China. Brazil and Canada, for example, have extremely low CO_2 emission intensity, as their electricity generations largely rely on renewable energy (mostly hydro-power). If Brazil rather than China were the country that conducted processing activities, the same amount of processing exports of China (amounting to 609 billion USD in 2007) would only emit 6.61 million tonnes of CO_2, and the global CO_2 emissions would be reduced by as high as 62 million tonnes. In the scenarios that USA, Europe or East Asia conducted processing activities of China, the reductions of global CO_2 emissions would reach 19-35 million tonnes. From a perspective the global climate change mitigation, it seems that China need further reduce its CO_2 emission intensity of electricity generation, so that such considerable processing activities could continue to concentrate in China. In this context, the improvement of energy usage efficiency and the increase of proportion of renewable energy in electricity generation, among all measures, should be attached with a great of priority in China (see, e.g. Fan et al., 2007; Zhang and Chen, 2009; Du et al., 2013; Xu et al., 2014).

4. Conclusions

In this paper we compiled a global multi-regional input-output tables where China's productions are differentiated into domestic use, processing exports and non-processing exports (WIOD-DPN table), to re-evaluate the net CO_2 emissions transfers embodied in international trade among countries for year 2007.

In general, the results show very similar trends with the previous literatures about global net CO_2 emission transfers, that are developed countries often have net imports of CO_2 emissions and developing countries often have net exports of CO_2 emissions. However, there exist underestimations/overestimations of net CO_2 emissions transfers, especially when China is concerned. China has net exports of CO_2 emissions to all the other regions. Without appropriate consideration of heterogeneity of trade in China, the net exports of CO_2 emissions from China have been seriously overestimated. Among all regions, the net exported CO_2 emissions from China to USA and EU27 have been overestimated the most, at 45.8 and 18.5 million tonnes, respectively, while they are followed by Mexico (3.3 million tonnes), Canada (2.3 million tonnes) and Australia (2.2 million tonnes). There also two regions, India and Indonesia, that have underestimations of net imported CO_2 emissions: the net imported CO_2 emissions of India and Indonesia from China have been underestimated at 3.4 and 1.0 million tonnes, respectively.

The failure of distinction of China's processing trade also distorts the balances of embodied emissions in the trade of countries other than China. USA, EU27 and East Asia are the top three trading partners of China in terms of processing trade in 2007. As a result, the embodied CO_2 emissions in their bilateral trade have been influenced the most. The net imported emissions of East Asia from USA and EU27, for example, are overestimated at 5.4 and 2.8 million tonnes, respectively.

At the aggregate level, we found that both the exports and imports of emissions have been overestimated for most regions (except for India and Indonesia), and the extents of exported emissions are coincidently lower than that of imported emissions. As a result, we found that the ordinary WIOD table overestimated the net emission transfers for most regions, ranged from 0.6 to 45.8 million tonnes. For India and Indonesia, we found underestimations of exported emissions and overestimations of imported emissions. Therefore, the ordinary WIOD overestimated the net exported emissions of India and Indonesia, at 2.7 million tonnes and 0.2 million tonnes, respectively.

Given the fact that processing exports are prevailing in quite a number of developing countries, such as Mexico, Indonesia and Vietnam, one implication of our results is that it should be careful to interpret the measurements of net CO_2 emissions transfers under the ordinary world-wide multi-regional input-output model. In addition, our results also sounds a warning to the future sustainable development of China, especially in terms of processing trade. Due to high dependency on coal as primary energy inputs, China's CO_2 emission intensity is much higher than most developed and developing countries. It is found that the *global* CO_2 emissions would reduce by 19-62 million tonnes, if the processing activities of China were shifted to other countries such as USA, Europe or Brazil. As the global climate change mitigation becomes increasingly important, China may consider to give priority on the reduction of CO_2 emission intensity in particularly in electricity generation, to avoid possible transfers of processing activities out of China.

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Appendix The compilation of WIOD-DPN table and the measurements of net CO_2 emissions transfers

1. The compilation of WIOD-DPN table

1.1 The construction of product by product type of world input-output table

As China's DPN IO table is a product by product type table, the same type of world input-output table (WIOT) is required. WIOD provides the industry by industry type WIOT instead of the product by product type. Therefore, we first need to estimate the product by product type table. It can be derived from a set of international SUTs for 40 countries in WIOD based on production technology assumptions. We adopt the industry production technology assumption which assumes that each industry has its own specific way of production, irrespective of its product mix. This assumption can avoid the inversion problems (such as the negative value and rectangular SUT problems) in the transformation.

The construction procedure is briefly introduced as follows. Frist, merge the international SUTs of 40 countries to obtain the world SUT. In the world SUT, the production of each country is connected. Second, transform the world SUT into the basic product by product type WIOT based on production technology assumptions. In the basic WIOT, rest of the world (RoW) is treated as an exogenous country, as there is no international SUT for RoW. Third, model RoW to an endogenous country. Finally, balance the table to obtain the final analytical product by product WIOT.

1.2 Distinguishing China's processing trade in the WIOT

The traditional way to treat China's processing trade in a national IO table is to classify China's production activities into three types. They are: production for domestic use (D), production of processing exports (P), and production of non-processing exports and other production of foreign invested enterprises (N). Like China's DPN IO table, these three types of production for each industry of China should be distinguished in the WIOT. Each China related cell in the WIOT is required to split into three parts (i.e. D, P and N). If the share of each production type in each China related cell of WIOT is given, the China related cell can be straightforwardly split into three cells (i.e. D,P and N).

We obtain these shares from China's DPN IO table. For instance, the share of product *i*'s gross output produced by production for domestic use (D) in the gross output of product *i* equals the gross output of product *i* of D (available in China's DPN IO table) over the sum of the gross output of product *i* of D, P and N (available in China's DPN IO table). Moreover, with respect to the sales structure of P and N in foreign countries and the sales structure of imports from foreign countries in China, we further take into account China's bilateral trade data by trade partners and by trade types (processing trade and non-processing trade) from the General Administration of Customs of China.

2. The estimations of CO_2 emissions

WIOD provides CO_2 emissions that covering 41 countries and 35 industries. Our first step is to transform the emissions data with classification by 35 industries into that by 59 products based on the supply table of each country. Our formula is:

$$E' = CA_I' \cdot \mathrm{D} \cdot \hat{\mathrm{X}} \quad \text{(S.1)}$$

where E is the emission vector by products; CA_I is the emission coefficient vector by industry; D is the market share matrix calculated from the supply table (its element d_{ij} represents the share in total product j supplied by industry i); $\hat{\mathrm{X}}$ is a diagonal matrix transformed from the gross output vector by products.

It should be noted that RoW has no supply table, so as suggested by Timmer et al. (2012), we use the average of the supply tables of BRICIM (i.e. Brazil, Russia, India, China, Indonesia and Mexico) for RoW.

Then we adopted the idea of Jiang *et al.* (2015), that is using intermediate energy use in input-output table to proportionally decompose the CO_2 emissions of China by production type, i.e. domestic use, processing exports and non-processing exports. There are three primary-energy-related products exhibited in the WIOD-DPN table: Product 4, coal, lignite and peat; Product 5, crude petroleum and natural gas; and Product 17, coke, refined petroleum products and nuclear fuels. The intermediate use of these three products by production type is used to proportionally separate the corresponding CO_2 emissions in the *i-th* product. Let (i) ε_j indicate the CO_2 emissions of China in the *j-th* product; (ii) ρ_j^l indicate the intermediate use from energy products to *j-th* product for the production type l (=D, P and N), and (iii) ρ_j indicates the total intermediate use of energy products in the *i-th* product, i.e. $\rho_j = \sum_l \rho_j^l$ (l = D, P, N), the estimated CO_2 emissions by production type for the *j-th* product can then be obtained as:

$$\varepsilon_j^l = \frac{\rho_j^l}{\rho_j}\varepsilon_j \quad \text{where } l = \text{D, P, N}; j = 1, \ldots, n \tag{S.2}$$

3. The measurements of CO_2 emissions embodied in exports, imports and net CO2 transfers based on WIOD-DPN table

For the sake of simplicity, in this section the measurements are described using the simplest case with three regions and one sector. Table S.1 outlines the scheme of a traditional inter-country input-output table with three countries. In a similar way with single-country input-output table, Z describe the intermediate uses, F describe the final use (incl. consumption, investment and changes in inventories), V describe the value-added (incl. compensations of employees, production taxes, depreciation of fixed capital and net operation profits), X indicate total outputs and superscript *r* (=1,2,3) represent country. For example, Z^{13} represent the intermediate use from country 1 to country 3.

Table S.1. The inter-country input-output table, three countries

		Intermediate Use			Final Use			Total Output
		Country 1	Country 2	Country 3	Country 1	country 2	Country m	
Intermedi	Country 1	Z^{11}	Z^{12}	Z^{13}	F^{11}	F^{12}	F^{13}	X^1
	Country 2	Z^{21}	Z^{22}	Z^{23}	F^{21}	F^{22}	F^{23}	X^2
	Country 3	Z^{31}	Z^{32}	Z^{33}	F^{31}	F^{32}	F^{33}	X^3
Value Added		V^1	V^2	V^3				
Total Input		X^1	X^2	X^3				

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

$$\begin{bmatrix} Z^{11} & Z^{12} & Z^{13} \\ Z^{21} & Z^{22} & Z^{23} \\ Z^{31} & Z^{32} & Z^{33} \end{bmatrix} + \begin{bmatrix} F^{11} + F^{12} + F^{13} \\ F^{21} + F^{22} + F^{23} \\ F^{31} + F^{32} + F^{33} \end{bmatrix} = \begin{bmatrix} X^1 \\ X^2 \\ X^3 \end{bmatrix} \tag{S.3}$$

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

$$A^{rs} = Z^{rs}(\widehat{X^s})^{-1} \tag{S.4}$$

where *r*, *s* = 1, 2, 3, and $(\widehat{X^s})^{-1}$ denotes the inverse of a diagonal matrix of total outputs in country s.

Define input coefficients matrix $\mathrm{A} = \begin{bmatrix} A^{11} & A^{12} & A^{13} \\ A^{21} & A^{22} & A^{23} \\ A^{31} & A^{32} & A^{33} \end{bmatrix}$ with A^{rs} is the input coefficient from country *r* to country *s*, the Leontief inverse can be calculated as $\mathrm{B} = (\mathrm{I} - \mathrm{A})^{-1}$, that is, $\mathrm{B} = \begin{bmatrix} B^{11} & B^{12} & B^{13} \\ B^{21} & B^{22} & B^{23} \\ B^{31} & B^{32} & B^{33} \end{bmatrix} = \begin{bmatrix} I - A^{11} & -A^{12} & -A^{13} \\ -A^{21} & -A^{22} & -A^{23} \\ -A^{31} & -A^{32} & -A^{33} \end{bmatrix}^{-1}$, 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 countries and sectors.

Using E^r denotes the carbon emission in country *r*, and $CA^r = E^r(\widehat{X^r})^{-1}$ denotes the carbon emission coefficient per unit of outputs in country *r*, the carbon emissions generated along production chains can be traced as:

$$\begin{bmatrix} E^1 \\ E^2 \\ E^3 \end{bmatrix} = \begin{bmatrix} \widehat{CA}^1 & 0 & 0 \\ 0 & \widehat{CA}^2 & 0 \\ 0 & 0 & \widehat{CA}^3 \end{bmatrix} \begin{bmatrix} B^{11} & B^{12} & B^{13} \\ B^{21} & B^{22} & B^{23} \\ B^{31} & B^{32} & B^{33} \end{bmatrix} \begin{bmatrix} F^{11} + F^{12} + F^{13} \\ F^{21} + F^{22} + F^{23} \\ F^{31} + F^{32} + F^{33} \end{bmatrix} \quad \text{(S.5)}$$

According to Eq. (S.5), the carbon emission generated in country 1 due to all final demands of country 2 can be considered as the exported carbon dioxide emission from country 1 to country 2, that is:

$$E\_ex(F^{12}) = \begin{bmatrix} CA^1 & 0 & 0 \end{bmatrix} \begin{bmatrix} B^{11} & B^{12} & B^{13} \\ B^{21} & B^{22} & B^{23} \\ B^{31} & B^{32} & B^{33} \end{bmatrix} \begin{bmatrix} F^{12} \\ F^{22} \\ F^{32} \end{bmatrix} \quad \text{(S.6)}$$

Similarly, the carbon emission generated in country 2 due to all final demands of country 1 can be considered as the imported carbon dioxide emission of country 1 from country 2, that is:

$$E\_im(F^{12}) = \begin{bmatrix} 0 & CA^2 & 0 \end{bmatrix} \begin{bmatrix} B^{11} & B^{12} & B^{13} \\ B^{21} & B^{22} & B^{23} \\ B^{31} & B^{32} & B^{33} \end{bmatrix} \begin{bmatrix} F^{11} \\ F^{21} \\ F^{31} \end{bmatrix} \quad \text{(S.7)}$$

The net carbon emissions transfers between country 1 and country 2 (i.e. at bilateral trade) therefore are:

$$E\_T(F^{12}) = E\_ex(F^{12}) - E\_im(F^{12}) \quad \text{(S.8)}$$

The carbon emissions embodied in the exports and imports of country 1 are:

$$E\_ex(F^1) = \begin{bmatrix} CA^1 & 0 & 0 \end{bmatrix} \begin{bmatrix} B^{11} & B^{12} & B^{13} \\ B^{21} & B^{22} & B^{23} \\ B^{31} & B^{32} & B^{33} \end{bmatrix} \begin{bmatrix} F^{12} + F^{13} \\ F^{22} + F^{23} \\ F^{32} + F^{33} \end{bmatrix} \quad \text{(S.9)}$$

$$E\_im(F^1) = \begin{bmatrix} 0 & CA^2 & CA^3 \end{bmatrix} \begin{bmatrix} B^{11} & B^{12} & B^{13} \\ B^{21} & B^{22} & B^{23} \\ B^{31} & B^{32} & B^{33} \end{bmatrix} \begin{bmatrix} F^{11} \\ F^{21} \\ F^{31} \end{bmatrix} \quad \text{(S.10)}$$

Then we have the net carbon emissions transfers of country 1 as:

$$E\_T(F^1) = E\_ex(F^1) - E\_im(F^1) \quad \text{(S.11)}$$

Table S.2 outlines the scheme of an inter-country input-output table with three countries, where the productions of country 1 are differentiated into domestic use (D), processing exports (P) and non-processing exports (N).

Table S.2. The inter-country input-output table capturing heterogeneity of trade mode, three countries

			Intermediate Use					Final Use			Total Output
			Country 1			Country 2	Country 3	Country 1	Country 2	Country 3	
			D	P	N						
Intermediate Use	Country 1	D	Z^{1D_1D}	Z^{1D_1P}	Z^{1D_1N}	Z^{1D_2}	Z^{1D_3}	F^{1D_1}	F^{1D_2}	F^{1D_3}	X^{1D}
		P	Z^{1P_1D}	Z^{1P_1P}	Z^{1P_1N}	Z^{1P_2}	Z^{1P_3}	F^{1P_1}	F^{1P_2}	F^{1P_3}	X^{1P}
		N	Z^{1N_1D}	Z^{1N_1P}	Z^{1N_1N}	Z^{1N_2}	Z^{1N_3}	F^{1N_1}	F^{1N_2}	F^{1N_3}	X^{1N}
	Country 2		Z^{2_1D}	Z^{2_1P}	Z^{2_1N}	Z^{22}	Z^{23}	F^{21}	F^{22}	F^{23}	X^2
	Country 3		Z^{3_1D}	Z^{3_1P}	Z^{3_1N}	Z^{32}	Z^{33}	F^{31}	F^{32}	F^{33}	X^3
Value Added			V^{1D}	V^{1P}	V^{1N}	V^2	V^3				
Total Input			X^{1D}	X^{1P}	X^{1N}	X^2	X^3				

Using E^{1l} denotes the carbon emission of production type l (=D, P, N) in country 1, and $CA^{1l} = E^{1l}(\widehat{X^{1l}})^{-1}$ denotes the carbon emission coefficient per unit of outputs of production l (=D, P, N) in country 1, the carbon emissions generated along production chains can be traced as:

$$\begin{bmatrix} E^{1D} \\ E^{1P} \\ E^{1N} \\ E^{2} \\ E^{3} \end{bmatrix} = \tag{S.12}$$

$$\begin{bmatrix} \widehat{CA}^{1D} & 0 & 0 & 0 & 0 \\ 0 & \widehat{CA}^{1P} & 0 & 0 & 0 \\ 0 & 0 & \widehat{CA}^{1N} & 0 & 0 \\ 0 & 0 & 0 & \widehat{CA}^{2} & 0 \\ 0 & 0 & 0 & 0 & \widehat{CA}^{3} \end{bmatrix} \begin{bmatrix} B^{1D\_1D} & B^{1D\_1P} & B^{1D\_1N} & B^{1D\_2} & B^{1D\_3} \\ B^{1P\_1D} & B^{1P\_1P} & B^{1P\_1N} & B^{1P\_2} & B^{1P\_3} \\ B^{1N\_1D} & B^{1N\_1P} & B^{1N\_1N} & B^{1N\_2} & B^{1N\_3} \\ B^{2\_1D} & B^{2\_1P} & B^{2\_1N} & B^{2\_2} & B^{2\_3} \\ B^{2\_1D} & B^{3\_1P} & B^{3\_1N} & B^{3\_2} & B^{3\_3} \end{bmatrix} \begin{bmatrix} F^{1D\_1} + F^{1D\_2} + F^{1D\_3} \\ F^{1P\_1} + F^{1P\_2} + F^{1P\_3} \\ F^{1N\_1} + F^{1N\_2} + F^{1N\_3} \\ F^{21} + F^{22} + F^{23} \\ F^{31} + F^{32} + F^{33} \end{bmatrix}$$

where $F^{1D\_2} = F^{1D\_3} = F^{1P\_1} = F^{1N\_1} = 0$

In an analogous way, the carbon emission generated in country 1 due to all final demands of country 2 based on WIOD-DPN scheme can be measured as:

$$\widetilde{E\_ex}(F^{12}) =$$

$$[CA^{1D} \quad CA^{1P} \quad CA^{1N} \quad 0 \quad 0] \begin{bmatrix} B^{1D\_1D} & B^{1D\_1P} & B^{1D\_1N} & B^{1D\_2} & B^{1D\_3} \\ B^{1P\_1D} & B^{1P\_1P} & B^{1P\_1N} & B^{1P\_2} & B^{1P\_3} \\ B^{1N\_1D} & B^{1N\_1P} & B^{1N\_1N} & B^{1N\_2} & B^{1N\_3} \\ B^{2\_1D} & B^{2\_1P} & B^{2\_1N} & B^{2\_2} & B^{2\_3} \\ B^{2\_1D} & B^{3\_1P} & B^{3\_1N} & B^{3\_2} & B^{3\_3} \end{bmatrix} \begin{bmatrix} F^{1D\_2} \\ F^{1P\_2} \\ F^{1N\_2} \\ F^{22} \\ F^{32} \end{bmatrix} \tag{S.13}$$

The carbon emission generated in country 2 due to all final demands of country 1 under WIOD-DPN scheme can be considered as the imported carbon dioxide emission of country 1 from country 2, that is:

$$\widetilde{E\_\imath m}(F^{12}) = [0 \quad 0 \quad 0 \quad CA^{2} \quad 0] \begin{bmatrix} B^{1D\_1D} & B^{1D\_1P} & B^{1D\_1N} & B^{1D\_2} & B^{1D\_3} \\ B^{1P\_1D} & B^{1P\_1P} & B^{1P\_1N} & B^{1P\_2} & B^{1P\_3} \\ B^{1N\_1D} & B^{1N\_1P} & B^{1N\_1N} & B^{1N\_2} & B^{1N\_3} \\ B^{2\_1D} & B^{2\_1P} & B^{2\_1N} & B^{2\_2} & B^{2\_3} \\ B^{2\_1D} & B^{3\_1P} & B^{3\_1N} & B^{3\_2} & B^{3\_3} \end{bmatrix} \begin{bmatrix} F^{1D\_1} \\ F^{1P\_1} \\ F^{1N\_1} \\ F^{21} \\ F^{31} \end{bmatrix} \tag{S.14}$$

The net carbon emissions transfers between country 1 and country 2 (i.e. at bilateral trade) under WIOD-DPN framework therefore are:

$$\widetilde{E\_T}(F^{12}) = \widetilde{E\_ex}(F^{12}) - \widetilde{E\_\imath m}(F^{12}) \tag{S.15}$$

The carbon emissions embodied in the exports and imports of country 1 under WIOD-DPN framework are:

$$\widetilde{E_{ex}}(F^{1}) =$$

$$[CA^{1D} \quad CA^{1P} \quad CA^{1N} \quad 0 \quad 0] \begin{bmatrix} B^{1D\_1D} & B^{1D\_1P} & B^{1D\_1N} & B^{1D\_2} & B^{1D\_3} \\ B^{1P\_1D} & B^{1P\_1P} & B^{1P\_1N} & B^{1P\_2} & B^{1P\_3} \\ B^{1N\_1D} & B^{1N\_1P} & B^{1N\_1N} & B^{1N\_2} & B^{1N\_3} \\ B^{2\_1D} & B^{2\_1P} & B^{2\_1N} & B^{2\_2} & B^{2\_3} \\ B^{2\_1D} & B^{3\_1P} & B^{3\_1N} & B^{3\_2} & B^{3\_3} \end{bmatrix} \begin{bmatrix} F^{1D\_2} + F^{1D\_3} \\ F^{1P\_2} + F^{1P\_3} \\ F^{1N\_2} + F^{1N\_3} \\ F^{22} + F^{23} \\ F^{32} + F^{33} \end{bmatrix} \tag{S.16}$$

$$\widetilde{E\_\imath m}(F^{1}) = [0 \quad 0 \quad 0 \quad CA^{2} \quad CA^{3}] \begin{bmatrix} B^{1D\_1D} & B^{1D\_1P} & B^{1D\_1N} & B^{1D\_2} & B^{1D\_3} \\ B^{1P\_1D} & B^{1P\_1P} & B^{1P\_1N} & B^{1P\_2} & B^{1P\_3} \\ B^{1N\_1D} & B^{1N\_1P} & B^{1N\_1N} & B^{1N\_2} & B^{1N\_3} \\ B^{2\_1D} & B^{2\_1P} & B^{2\_1N} & B^{2\_2} & B^{2\_3} \\ B^{2\_1D} & B^{3\_1P} & B^{3\_1N} & B^{3\_2} & B^{3\_3} \end{bmatrix} \begin{bmatrix} F^{1D\_1} \\ F^{1P\_1} \\ F^{1N\_1} \\ F^{21} \\ F^{31} \end{bmatrix} \tag{S.17}$$

Then we have the net carbon emissions transfers of country 1 under WIOD-DPN framework as:

$$\widetilde{E\_T}(F^1) = \widetilde{E\_ex}(F^1) - \widetilde{E\_\imath m}(F^1) \quad \text{(S.18)}$$