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Measuring the Impacts of International Trade on Carbon Emissions Intensity: A Global Value Chain Perspective

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ABSTRACT: Global international trade has had a tremendous impact on global economic development and carbon dioxide (CO_2) emissions. By making the link between embodied CO_2 emissions and the global value chain in the context of global multiregional input–output models, this study constructs a macro carbon trade intensity index to measure the carbon efficiency of international trade. Empirical results on 14 major economies from 1995 to 2009 are presented as follows: (1) The characteristics of the carbon trade vary between developing economies (or transition economies) and developed economies. On average, developing and transition economies have an export carbon intensity (ECI) 3.5 times that of their import carbon intensity (ICI), whereas the latter have an ICI 2.0 times that of their ECI; (2) The three carbon intensity indices in almost all economies decreased compared with 1995; however, the degree of reduction vary from 2% to 52%; (3) China's ECIs showed little change compared with those of India. Russia's ECIs were higher than those of China and India. In addition, countries with higher intensity are generally developing and transition economies.

KEY WORDS: Carbon intensity, developed and developing economies, global value chain, international trade, multiregional input–output models

With the globalization of the world economy, multiple parts of the production of a commodity are gradually performed in different countries, and numerous intermediate products flow between different countries (Acquaye et al. 2017; Zhang, Zhu, and Hewings 2017). However, the flows of goods and services within these global supply chains are not always accurately reflected in conventional accounts of international trade. That is, the total value of goods or services in official statistics is measured across country boundaries, which includes not only the value added to goods in exporting countries but also the value of intermediate inputs purchased by the producers, with the latter accounted for twice (Koopman, Wang, and Wei 2014; Timmer et al. 2014). This gross trade accounting method leads to nonconformity with the System of National Accounts. The concept of the global value chain emerged, which indicates the value that different countries acquire by participating in the different stages of production of commodities in a complex international production and consumption network (Koopman, Wang, and Wei 2014; Krugman 1995). In terms of an individual product, a well-known case is the value segmentation of Apple's iPod. The factory gate price of an assembled iPod in China is reported to be $144, of which only $4 of the value added is produced in China, whereas the remaining $140 is generated in the United States and other countries (Dedrick, Kraemer, and Linden 2009). Therefore, accounting for the distribution of the value added embodied in goods among different countries is essential for understanding the position of each country in global value chains (Cingolani, Panzarasa, and Tajoli 2017).

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Consistent with the division of the global value chain, the carbon dioxide (CO_2) emissions embodied in the goods and services of a country can also be distributed to different countries through the production process and flow of goods between countries. Many studies have adopted bilateral trade input–output (BTIO) or single-region input–output (SRIO) models to account for the CO_2 emissions embodied in trade (Gavrilova and Vilu 2012; Liu and Liang 2017; Peters 2008; Wu et al. 2016). Guo, Zou, and Wei (2010) applied the China–US BTIO model and determined that Chinese exports to the US accounted for 304.75 Mt of China's CO_2 emissions, whereas exports from the US to China generated CO_2 emissions of only 25.53 Mt; the difference of 279.22 Mt comprised 5.8% of China's total CO_2 emissions for that year. Kim, Yoo, and Oh (2015) used the SRIO model to investigate Korea's final demand structure and contribution to CO_2 emissions. In addition, a life-cycle assessment is typically conducted to identify the carbon footprint of a specific sector or good (Levasseur et al. 2016; Notarnicola et al. 2017; Wiloso, Heijungs, and de Snoo 2012). However, because of the limitations of the models and data, these studies failed to explain the complex relationship between CO_2 emissions and intermediate product chains. By contrast, multiregional input–output (MRIO) models enable us to trace emissions back to the region that generated them, even when products cross between different regions multiple times during the product supply chain. This allows a better examination of the relationship between CO_2 emissions and intermediate product chains. Many empirical studies have highlighted the importance of accounting for spillover and the feedback effect in the context of supply chain when calculating embodied emissions (Acquaye et al. 2017; Fan et al. 2016, 2018; Liu, Liang, and Wang 2015; Peters 2007; Weber and Matthews 2007).

From the perspective of the formation mechanism, both the global value chain and CO_2 emissions trade are based on the spillover and feedback of the supply chain; thus, they can be analyzed in the same framework of the global MRIO model (Cingolani, Panzarasa, and Tajoli 2017; Daudin, Rifflart, and Schweisguth 2011; Feng et al. 2013; Mi et al. 2016). Benefiting from the development of the global input–output database (Dietzenbacher et al. 2013), some researchers have conducted studies on the global value chain and carbon emissions trade separately (Dolter and Victor 2016; Liou et al. 2016; Pothen 2017; Xu and Dietzenbacher 2014). Timmer et al. (2014) decomposed the global value chain of the global manufacturing industry and analyzed the direct and indirect labor and capital structure of production. Xu and Dietzenbacher (2014) conducted a structural decomposition analysis of the driving factors of CO_2 emissions embodied in global trade. However, few studies have examined the efficiency of CO_2 emissions trade by combining the global value chain with the CO_2 emissions embodied in trade. Some researchers investigated the changes in value added and the CO_2 emissions embodied in international (Jiang and Liu 2015; Xu, Mu, and Wang 2017; Zhao et al. 2017) or interregional trade (Meng et al. 2018, 2013); however, they have failed to define the linkage between value added and CO_2 emissions. From a comprehensive perspective on both the global value chain and CO_2 emissions trade, the present study proposes a measure of trade efficiency (i.e., carbon trade intensity), namely, the amount of CO_2 emissions trade driven per unit of value added. This study also uses the index to evaluate the carbon trade efficiency for different economies under the global value chain.

The carbon trade intensity index plays a significant role in helping each economy understand its emissions responsibilities. The focus of debate in international climate negotiations has long been the issue of responsibility for reducing greenhouse gas emissions between developed and developing economies. One important debate is who should take responsibility for the carbon transfer and carbon leakage resulting from the transfer of energy-intensive and carbon-intensive industries from developed economies to developing economies. Some argue that the producers should take responsibility for reducing emissions, mainly because producers obtain corresponding economic benefits for their CO_2 emissions. However, quantifying the benefits that developing economies (or CO_2 emitters) obtain from carbon transfer or carbon leakage remains a scientific problem that has not been solved. To address this problem, in this study we propose an index of carbon trade intensity combined with the global value chain. On the basis of the global value chain and carbon emissions spillover effects, this index can be regarded as the negative externalities of the economy, which may include economic benefits. The carbon trade intensity of exports measures the negative externality of foreign consumption in the domestic economy, whereas the carbon trade intensity of imports measures the opposite. The higher the carbon trade intensity is, the stronger the negative externality. Notably, the domestic carbon intensity (DCI) indicates the negative externality of domestic consumption to a country's own economy, which can be compared with carbon emissions in exports and carbon trade in imports.

Therefore, combining the value-added extended global multiregional input–output (GMRIO) model with the environmentally extended GMRIO model, this study mainly measures and analyzes the impacts of international trade on carbon emissions intensity from the perspective of the global value chain. Specifically, this study focuses on an empirical analysis of the carbon trade intensity of major economies to address the following questions:

1. From a global perspective, what is the global carbon trade intensity under the division framework of the global value chain?
2. In the major economies, what is the relationship between CO_2 emissions export intensity, CO_2 emissions import intensity, and domestic CO_2 emissions intensity?
3. From a time-series perspective, what is the difference between developed and developing economies in terms of the trend of change in carbon trade intensity over time?
4. Finally, with respect to economies with high export or import trade intensity, what is the bilateral carbon trade intensity of economies with high CO_2 emissions export and import intensity from other economies?

Section 1 introduces the model and data used in this study. Section 2 comprehensively analyzes the overall carbon trade intensity in the global value chain, which responds to question 1. The main results for related indicators of carbon trade intensity in major economies are presented in Section 3 and respond to questions 2 and 3 from the carbon intensity and time-series perspectives. It is followed by bilateral carbon trade intensity analysis of selected economies in Section 4, which responds to question 4. Lastly, the main conclusions and implications are presented in Section 5.

1. Methodology and Data

1.1. Multiregional Input-Output Model

The basic methodology used in this study is the GMRIO model from the perspective of both the environment and the global value chain. With reference to the original input-output (IO) technology (Miller and Blair 2009), the basic equation in the single-country IO model is expressed as Equation (1) or Equation (2).

$$X = AX + F \tag{1}$$

$$X = (I - A)^{-1} F \tag{2}$$

where X is the vector of output value, and A is the matrix of direct input coefficients formed with the elements of $a_{ij} = x_{ij} / X_j$, where x_{ij} is the output of the ith sector (or the ith goods) that are directly consumed by the jth sector (or the jth goods), I denotes the identity matrix with the same dimensions as A, and $(I - A)^{-1} = (I + A + A^2 + A^3 + L + A^{k+1} + \cdots)$ is the Leontief inverse matrix or total demand coefficient matrix, and F represents the final use vector.

Further, Equation (1) can be expressed in terms of Equation (3), which represents the GMRIO framework.

$$\begin{pmatrix} \mathbf{x}_1 \\ \vdots \\ \mathbf{x}_m \\ \vdots \\ \mathbf{x}_N \end{pmatrix} = \begin{pmatrix} \mathbf{A}_{11} & \cdots & \mathbf{A}_{1v} & \cdots & \mathbf{A}_{1N} \\ \vdots & \ddots & \vdots & \iddots & \\ \mathbf{A}_{m1} & \cdots & \mathbf{A}_{mv} & \cdots & \mathbf{A}_{mN} \\ \vdots & \iddots & \vdots & \ddots & \\ \mathbf{A}_{N1} & \cdots & \mathbf{A}_{Nv} & \cdots & \mathbf{A}_{NN} \end{pmatrix} \begin{pmatrix} \mathbf{x}_1 \\ \vdots \\ \mathbf{x}_m \\ \vdots \\ \mathbf{x}_N \end{pmatrix} + \sum_{m=1}^{N} \begin{pmatrix} \mathbf{f}_{1m} \\ \vdots \\ \mathbf{f}_{vm} \\ \vdots \\ \mathbf{f}_{Nm} \end{pmatrix} \tag{3}$$

where $\mathbf{x_m}$ is the vector of the total output of region m, with $m = 1, \cdots, N$; $\mathbf{A_{mv}}$ is the interindustrial matrix between region m and region v ($v = 1, \cdots, N$), where the elements are measured per unit of output; and $\mathbf{f_{vm}}$ is the vector of the final demand in region m provided by region v, and its elements are the sum of all final demand items, including investment, household consumption, government consumption, and changes in inventory.

Let L represent the Leontief inverse matrix, as shown in Equation (4).

$$L = (I - A)^{-1} \tag{4}$$

Extending Equation (4) into the GMRIO framework enables us to obtain the relationship between the final consumption of each region and total output of each industry. The CO_2 flow matrix can be derived using the carbon emissions factor vector of each region, which indicates the CO_2 emissions per industry output in region m. For simplicity, we use as an example the IO model of three regions (regions A, B, and R), as shown in Equation (5).

$$\begin{bmatrix} \mathbf{C_{AA}} & \mathbf{C_{AB}} & \mathbf{C_{AR}} \\ \mathbf{C_{BA}} & \mathbf{C_{BB}} & \mathbf{C_{BR}} \\ \mathbf{C_{RA}} & \mathbf{C_{RB}} & \mathbf{C_{RR}} \end{bmatrix} = \begin{bmatrix} (\mathbf{E_A})' & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & (\mathbf{E_B})' & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & (\mathbf{E_R})' \end{bmatrix} \begin{bmatrix} \mathbf{L_{AA}} & \mathbf{L_{AB}} & \mathbf{L_{AR}} \\ \mathbf{L_{BA}} & \mathbf{L_{BB}} & \mathbf{L_{BR}} \\ \mathbf{L_{RA}} & \mathbf{L_{RB}} & \mathbf{L_{RR}} \end{bmatrix} \begin{bmatrix} \mathbf{f_{AA}} & \mathbf{f_{AB}} & \mathbf{f_{AR}} \\ \mathbf{f_{BA}} & \mathbf{f_{BB}} & \mathbf{f_{BR}} \\ \mathbf{f_{RA}} & \mathbf{f_{RB}} & \mathbf{f_{RR}} \end{bmatrix} \tag{5}$$

For example, C_{AB} refers to the CO_2 emissions of region A embodied in the final consumption of region B and is defined as CO_2 exports from region A to region B.[1] At the same time, other elements have the same meaning, except for the subscripts, which denote the source and destination of the carbon flow. $\mathbf{E}_A$,$\mathbf{E}_B$, and $\mathbf{E}_R$ are the carbon emissions factor vectors of regions A, B, and R, respectively. Other symbols represent the same variables as in Equations (2) to (4), except for the various subscripts. For instance, $\mathbf{f_{AB}}$ denotes the final demand of region B for commodities produced in region A. Extending this example to multiple regions, the CO_2 flow matrix, which is the concern of this study, can be expressed as Equation (6).

$$\mathrm{C} = \begin{pmatrix} C_{11} & \cdots & C_{1v} & \cdots & C_{1N} \\ \vdots & \ddots & \vdots & \iddots & \\ C_{m1} & \cdots & C_{mv} & \cdots & C_{mN} \\ \vdots & \iddots & \vdots & \ddots & \\ C_{N1} & \cdots & C_{Nv} & \cdots & C_{NN} \end{pmatrix} \tag{6}$$

where C_{mv} refers to the CO_2 exports from region m to region v. The total exported production emissions from region m, represented by $C_m^{\exp}$, is the sum of production emissions in region m embodied in the final consumption of all the other regions in the global supply chain (see Equation (7)). At the same time, the total imported consumption emissions into region v, C_v^{imp}, is represented by the sum of emissions from all the other regions in the global supply chain (see Equation (8)). For simplicity, we call $C_m^{\exp}$ and C_v^{imp} exports and imports of CO_2 emissions, respectively.

$$C_m^{\exp} = \sum_{v \neq m}^{N} C_{mv} \tag{7}$$

$$C_v^{imp} = \sum_{m \neq v}^{N} C_{mv} \tag{8}$$

A related indicator is then obtained to represent the difference between CO_2 exports and imports, which can be referred to as the CO_2 emissions trade balance (CETB), as shown in Equation (9).

$$C_v^{net} = C_v^{\exp} - C_v^{imp} \tag{9}$$

where C_v^{net} is the CETB of region v, represented by the difference between CO_2 emissions exports and imports (i.e., net exports). A positive CETB indicates that the region emits more than others, whereas a negative CETB indicates that foreign regions emit more to meet domestic consumption needs. CETB also equals the difference between the production-based principle (PBP) CO_2 emissions and the consumption-based principle (CBP) emissions of a region. A positive trade balance implies that the PBP CO_2 emissions are higher than the CBP CO_2 emissions of the regions.

The global value flow matrix in the context of the three regions (regions A, B, and R) can be obtained by replacing **E** in Equation (5) with the value-added factor vector Vin Equation (10)).

$$\begin{bmatrix} \mathbf{VA_{AA}} & \mathbf{VA_{AB}} & \mathbf{VA_{AR}} \\ \mathbf{VA_{BA}} & \mathbf{VA_{BB}} & \mathbf{VA_{BR}} \\ \mathbf{VA_{RA}} & \mathbf{VA_{RB}} & \mathbf{VA_{RR}} \end{bmatrix} = \begin{bmatrix} (V_{\mathbf{A}})' & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & (V_{\mathbf{B}})' & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & (V_{\mathbf{R}})' \end{bmatrix} \begin{bmatrix} \mathbf{L_{AA}} & \mathbf{L_{AB}} & \mathbf{L_{AR}} \\ \mathbf{L_{BA}} & \mathbf{L_{BB}} & \mathbf{L_{BR}} \\ \mathbf{L_{RA}} & \mathbf{L_{RB}} & \mathbf{L_{RR}} \end{bmatrix} \begin{bmatrix} \mathbf{f_{AA}} & \mathbf{f_{AB}} & \mathbf{f_{AR}} \\ \mathbf{f_{BA}} & \mathbf{f_{BB}} & \mathbf{f_{BR}} \\ \mathbf{f_{RA}} & \mathbf{f_{RB}} & \mathbf{f_{RR}} \end{bmatrix} \tag{10}$$

where $\mathbf{VA_{AB}}$ represents the value added of region A embodied in (or driven by) the final consumption of region B and thus can be referred to as the induced value added in region A by exports from region A to region B. Simply stated, $\mathbf{VA_{AB}}$ refers to the value added in exports from region A to region B (or value added imported from region B to region A). Other elements have the same meaning, except for the subscripts. V_A, V_B, and V_R indicate the value-added ratio vector of regions A, B, and R, respectively. Like the carbon emissions factor, they are measured by the ratio of value added and output per industry in each region. This is an important reflection of the global value chain embodied in products, expressed as the flow of added value in the production process of products. Like Koopman, Wang, and Wei (2014), we did not divide the global value chain among different economies for specific goods but focused on the entire value chain for specific international trade economies.

As in the aforementioned carbon flow matrix, when extending the example involving the three regions, we can obtain the value-added flow matrix **VA** among N regions (see Equation (11)). VA_{mv} in **VA** represents the value added in region m induced by exports from region m to region v.

$$\mathrm{VA} = \begin{pmatrix} VA_{11} & \cdots & VA_{1v} & \cdots & VA_{1N} \\ \vdots & \ddots & \vdots & \iddots & \\ VA_{m1} & \cdots & VA_{mv} & \cdots & VA_{mN} \\ \vdots & \iddots & \vdots & \ddots & \\ VA_{N1} & \cdots & VA_{Nv} & \cdots & VA_{NN} \end{pmatrix} \tag{11}$$

In addition, a constant price adjustment of the value added by different economies is required for the carbon trade intensity to be comparable among different years. To achieve this adjustment, we first calculate the value-added matrices at previous-year prices using the same methods, except for global I–O tables at previous-year prices rather than at current-year prices, as shown in Equation (12).

$$\begin{bmatrix} \overline{\mathbf{VA}}_{\mathbf{AA}} & \overline{\mathbf{VA}}_{\mathbf{AB}} & \overline{\mathbf{VA}}_{\mathbf{AR}} \\ \overline{\mathbf{VA}}_{\mathbf{BA}} & \overline{\mathbf{VA}}_{\mathbf{BB}} & \overline{\mathbf{VA}}_{\mathbf{BR}} \\ \overline{\mathbf{VA}}_{\mathbf{RA}} & \overline{\mathbf{VA}}_{\mathbf{RB}} & \overline{\mathbf{VA}}_{\mathbf{RR}} \end{bmatrix} = \begin{bmatrix} (\overline{V}_{\mathbf{A}})' & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & (\overline{V}_{\mathbf{B}})' & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & (\overline{V}_{\mathbf{R}})' \end{bmatrix} \begin{bmatrix} \overline{\mathbf{L}}_{\mathbf{AA}} & \overline{\mathbf{L}}_{\mathbf{AB}} & \overline{\mathbf{L}}_{\mathbf{AR}} \\ \overline{\mathbf{L}}_{\mathbf{BA}} & \overline{\mathbf{L}}_{\mathbf{BB}} & \overline{\mathbf{L}}_{\mathbf{BR}} \\ \overline{\mathbf{L}}_{\mathbf{RA}} & \overline{\mathbf{L}}_{\mathbf{RB}} & \overline{\mathbf{L}}_{\mathbf{RR}} \end{bmatrix} \begin{bmatrix} \overline{\mathbf{f}}_{\mathbf{AA}} & \overline{\mathbf{f}}_{\mathbf{AB}} & \overline{\mathbf{f}}_{\mathbf{AR}} \\ \overline{\mathbf{f}}_{\mathbf{BA}} & \overline{\mathbf{f}}_{\mathbf{BB}} & \overline{\mathbf{f}}_{\mathbf{BR}} \\ \overline{\mathbf{f}}_{\mathbf{RA}} & \overline{\mathbf{f}}_{\mathbf{RB}} & \overline{\mathbf{f}}_{\mathbf{RR}} \end{bmatrix} \tag{12}$$

where $\overline{\mathbf{VA}}$, $\overline{V}$, $\overline{\mathbf{L}}$, and $\overline{\mathbf{f}}$ have the same meanings as those without bars. They are all calculated based on I–O data at previous-year prices.

After introducing the code for year t, the element of the value-added matrix at 1995 constant prices (the real value added) can be obtained using Equation (13).

$$\overline{\overline{VA}}_{mvt} = \begin{cases} \overline{VA}_{mvt} & t=1996 \\ \overline{VA}_{mvt} \Big/ \prod_{t=1997}^{t} \left(VA_{mv(t-1)} / \overline{VA}_{mv(t-1)} \right) & t \geq 1997 \end{cases} \tag{13}$$

where $\overline{\overline{VA}}_{mvt}$ denotes the real value added in region m induced by exports from region m to region v in year t (at 1995 constant prices). $\overline{VA}_{mvt}$ is the same as $\overline{\mathbf{VA}}_{\mathbf{AB}}$ in Equation (12), except that subscript AB extended into mv and subscript t added, which indicates that the value is in year t.

Accordingly, the total value-added exports of region m in the global value chain ($\overline{\overline{VA}}_m^{\exp}$) can be obtained using Equation (14)—that is, the sum of the value added in exports from region m is embodied in the final consumption of all the other regions. At the same time, the total value-added imports of region v ($\overline{\overline{VA}}_v^{imp}$) can be obtained using Equation (15)—that is, the sum of the value added in each region from which products are exported to region v. For simplicity, we call $\overline{\overline{VA}}_m^{\exp}$ and $\overline{\overline{VA}}_v^{imp}$ exports and imports of value added, analogous to the definition of emissions.

$$\overline{\overline{VA}}_m^{\exp} = \sum_{v \neq m}^{N} \overline{\overline{VA}}_{mv} \tag{14}$$

$$\overline{\overline{VA}}_v^{imp} = \sum_{m \neq v}^{N} \overline{\overline{VA}}_{mv} \tag{15}$$

Thus, global carbon intensity (GCI) and global trade carbon intensity (TCI) can be calculated using Equations (16–17).

$$GCI = \sum_{m=1}^{N} \sum_{v=1}^{N} C_{mv} / \sum_{m=1}^{N} \sum_{v=1}^{N} \overline{\overline{VA}}_{mv} \tag{16}$$

where GCI indicates that the carbon emissions per unit of global value added measures overall carbon intensity at the global level.

$$TCI = \sum_{m=1}^{N} \sum_{v=1}^{N} C_{mv} / \sum_{m=1}^{N} \sum_{v=1}^{N} \overline{\overline{VA}}_{mv} (m \neq v) \tag{17}$$

where TCI is the carbon emissions per unit of global value added in international trade and measures the carbon trade intensity at the global level in terms of both emissions reduction and the global value chain.

In addition, bilateral intensity is defined as carbon trade intensity between two economies, which includes bilateral export carbon intensity (ECI) (Equation (18)) and bilateral import carbon intensity (ICI) (Equation (19)).

$$CI_{mv}^{\exp} = C_{mv}/\overline{\overline{VA}}_{mv}(v \neq m) \tag{18}$$

where $CI_{mv}^{\exp}$ is the bilateral export carbon intensity from region m to region v, which indicates the CO_2 export per unit of value-added exports from region m to region v.

$$CI_{mv}^{imp} = C_{vm}/\overline{\overline{VA}}_{vm}(m \neq v) \tag{19}$$

where CI_{vm}^{imp} is the bilateral import carbon intensity from region m to region v, which indicates the CO_2 imports per unit of value-added imports from region m to region v.

Thus the ECI of region m ($CI_m^{\exp}$) (Equation (20)) and ICI of region v (CI_v^{imp}) (Equation (21)) can be expressed as:

$$CI_m^{\exp} = C_m^{\exp}/\sum_{v \neq m}^{N} \overline{\overline{VA}}_{mv} \tag{20}$$

where $CI_m^{\exp}$ indicates the CO_2 exports per unit of value-added exports of region m.

$$CI_v^{imp} = C_v^{imp}/\sum_{m \neq v}^{N} \overline{\overline{VA}}_{mv} \tag{21}$$

where CI_v^{imp} indicates that the the CO_2 imports per unit of value-added imports of region v.

The additional local carbon intensity CI_m^{loc} is included for comparison, as it is comparable to the other two intensities in the framework of global value added (Equation (22)).

$$CI_m^{loc} = C_{mv}/\overline{\overline{VA}}_{mv}(v = m) \tag{22}$$

where CI_m^{loc} indicates that the CO_2 per unit of value added of region m.

1.2. Data Source

The data source for this study is the world input–output database (WIOD). WIOD provides continuous time series (1995–2009) in non-competitive world IO tables.[2] It covers 41 economies (40 economies and a "rest-of-the-world" entry) and 35 sectors, including IO tables, corresponding to socioeconomic data (e.g., price indices) and environmental accounts (Dietzenbacher et al. 2013). These data have been successfully used in many empirical studies in multiple fields (Fajgelbaum and Khandelwal 2016; Huang et al. 2018; Johnson and Noguera 2012; Timmer et al. 2014; Xu and Dietzenbacher 2014). This study uses both current and previous prices in the WIOD as well as the emissions factor by sector in every economy (see Table 1).

Consistent with the data sources, the national CO_2 emissions in this study refer to energy-related carbon emissions, excluding emissions caused by direct household energy consumption.

2. Overview of Global Carbon Intensity and Trade Carbon Intensity

As shown in Figure 1, both total global CO_2 emissions and global value-added generally increase during the 1995–2009 period but slightly decrease in 2009 because of the economic crisis. Compared

Table 1. Data description.

Names	Years	Description
World input–output table at current prices	1995–2009	41 economies
World input–output table at previous-year prices		35 industries
Emission factors		

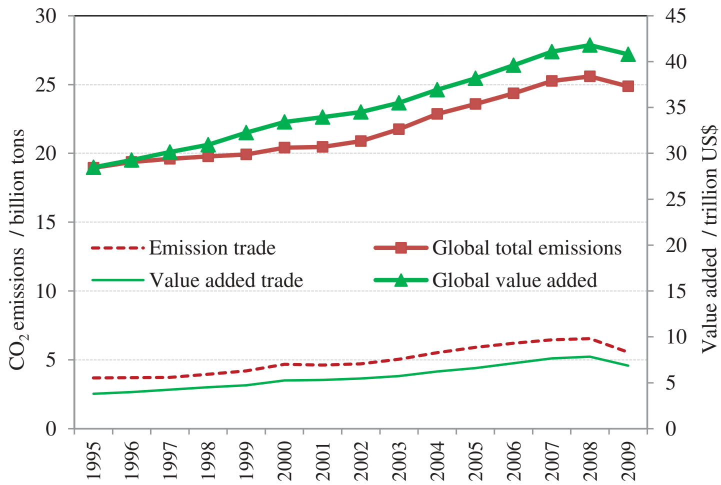

Figure 1. CO_2 emissions and value added at global and trade levels from 1995 to 2009.
Note: The global value added and value-added trade are measured at constant 1995 prices in USD. The global value added here is calculated through combining the row of value added in the world input-output table provided by the WIOD, thus is slightly different with the global GDP due to the difference in the statistical caliber.

with global CO_2 emissions, global value added grew more rapidly, with an annual growth rate of 2.99% during the 1995–2008 period (compared growth of 2.34% in CO_2 emissions). Meanwhile, in addition to a slight decline in 2009, both global CO_2 emissions trading and value-added trade showed an upward trend during the 1995–2009 period; value-added trade also increased more rapidly. Global CO_2 emissions trading increased from 3.69 billion tons in 1995 to 5.56 billion tons in 2009, at an average annual growth of 2.98%. Value-added trade increased from USD 3.79 trillion in 1995 to USD 6.85 trillion in 2009, at an average annual growth of 4.32%.

However, a comparison of the ratio of CO_2 emissions to value added (namely, carbon intensity) at a global perspective with that of the trading perspective indicates that trade CO_2 intensity is higher than GCI (Figure 2). This finding suggests that, with the integration of the global supply chain, per-unit value-added trade involved higher CO_2 emissions than the global average. Figure 2 also shows that from 1995 to 2009, global CO_2 emission trade intensity under the global value chain shows an overall downward trend. Specifically, fluctuation occurs from 1995 to 2005, and a prominent declining trend is seen from 2005 to 2009, similar to the findings in Wang, Ang, and Su (2017). It decreases from 0.89 kg of CO_2 per USD in 2005 to 0.81 kg of CO_2 per USD in 2009, a reduction of 9.2%. This finding indicates that the development of the global supply chain contributed to a decrease in global CO_2 emissions intensity.

3. Comparison of CO_2 Trade Intensity in Major Economies

We selected 14 of the 41 economies to conduct an analysis based on total emissions and emissions embodied in international trade, which is consistent with our previous studies (Fan et al. 2016, 2017):[3]

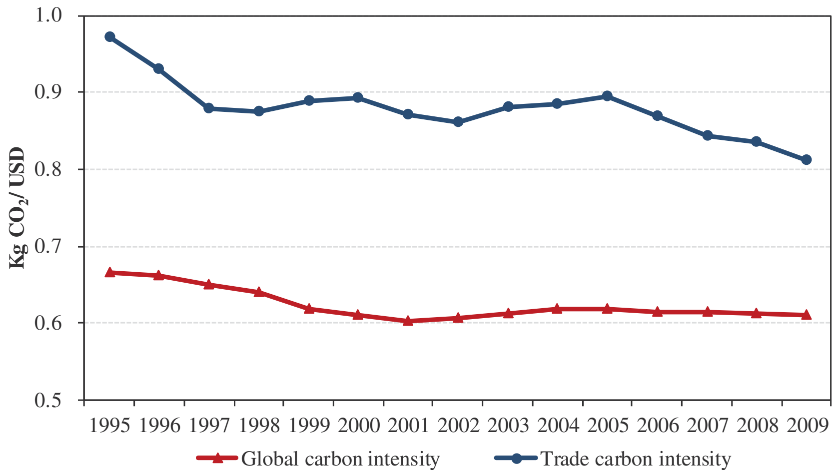

Figure 2. Global carbon intensity and trade carbon intensity under the global value chain from 1995 to 2009.

Australia (AUS), Canada (CAN), China (CHN),[4] Germany (DEU), Spain (ESP), France (FRA), the United Kingdom (GBR), India (IND), Italy (ITA), Japan (JPN), Korea (KOR), Russia (RUS), Chinese Taiwan (TWN), the United States (USA), and the rest of the world (ROW). By including more countries, our ROW sample differs from the WIOD. To avoid deviations from the calculation, we did not merge the original IO table but, instead, aggregated the indicators based on the emissions accounting results.

Figure 3 shows the CO_2 trade intensity of these 14 economies, including export intensity, import intensity, and local/domestic intensity. A comparison of these three types of intensity indicates differences between developed economies and developing economies (or transition economies). An exception is Australia, whose export intensity is slightly higher than its import intensity. The intensity of other developed economies reveals the following characteristics: import intensity > export intensity > domestic intensity. In China, India, Chinese Taiwan, and Russia (a transition economy), export intensity is considerably higher than domestic intensity. In China, local carbon intensity is higher than import intensity, but in the other three economies it is lower. In addition, no notable difference in imported CO_2 intensity is observed between economies, unlike export CO_2 intensity, which has a range of 0.55–1.24 kg of CO_2 per USD, perhaps because most developed countries have a dispersed import structure of commodities, which makes the average carbon intensity similar. Four economies have an import intensity exceeding 0.9 kg of CO_2 per USD—India, Japan, Korea, and Canada, listed from high to low. These values reflect higher negative externalities in their own domestic consumption compared to the CO_2 emissions in other economies. In addition, three economies have an import intensity below 0.65 kg of CO_2 per USD—the United Kingdom, Chinese Taiwan, and Russia, listed from high to low. Accordingly, these economies have lower negative externalities in their domestic consumption to the CO_2 emissions of other economies.

However, developing and developed economies have apparent differences in export intensity, with the former having significantly higher export intensity than the latter, except for Australia. This is related to Australia's particular structure of import and export trade. Australia exports a large number of products with high carbon intensity, such as iron ore steel, and mining and fuels metals, while its imports are concentrated in industries such as tourism and transportation, which have relatively low carbon intensity (Hao et al. 2018; Shafiullah, Selvanathan, and Naranpanawa 2017). For example, in 2009 exports from the mining and quarrying sector accounted for 40.8% of Australia's total exports, with the second largest (13.2%) from the basic metals and percussion metal sector (Timmer et al. 2015).

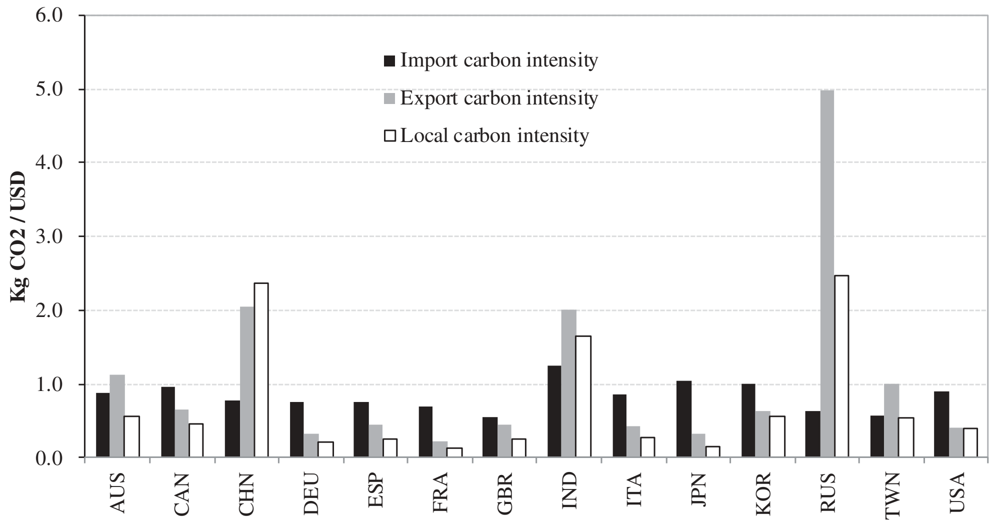

Figure 3. Import, export and local carbon intensities of major economies under the global value chain (in 2009).
Note: Kg = kilogram.

Russia has the highest export intensity, as much as 4.98 kg of CO_2 per USD. China, India, Australia, and Chinese Taiwan follow, with export intensity of 2.05, 2.00, 1.12, and 1.00 kg of CO_2 per USD, respectively. The other economies, all developed countries, have export intensity below 0.7 kg of CO_2 per USD. Among these economies, France has the lowest export intensity (0.22 kg of CO_2 per USD), followed by Germany and Japan, with export intensity below 0.4 kg of CO_2 per USD. This indicates that foreign consumption under the global supply chain has created more serious negative externalities in developing economies than in developed economies and that their CO_2 exports have relatively low economic efficiency. Another common characteristic for developing economies is that their domestic CO_2 intensity is significantly higher than that of developed economies, except China, even though it is lower than their export intensity. Economies with a higher domestic CO_2 intensity, listed from high to low, are Russia, China, and India, with 2.47, 2.37, and 1.65 kg of CO_2 per USD, respectively. Therefore, on the basis of the experience in developed economies, reducing domestic and exported carbon intensity while increasing import intensity is a feasible method for developing economies to use for achieving development with lower carbon emissions.

Figure 4 shows the changes in the three types of CO_2 intensity in the major economies between 1995 and 2009. Except for the import intensity of Canada, the export intensity of Australia, and Chinese Taiwan, all the other data points are located below the diagonal. This observation indicates that almost all export intensity, import intensity, and domestic intensity was lower in 2009 than in 1995. However, as represented by the distance from the diagonal, the degree of decline varies among the economies. All three types of carbon emissions intensity in developed economies are concentrated mostly in the vicinity of the bottom left of the line, indicating that the carbon trade intensity of these economies is generally low and has not significantly decreased. At the same time, the export and domestic intensity of China, India, and Russia is located on the right side and at a significant distance from the line, with China's export intensity showing the largest decrease (51.97%). This finding indicates that the export and domestic intensity of these economies is high but has declined significantly, particularly their CO_2 export trade efficiency, which contributes significantly to reduction in domestic and global emissions. In addition, the import intensity of these three economies is located near the line, which indicates the absence of notable change from 1995 to 2009. In addition, the import intensity of Canada increased during this period, which reflects an increase in the negative

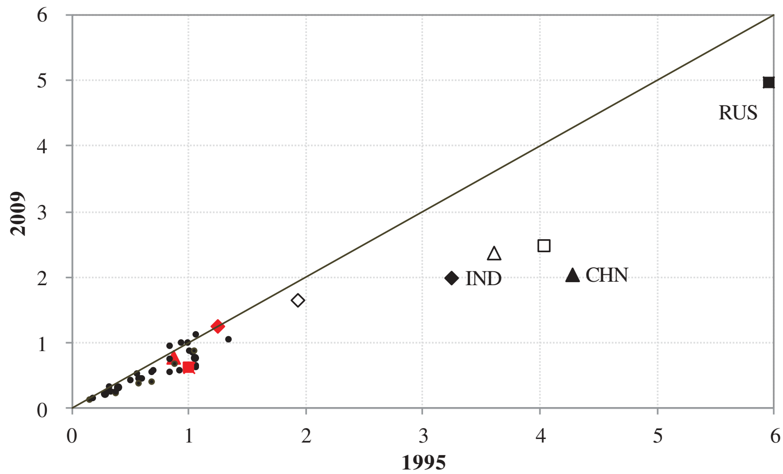

Figure 4. Changes in import, export and local carbon intensities for major economies under the global value chain from 1995 to 2009.
Note: The unit of measurement is kg of CO_2 per USD; 42 scatter points are found (14 economies * 3 types of intensity). Several points are specifically marked: China (CHN), India (IND), and Russia (RUS) are represented by a triangle, a diamond, and a square, respectively; shapes filled with black, white, and red represent export carbon intensity, local carbon intensity, and import carbon intensity, respectively.

externality effect of its consumption on foreign CO_2 emissions. However, the corresponding effects and factors for this change require further study. Australia and Chinese Taiwan's increase in export intensity indicates that the negative externalities of foreign consumption to these two economies increase with time. This situation could hinder the energy-saving and emission reduction efforts in these economies.

Comparisons between export and import intensity from 1995 to 2009, as shown in Figure 5, reveal that the curves of India, China, Russia, and Chinese Taiwan, as well as part of the curves of Australia and Canada, are located above the line for an equal ratio,[5] indicating higher export intensity than import intensity for these economies. However, the relative position and characteristics of the curves for these economies differ. The export intensity of India is lower than that of Russia and China but higher than that of Chinese Taiwan. The import intensity of India is higher than that of the other three economies, which results in locations at the center and slightly leaning toward the right side of the curve. Meanwhile, because of the fluctuation in India's import intensity (increasing and decreasing trends from 2005 to 2009), its curve significant fluctuates and extends from left to right. In general, India's export intensity decreased, and import intensity changed only slightly, decreasing from 1.25 kg of CO_2 per USD in 1995 to 1.24 kg of CO_2 per USD in 2009, thereby narrowing the difference between the two kinds of carbon intensity, and pushing the curve close to the equal ratio line. The curves of Russia and China are located on the top left side and are generally spread from the upper right to the bottom left over time, indicating that both their export and import intensity has declined and that the difference between them decreases over time. Meanwhile, the curve of Russia markedly fluctuates and also shifts between left and right, specifically showing the highest export intensity, 11.17 kg of CO_2 per USD, and the lowest import intensity, 0.32 kg of CO_2 per USD in 1998. This results from the Russian financial crisis as well as the significant devaluation of the ruble during the crisis in 1998. For example, Russian export value added significantly declined in 1995–1998, from USD 73,049 million to USD 44,431 million (in 1995 constant prices). The curve of China shifts significantly between left and right, which reflects the fluctuation in import intensity, particularly the significant decrease in recent years (since 2002). This is related to China's accession to the WTO. For instance, China's imports increased rapidly, 40.0% in 2003 compared with 2002, far

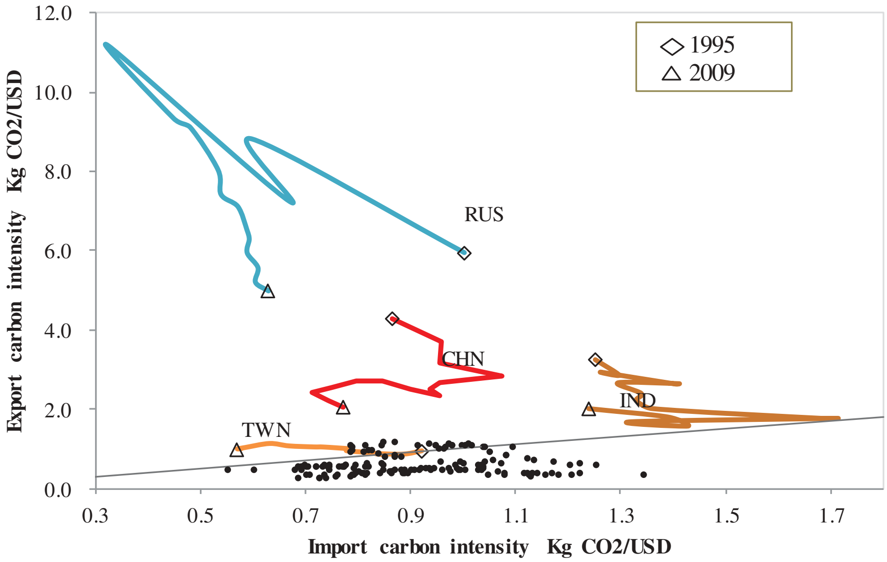

Figure 5. Export and import carbon intensity of major economies from 1995 to 2009.
Note: The line in the figure is the equal ratio line, which consists of points with equal export and import intensity. Economies below the line are represented by black points in a scatter plot, and those above the line are represented by curves. A total of 131 black points comprise the scatter plot for 9 economies over the 14-year period.

more than before 2002 (NBS 2004). Imported goods may largely consist of high value-added products, thus driving further growth in global value added and decreasing ICI. The curve of Chinese Taiwan is closest to the equal ratio line and is unidirectional from right to left (front to back), reflecting an apparent and continuous decrease in import intensity, indicating that its demand for carbon-intensive products is increasingly dependent on imports, and the negative externality effect of its consumption on foreign CO_2 emissions is declining. Economies with curves located below the equal ratio line are developed economies, which suggests that the export intensity of these economies is consistently lower than their import intensity for the period 1995 to 2009.

4. Bilateral Carbon Trade Intensity in the Major Economies

This study further examines the bilateral TCI (including domestic intensity) of economies with high export carbon intensity (ECI) and high import trade intensity (Figure 6).[6] No large difference in China's export intensity with the other economies is found; all values are in the 1.48–2.68 kg of CO_2/USD range. China's highest ECI is with Canada and Spain in bilateral trade (both have an intensity of more than 2.4 kg of CO_2/USD) and lowest ECI with Russia (1.5 kg of CO_2/USD). Moreover, China has a high domestic intensity relative to the export intensity of most economies, which is consistent with the results shown in Figure 3. India's intensity with other economies ranges from 1.50 to 4.17 kg of CO_2/USD. Its ECI with Canada, China, and South Korea exceeds 3 kg of CO_2/USD and that with the US and the UK is about 1.5 kg of CO_2/USD. In particular, India's DCI is lower than all others, except that of the UK and the US. Russia's export intensity with other economies is generally high, ranging from 2.47 to 7.13 kg of CO_2/USD.[7] Its intensity with Canada and Italy is the highest, at approximately 7 kg of CO_2/USD.

As shown in Figure 7, India, Japan, and South Korea have characteristics similar to the countries with which they trade in terms of import intensity with foreign economies: the economies with a higher intensity are mainly developing and transition economies. First, compared with India's bilateral ICI, Russia has the highest import intensity, as much as 4.87 kg of CO_2/USD, followed by China, India, and Australia, which have an import intensity of 2.05, 1.65, and 1.35 kg of CO_2 per

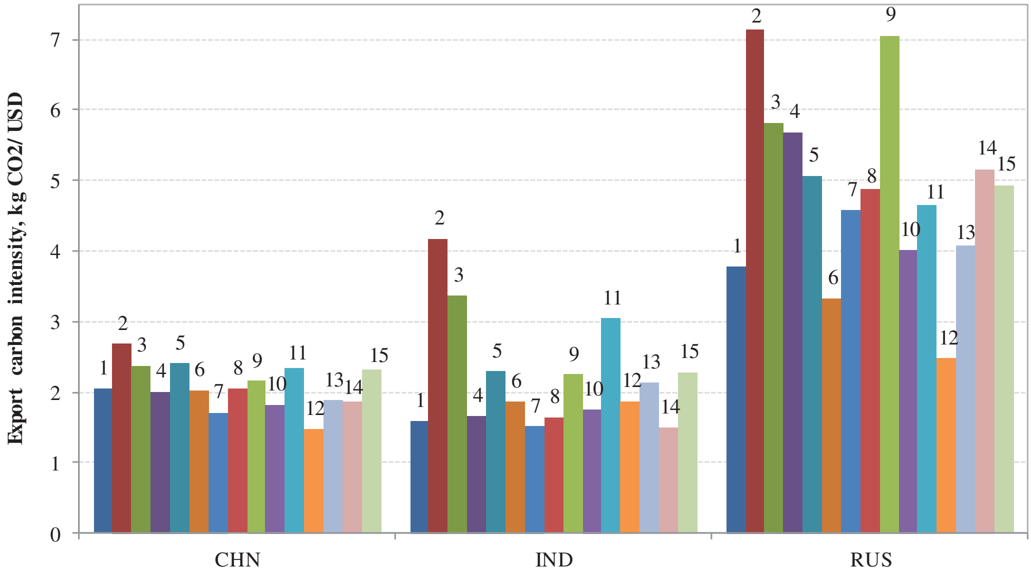

Figure 6. Bilateral export carbon intensity of selected developing economies in 2009.

Note: 1- Australia (AUS), 2-Canada (CAN), 3-China (CHN), 4-Gemany (DEU), 5- Spain (ESP), 6- France (FRA), 7-Great Britain (GBR), 8- India (IND), 9- Italy (ITA), 10-Japan (JPN), 11- Korea (KOR), 12- Russia (RUS), 13- Chinese Taiwan (TWN), 14- the USA (USA), and 15- Rest-of-the-World (ROW). We emphasize these three economies because their ECIs are higher than those of other economies.

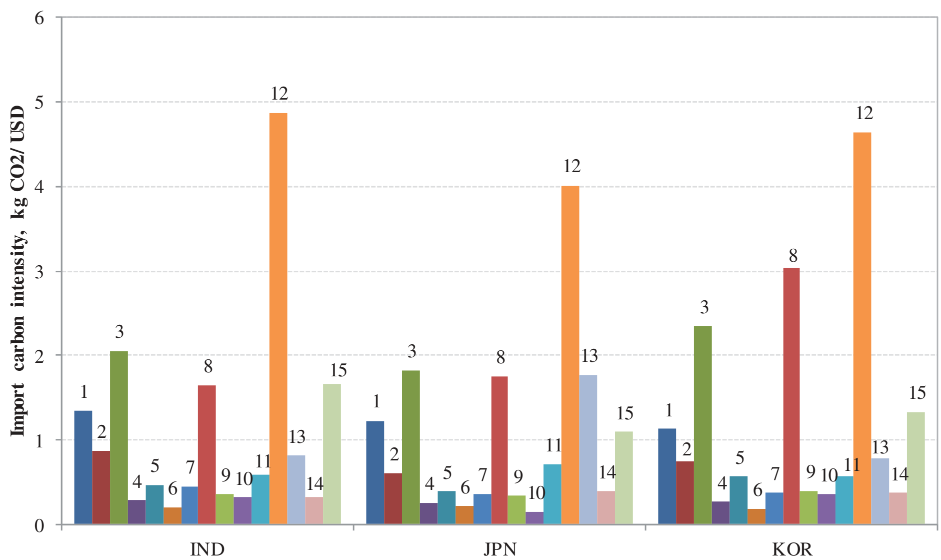

Figure 7. Bilateral import carbon intensity of selected economies in 2009.

Note: 1-Australia (AUS), 2-Canada (CAN), 3-China (CHN), 4-Gemany (DEU), 5-Spain (ESP), 6-France (FRA), 7-Great Britain (GBR), 8-India (IND), 9-Italy (ITA), 10-Japan (JPN), 11-Korea (KOR), 12-Russia (RUS), 13-Chinese Taiwan (TWN), 14-US (USA), and 15-Rest-of-the-World (ROW). These economies are presented and analyzed because they are the three economies with the highest import carbon intensity (ICI).

USD respectively. The import intensity from the other economies is below 1 kg of CO_2 per USD, except for ROW, whereas that from France is the lowest, 0.2 kg of CO_2 per USD. Like India, Japan has the highest import intensity from Russia, 4.0 kg of CO_2 per USD, which is 27 times that of domestic intensity (which is the lowest level). China, Chinese Taiwan, and India follow, with more than 1.7 kg of CO_2 per USD. In addition, the import intensity of Japan from Australia is also rather high (1.23 kg of CO_2 per USD). South Korea has the highest import intensity from Russia, 4.64 kg of CO_2 per USD, followed by that from India, China, Australia, and ROW, with corresponding import intensity of 3.04, 2.34, 1.33, and 1.12 kg of CO_2 per USD respectively. Intensity from the other economies is below 1 kg of CO_2 per USD. Obviously, all three selected economies have the highest import intensity with Russia. This is because three economies import a large number of carbon-intensive products from Russia. For example, in 2009, 34.58% of Japanese imports of Russian products were in the coke, refined petroleum, and nuclear fuel sectors. Basic metals and fabricated metal accounted for 22.88% of imports to Japan from Russia. Both of these sectors sell carbon-intensive products. Similarly, Korean imports of coke, refined petroleum, and nuclear fuel from Russia comprised 47.77% of its imports (Timmer et al. 2015). This implies that to lower global carbon emissions caused by Russian exports, Russian policy makers should formulate future emissions reduction plans and measures in carbon-intensive industries.

5. Main Conclusions and Implications

On the basis of comprehensive perspectives on the global value chain and international carbon trade segmentation, this study proposes a new index to evaluate carbon trade efficiency—that is, carbon trade intensity under the global value chain—and conducts an empirical calculation for the 14 major emitters in the period 1995–2009. Our main conclusions and implications are as follows.

5.1. Main Conclusions

Overall, global TCI under the perspective of global value chain has declined over time. This indicates that international trade has begun to have less environmental impact, but these impacts vary by country.

First, in 2009, the carbon trade intensity of developing economies (or transition economies) varies a great deal from that of developed economies. Among the 14 major economies studied here, China, India, Chinese Taiwan, and Russia have considerably higher export intensity than domestic intensity and import intensity. In the other economies, import intensity is higher than export intensity and domestic intensity. At the same time, no noteworthy difference in imported CO_2 intensity is observed between economies, whereas obvious differences between them exist in terms of their export intensity. Moreover, the export intensity of developing economies (including transition economies) is significantly higher than that of developed economies.

Second, compared with 1995, the three types of carbon intensity decreased for almost all economies, although at varying degrees. The carbon trade intensity of developed economies is concentrated and shows no notable reduction, whereas the export and domestic intensity of China, India, and Russia are high and have significantly decreased; China showed the highest decrease in export intensity (52.0%). Specifically, the increase in export intensity of Australia and Chinese Taiwan could impede efforts toward energy savings and emissions reduction. From a continuous time-series perspective, the export intensity of developing and transition economies reveals an unstable and fluctuating trend; meanwhile, the export intensity of developed economies in general is consistently lower than their import intensity.

Third, on the basis of bilateral carbon trade intensity (in 2009), no large difference exists in the intensity of Chinese exports to other economies, which ranges from 1.5 (to Russia) to 2.7 (to Canada) kg of CO_2/USD. In India, larger differences exist in the intensity of exports to other economies, from 1.5 (to the UK) to 4.2 kg of CO_2/USD (to Canada). Russia's export intensity to other economies is typically high, from 2.5 to 7.1 kg of CO_2/USD. In addition, the import intensity of

India, Japan, and South Korea with foreign economies shows that countries with higher intensity are mainly developing and transition economies.

5.2. Policy Implications

The main policy implications of this study come from the objective function of the carbon trade intensity index and scientific emission reductions pathways available to developing economies, as follows.

First, the carbon emissions trade intensity index objectively describes the economic characteristics of carbon emissions spillovers in the context of globalization. It also explains the economic motivations for carbon transfer from developed to developing economies. By comparing the carbon emissions trade intensity indices between different economies, we can comprehensively and objectively evaluate the economic efficiency of carbon emissions trading (imports and exports) under the global value chain and deepen research on the rights and responsibilities of each economy in negotiations over how to confront climate change. For example, the export intensity of China, India, and Russia is significantly higher than that of the developed economies, which indicates that they have relatively high CO_2 emissions from the consumption of other economies—that is, obtaining relatively less revenue for value added at the cost of higher CO_2 emissions.

Second, the excessively high export intensity and somewhat high domestic intensity, as well as the low import intensity from (part of) other economies to developing economies continue to hinder their low-carbon development. The experiences of developed economies also show that reducing the difference between export and import intensity can effectively reduce carbon emissions. Therefore, developing economies should implement measures to reduce domestic and exported carbon intensity and narrow the difference between export and import intensity without causing an additional increase in global carbon emissions to realize their carbon intensity reduction targets. In 2016 China submitted a declaration to the United Nations and decided to reduce its CO_2 emissions per unit of gross domestic product (GDP) by 60%–65% of the 2005 level by 2030. Therefore, to achieve this stringent reduction target, apart from reducing the DCI using several measures, such as enhancing energy efficiency and promoting technological innovation, China also needs to improve its carbon emissions trade efficiency by optimizing the structure of imports and exports and enhancing its position in the global value chain. China can implement several measures, such as reducing exports of high energy-consuming products and promoting exports of high-technology products, as well as by increasing imports of highly energy-efficient products, among others.

5.3. Further Perspectives

This study involves numerous calculations by combining the global value chain and international carbon trade with an environmentally extended GMRIO model. The carbon emission trade efficiency of developing economies is compared with that of developed economies. However, constrained by space limitations and our scope, this study is still preliminary, and the carbon intensity indices are only at the level of the economy and not at a micro-level. Therefore, more comprehensive and in-depth research needs to be conducted in the future, including a comparison of the sectoral carbon trade intensity among different economies and an analysis of the driving factors behind changes in carbon trade intensity in the major economies. In addition, given the limited time-span of the environmental data from WIOD, we aim to develop a new database and explore more recent evidence in the near future.

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Notes

1. This is because it can be explained as production emissions from exports from region A to region B, becoming imported consumption emissions.
2. Although the IO table in the WIOD is updated to 2014, the carbon emissions data remain those for 2009, which determines our study period.
3. Here, each of the 14 economies is compared with the 40 economies in the WIOD, possibly rendering the ranking results inconsistent with those for the entire world. According to our calculation, total emissions of these 14 economies accounted for approximately two-thirds of total global emissions.
4. In line with WIOD data collection, in this study China only represents mainland China.
5. The two developed economies in this figure are not marked because they are very close to the equal ratio line.
6. Regarding bilateral carbon trade intensity, the ECI of region A to region B equals the ICI of region B from region A.
7. Here Russia has the lowest domestic carbon intensity, 2.47 kg of CO_2 per USD.

References

Acquaye, A., K. Feng, E. Oppon, S. Salhi, T. Ibn-Mohammed, A. Genovese, and K. Hubacek. 2017. Measuring the environmental sustainability performance of global supply chains: A multi-regional input-output analysis for carbon, sulphur oxide and water footprints. *Journal of Environmental Management* 187:571–85. doi:10.1016/j.jenvman.2016.10.059.

Cingolani, I., P. Panzarasa, and L. Tajoli. 2017. Countries' positions in the international global value networks: Centrality and economic performance. *Applied Network Science* 2:21in press. doi:10.1007/s41109-017-0041-4.

Daudin, G., C. Rifflart, and D. Schweisguth. 2011. Who produces for whom in the world economy? Qui produit pour qui dans l'économie mondiale? *Canadian Journal of Economics/Revue Canadienne D'économique* 44:1403–37. doi:10.1111/j.1540-5982.2011.01679.x.

Dedrick, J., K. L. Kraemer, and G. Linden. 2009. Who profits from innovation in global value chains? A study of the iPod and notebook PCs. *Industrial and Corporate Change* 19:81–116. doi:10.1093/icc/dtp032.

Dietzenbacher, E., B. Los, R. Stehrer, M. Timmer, and G. De Vries. 2013. The construction of world input–output tables in the WIOD project. *Economic Systems Research* 25:71–98. doi:10.1080/09535314.2012.761180.

Dolter, B., and P. A. Victor. 2016. Casting a long shadow: Demand-based accounting of Canada's greenhouse gas emissions responsibility. *Ecological Economics* 127:156–64. doi:10.1016/j.ecolecon.2016.04.013.

Fajgelbaum, P. D., and A. K. Khandelwal. 2016. Measuring the unequal gains from trade. *Quarterly Journal of Economics* 131:1113–80. doi:10.1093/qje/qjw013.

Fan, J. L., J. D. Wang, L. S. Kong, and X. Zhang. 2018. The carbon footprints of secondary industry in China: An input-output subsystem analysis. *Natural Hazards* 91 (2):635–57. doi:10.1007/s11069-017-3147-1.

Fan, J. L., Q. Wang, S. Yu, Y. B. Hou, and Y. M. Wei. 2017. The evolution of CO_2 emissions in international trade for major economies: A perspective from the global supply chain. *Mitigation and Adaptation Strategies for Global Change* 22:1229–48. doi:10.1007/s11027-016-9724-x.

Fan, J. L., Y. B. Hou, Q. Wang, C. Wang, and Y. M. Wei. 2016. Exploring the characteristics of production-based and consumption-based carbon emissions of major economies: A multiple-dimension comparison. *Applied Energy* 184:790–99. doi:10.1016/j.apenergy.2016.06.076.

Feng, K., S. J. Davis, L. Sun, X. Li, D. Guan, W. Liu, Z. Liu, and K. Hubacek. 2013. Outsourcing CO_2 within China. *Proceedings of the National Academy of Sciences* 110: 11654–59. doi:10.1073/pnas.1219918110.

Gavrilova, O., and R. Vilu. 2012. Production-based and consumption-based national greenhouse gas inventories: An implication for Estonia. *Ecological Economics* 75:161–73. doi:10.1016/j.ecolecon.2012.01.020.

Guo, J., L. L. Zou, and Y. M. Wei. 2010. Impact of inter-sectoral trade on national and global CO_2 emissions: An empirical analysis of China and US. *Energy Policy* 38:1389–97. doi:10.1016/j.enpol.2009.11.020.

Hao, X., H. An, X. Sun, and W. Zhong. 2018. The import competition relationship and intensity in the international iron ore trade: From network perspective. *Resources Policy* 57:45–54. doi:10.1016/j.resourpol.2018.01.005.

Huang, L., G. Krigsvoll, F. Johansen, Y. Liu, and X. Zhang. 2018. Carbon emission of global construction sector. *Renewable and Sustainable Energy Reviews* 81:1906–16. doi:10.1016/j.rser.2017.06.001.

Jiang, X., and Y. Liu. 2015. Global value chain, trade and carbon: Case of information and communication technology manufacturing sector. *Energy for Sustainable Development* 25:1–7. doi:10.1016/j.esd.2014.12.001.

Johnson, R. C., and G. Noguera. 2012. Accounting for intermediates: Production sharing and trade in value added. *Journal of International Economics* 86:224–36. doi:10.1016/j.jinteco.2011.10.003.

Kim, Y. G., J. Yoo, and W. Oh. 2015. Driving forces of rapid CO_2 emissions growth: A case of Korea. *Energy Policy* 82:144–55. doi:10.1016/j.enpol.2015.03.017.

Koopman, R., Z. Wang, and S. J. Wei. 2014. Tracing value-added and double counting in gross exports. *American Economic Review* 104:459–94. doi:10.1257/aer.104.2.459.

Krugman, P. 1995. Increasing returns, imperfect competition and the positive theory of international trade. *Handbook of international economics*, Vol. 3, 1243–77. doi:10.1016/S1573-4404(05)80004-8.

Levasseur, A., O. Cavalett, J. S. Fuglestvedt, T. Gasser, D. J. A. Johansson, S. V. Jørgensen, M. Raugei, A. Reisinger, G. Schivley, A. Strømman, et al. 2016. Enhancing life cycle impact assessment from climate science: Review of recent findings and recommendations for application to LCA. *Ecological Indicators* 71:163–74. doi:10.1016/j.ecolind.2016.06.049.

Liou, R. W., H. C. Lin, C. C. Chang, and S. H. Hsu. 2016. Unveiling the true value of across-strait trade: The global value chain approach. *China Economic Review* 41:159–80. doi:10.1016/j.chieco.2016.10.001.

Liu, L. C., Q. M. Liang, and Q. Wang. 2015. Accounting for China's regional carbon emissions in 2002 and 2007: Production-based versus consumption-based principles. *Journal of Cleaner Production* 103:384–92. doi:10.1016/j.jclepro.2014.07.009.

Liu, L. J., and Q. M. Liang. 2017. Changes to pollutants and carbon emission multipliers in China 2007-2012: An input-output structural decomposition analysis. *Journal of Environmental Management* 203:76–86. doi:10.1016/j.jenvman.2017.07.061.

Meng, B., G. P. Peters, Z. Wang, and M. Li. 2018. Tracing CO2 emissions in global value chains. *Energy Economics* 73:24–42. doi:10.1016/j.eneco.2018.05.013.

Meng, B., J. J. Xue, K. S. Feng, D. B. Guan, and X. Fu. 2013. China's inter-regional spillover of carbon emissions and domestic supply chains. *Energy Policy* 61:1305–21. doi:10.1016/j.enpol.2013.05.108.

Mi, Z. F., Y. Zhang, D. B. Guan, Y. L. Shan, Z. Liu, R. Cong, X. C. Yuan, and Y. M. Wei. 2016. Consumption-based emission accounting for Chinese cities. *Applied Energy* 184:1073–81. doi:10.1016/j.apenergy.2016.06.094.

Miller, R. E., and P. D. Blair. 2009. *Input-output analysis: Foundations and extensions*. 2nd ed. New York: Cambridge University Press.

NBS. 2004. *China statistical yearbook*. Beijing: China Statistics Press.

Notarnicola, B., G. Tassielli, P. A. Renzulli, and F. Monforti. 2017. Energy flows and greenhouses gases of EU (European Union) national breads using an LCA (Life Cycle Assessment) approach. *Journal of Cleaner Production* 140:455–69. doi:10.1016/j.jclepro.2016.05.150.

Peters, G. P. 2007. Opportunities and challenges for environmental MRIO modelling: Illustrations with the GTAP database. Paper presented at the 16th International Input-Output Conference, Istanbul. doi:10.1094/PDIS-91-4-0467B.

Peters, G. P. 2008. From production-based to consumption-based national emission inventories. *Ecological Economics* 65:13–23. doi:10.1016/j.ecolecon.2007.10.014.

Pothen, F. 2017. A structural decomposition of global raw material consumption. *Ecological Economics* 141:154–65. doi:10.1016/j.ecolecon.2017.05.032.

Shafiullah, M., S. Selvanathan, and A. Naranpanawa. 2017. The role of export composition in export-led growth in Australia and its regions. *Economic Analysis & Policy* 53:62–76. doi:10.1016/j.eap.2016.11.002.

Timmer, M. P., A. A. Erumban, B. Los, R. Stehrer, and G. J. de Vries. 2014. Slicing up global value chains. *Journal of Economic Perspectives* 28 (2):99–118. doi:10.1257/jep.28.2.99.

Timmer, M. P., E. Dietzenbacher, B. Los, R. Stehrer, and G. J. de Vries. 2015. An illustrated user guide to the world input–Output database: The case of global automotive production. *Review of International Economics* 23:575–605. doi:10.1111/roie.12178.

Wang, H., B. W. Ang, and B. Su. 2017. A multi-region structural decomposition analysis of global CO_2 emission intensity. *Ecological Economics* 142:163–76. doi:10.1016/j.ecolecon.2017.06.023.

Weber, C. L., and H. S. Matthews. 2007. Embodied environmental emissions in US international trade, 1997-2004. *Environmental Science & Technology* 41:4875–81. doi:10.1021/es0629110.

Wiloso, E. I., R. Heijungs, and G. R. de Snoo. 2012. LCA of second generation bioethanol: A review and some issues to be resolved for good LCA practice. *Renewable and Sustainable Energy Reviews* 16:5295–308. doi:10.1016/j.rser.2012.04.035.

Wu, R., Y. Geng, H. Dong, T. Fujita, and X. Tian. 2016. Changes of CO_2 emissions embodied in China–Japan trade: Drivers and implications. *Journal of Cleaner Production* 112:4151–58. doi:10.1016/j.jclepro.2015.07.017.

Xu, X., M. Mu, and Q. Wang. 2017. Recalculating CO_2 emissions from the perspective of value-added trade: An input-output analysis of China's trade data. *Energy Policy* 107:158–66. doi:10.1016/j.enpol.2017.04.026.

Xu, Y., and E. Dietzenbacher. 2014. A structural decomposition analysis of the emissions embodied in trade. *Ecological Economics* 101:10–20. doi:10.1016/j.ecolecon.2014.02.015.

Zhang, Z., K. Zhu, and G. J. D. Hewings. 2017. A multi-regional input–Output analysis of the pollution haven hypothesis from the perspective of global production fragmentation. *Energy Economics* 64:13–23. doi:10.1016/j.eneco.2017.03.007.

Zhao, Y., Y. Liu, Z. Zhang, S. Wang, H. Li, and A. Ahmad. 2017. CO_2 emissions per value added in exports of China: A comparison with USA based on generalized logarithmic mean Divisia index decomposition. *Journal of Cleaner Production* 144:287–98. doi:10.1016/j.jclepro.2017.01.031.