Shared responsibility of carbon emission for international trade based on carbon emission embodied between developing and developed countries

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Received: 30 November 2021 / Accepted: 6 October 2022 / Published online: 14 October 2022
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Abstract
Traditional Production-Based Accounting (PBA) principle does not consider the embodied carbon emissions in export and import trade. A multiregional input–output (MRIO) model is constructed to estimate the embodied carbon dioxide emissions of 41 countries and regions worldwide, based on the PBA and shared responsibility approach in this paper. The results indicate that the embodied carbon emissions in 2018 in China’s export trade were 1326 million tons higher than that of import trade. China, India, and the USA have a different carbon coefficient in the 35 sectors, but electricity, gas, and water supply sectors are the largest coefficient for them. A reduction in carbon emission coefficient would contribute to a decrease in imports and exports. Through the empirical analysis of the embodied carbon emissions in China’s import and export trade, it can be seen that China is a major producer of carbon emissions, not a consumer country, and has taken more carbon emissions responsibility for the world. The developed countries should take more shared carbon emission responsibility than the PBA. And it is more reasonable and impartial to assign developed and developing countries carbon emissions responsibility in the light of the shared responsibility method.

Keywords Embodied carbon · Producer responsibility · Shared responsibility · Input–output analysis · Developing countries · Developed countries

Introduction
The 21st United Nations Climate Change Conference, held in Paris in 2015, required signatories to meet the Paris Agreement’s national contribution to carbon emissions, or INDCs, to meet the goal of global temperature rises of no more than 2 °C. Both the Paris Agreement and Kyoto Protocol define the carbon emission responsibilities that a country needs to assume as carbon dioxide produced and emitted within a country’s territory, an accounting standard known as Production-Based Accounting (PBA) (Wang and Yang 2021). Carbon emissions calculations, based on the territorial scope and national boundaries, do not take into account issues such as carbon transfer, carbon concealment, and carbon emissions arising from the division of labor in global value chains and the globalization of trade.

Countries around the world have been working to come up with a convention that would reduce global greenhouse gas and properly allocate global carbon emissions responsibilities. But the only outcome of the idea so far has been the United Nations Conference on Climate Change, the Kyoto Protocol, signed in 1997, which requires developed countries to establish a greenhouse gas emission inventory (Yona et al. 2020). For countries in Annex I of the Kyoto Protocol, there is a need to reduce carbon emissions by 5% relative to 1995. Since China is not a country in Annex I of the Kyoto Protocol, it is not included in the mandatory
carbon reduction. Against the background of the many problems and deadlocks in international climate negotiations (Franzen and Mader 2018), how constructing a more equitable and effective new international climate regime is an urgent and serious challenge facing the international community (Ravindranath 2010).

In a global world, economies are tightly intertwined between developed and developing countries by international trade. The developing countries undertake industrial transfers from developed countries in import and export trade, which would result in a rise in developing countries’ carbon emissions and a decrease in carbon emissions of the developed countries. Under these circumstances, developed countries are inclined to import energy-intensive products to lower their carbon emissions. As the biggest carbon emitter and energy consumer in the world, China is also the biggest trade country (Cao 2010). The rapid growth of import and export trade is two of the main reasons for the increase in China’s carbon emissions (Chou et al. 2021). Compared with the USA and other developed countries, China’s export products have larger energy consumption and lower value-added. In the context of the prosperity of international trade, the shared responsibility for carbon emissions is considered a preferable approach to comprehensively reflect the nature of a country’s energy consumption.

The perception of the growth of the global economy as a “zero-sum game” has become deeply ingrained, where the economic growth of developed countries gains at the cost of developing countries that bear the environmental pollution. However, we ignore the well-known truth that all human beings’ activities and consumption pay the price of the finite and precious resources of the earth. Production-Base Accounting of emissions indicates that most developing countries take a greater ratio of the carbon emission responsibility than the ratio of value they earn from international trade. However, the shared responsibility can reassign carbon emissions accounting between developed and developing countries which can avoid the inequity of carbon emissions transfers led by international trade. As a fair and scientific carbon emission reduction method, the shared responsibility can be widely accepted by both developed and developing countries.

**Literature review**

Foreign trade and global warming are important issues of concern to the whole world today (Cui et al. 2015). According to the World Trade Organization, China has become the world’s largest exporter and the second largest trade importer for 12 consecutive years as of 2020, while the USA is the global second biggest exporter and top importer. However, from the perspective of the global value chain, China’s position and income in the global value chain are not high, and it has become a haven for carbon emissions in developed countries. Since the current global carbon emissions accounting standards are based on carbon dioxide produced and emitted within a country’s territory, carbon emissions are implied and transferred in the context of trade globalization and the international industrial division of labor. In particular, as the world’s largest exporter of commodity trade, China has borne the carbon emissions of many of the world’s trading imports, and there is a “Pollution Heaven” hypothesis (Nasir et al. 2019).

Wang and Yang (2021) compare the PBA carbon emission responsibility between China and Germany from 2000 to 2014, and they find that the consumption structure is the most significant decomposition factor for China and the per capita consumption is the largest contributor for Germany. According to the ratio of benefits gained by the global value chain, Zheng (2021) builds a non-differentiated producer responsibility method to estimate the carbon emission responsibility of 186 countries with the MRIO model. Shared responsibility is employed to analyze the embodied carbon emissions between China and South Korea between 2000 and 2014, and the result suggests that the traditional statistical method overestimates embodied carbon emissions by 60% (Zhang et al. 2021). Jiang et al. (2021) investigate the embodied carbon emissions between China and the countries along the Belt and the Road by MRIO approach, and the result shows that shared responsibility changes mainly between these two sides. From the viewpoint of carbon outflow and inflow, Zhu et al. (2018) explore embodied carbon in international trade between China-EU, Russia-EU, and China-Japan, which indicate that the USA and the EU are the biggest carbon importers and China and Russia are the biggest carbon exporters and the manufacturing industry is the primary sector of carbon outflows for China.

Environmental costs and real economic profits are calculated by embodied carbon emission and value-added trade between China and the USA, and according to gross import and export trade overestimate, China’s benefits in China-US trade are as high as 20% (Xiong and Wu 2021). Due to China-US trade frictions, China’s export carbon emissions have fallen sharply, but the import and export volumes of China have not changed significantly (Chou et al. 2021). Dai et al. (2021) employ the hypothetical extraction method to estimate the embodied carbon emission between China and the USA from 1996 to 2005 from a global value chain perspective. Their findings show that China shifts 6.4% of its carbon emission overseas for the goods of its exports to the USA, while the USA shifts 19% of its export to China. Zhao et al. (2016) used the structural decomposition analysis to investigate the driving factors of carbon emissions embodied in China-US trade, and the results indicate that the export market shares of final products at home and the
trade structure of intermediate products at home are the two biggest factors to increase carbon emissions embodied in Chinese exports to the USA. Du et al. (2011) employ the structural decomposition analysis to explore the carbon emissions embodied in China-US trade. The results demonstrate that the export volume was the main reason for the growth in embodied carbon emissions from 2002 to 2007.

The production, manufacture, and transportation of any commodity require energy and produce carbon emissions. First, the globalization of trade is not only a cross-border trade in goods but also the transfer and concealment of carbon emissions between different countries (Khan and Ozturk 2021). China has borne a lot of carbon emissions for consumers in developed countries such as the European Union, the USA, and Japan. Secondly, import and export trade occupies a significant proportion of China’s economic development, and efforts to achieve low-carbon trade will help China achieve the goal of carbon emission reduction (Zhang et al. 2018), so it is necessary and urgent to analyze and study the distribution and accounting principles of carbon emission responsibility between countries (Wei et al. 2014). According to income-based and consumption-based carbon accounting, Zhang et al. (2020) trace the embodied carbon emission along production chains from 1995 to 2009, and they find that 25% of embodied emissions crossed national boundaries more than in 2009. The paper is arranged as follows: the “Literature review” section reviewed relevant literature on the Production-Based Accounting principle and shared responsibility for carbon emissions. The “Methodology and data” section introduces the methodology and the data. The empirical results are presented in the “Results” section, followed by the analysis of Production-Based Accounting and shared responsibility, discussion, and conclusion of the results in the “Production-Based Accounting and shared responsibility” section, “Discussions” section, and “Conclusions” sections, respectively. The last part is the limitations of this paper.

Compared with the existing literature research, the main contribution of this paper is in three aspects: Firstly, we find that there is a mixed and complex effect on embodied carbon emission between developing and developed countries, and it is not a “zero-sum game,” while previous papers in this field have suggested that developing countries are net carbon emission exporters and developed countries are net importers. Moreover, the traditional Production-Based Accounting (PBA) principle is less fair and reasonable compared with the shared responsibility method. Based on the principle of shared responsibility, this paper examines the carbon emission responsibilities of the world’s major economies and major emitters and uses a global input–output model of 41 countries that better depicts the global production, trade, and carbon emission patterns, making the results more objective and accurate, and allows us to compare the impact of different accounting schemes on the carbon emission responsibilities between developing countries and developed countries.

Secondly, China and the USA are crucial trading partners, and the total bilateral trade volume between these two nations hit 755.6 billion dollars in 2021, and the China’s total export volume in 2021 was US$ 3,363,959 million. Meanwhile, China and the USA are the top two countries on the global carbon emission list. As the changes occur in China-US trade in recent years, there is a significant need for further studies on carbon emissions embodied between China and the USA. Then, this paper analyzes the change volumes of the carbon emissions embodied in imports and exports of China and the USA.

Thirdly, based on systematically combing the current single-liability carbon emission accounting indicators and carbon emission responsibility sharing scheme, breaking through the limitations of the SRIO model, the unified MRIO analysis framework of the existing carbon accounting scheme has been modified and expanded, so that these programs can consider the impact of the international trade, applicable to the analysis of the global carbon emissions liability distribution.

Methodology and data

Methodology

From the domestic technology hypothesis model of single-regional input–output (SRIO) to the bilateral trade input–output model (BTIO) which does not take into account intermediate input and to the multiregional input–output model (MRIO), which focuses on both technical differences and intermediate inputs, this is the three main stages of development experienced by the theory of environmental input–output. And from a producer, consumer, or shared point of view, the MRIO model is considered to be a better tool for analyzing carbon content in international trade.

The MRIO model can measure the number of carbon emissions implied in the import and export trade between countries and show the relationship between economic demand and supply between countries. Therefore, this paper uses the EU World Input and Output Table to construct a transnational input and output model of 41 countries and regions that can describe the overall international economic environment and conduct the analysis and study of carbon emissions.

This paper employs a multiregional input–output model (MRIO) to estimate trace trade-related emissions, and the MRIO framework is shown in Table 1. Production technology and trade models for countries or regions are analyzed in
the MRIO model. In the case of the three countries, formula (1) is the basic expression of the MRIO model:

$$X = AX + Y$$  \hspace{1cm} (1)

$$\begin{pmatrix}
X^1 \\
X^2 \\
X^3
\end{pmatrix} =
\begin{pmatrix}
A_{11} & A_{12} & A_{13} \\
A_{21} & A_{22} & A_{23} \\
A_{31} & A_{32} & A_{33}
\end{pmatrix} 
\begin{pmatrix}
X^1 \\
X^2 \\
X^3
\end{pmatrix} + 
\begin{pmatrix}
Y^1 + Y^{12} + Y^{13} \\
Y^{21} + Y^{22} + Y^{23} \\
Y^{31} + Y^{32} + Y^{33}
\end{pmatrix} \hspace{1cm} (2)

$$\begin{pmatrix}
X_1 \\
X_2 \\
X_n
\end{pmatrix} =
\begin{pmatrix}
A_{11} & A_{12} & \ldots & A_{1n} \\
A_{21} & A_{22} & \ldots & A_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
A_{n1} & A_{n2} & \ldots & A_{nn}
\end{pmatrix} 
\begin{pmatrix}
X_1 \\
X_2 \\
\vdots \\
X_n
\end{pmatrix} + 
\begin{pmatrix}
Y_{11} + Y_{12} + \ldots + Y_{1n} \\
Y_{21} + Y_{22} + \ldots + Y_{2n} \\
\vdots \\
Y_{n1} + Y_{n2} + \ldots + Y_{nn}
\end{pmatrix} \hspace{1cm} (3)

$$\begin{pmatrix}
X_1 \\
\vdots \\
X_n
\end{pmatrix} =
\begin{pmatrix}
A_{11} & \ldots & A_{1n} \\
\vdots & \ddots & \vdots \\
A_{n1} & \ldots & A_{nn}
\end{pmatrix} 
\begin{pmatrix}
X_1 \\
\vdots \\
X_n
\end{pmatrix} + 
\begin{pmatrix}
Y_{11} + \sum_{r \neq 1} Y_{1r} \\
\vdots \\
Y_{nn} + \sum_{s \neq n} Y_{ns}
\end{pmatrix} \hspace{1cm} (4)

$$X = (I - A)^{-1} Y $$  \hspace{1cm} (6)

In Eq. (2) $Y$ is the vector of final consumption, $A$ is the matrix of intermediate consumption, the term $X$ is the total output vector of the country $i$ ($i = 1, 2, 3$), and $I$ is the identity matrix. In Eq. (6) $(I - A)^{-1}$ is the global Leontief inverse matrix. The matrix on the right side of Eq. (1) consists of matrix $A^p$, and $A^d$, which reflects the production technology and industrial linkages of the world production system, the sub-matrix $A^p$ is the input coefficient matrix of the national $i$ production sector for domestic intermediate products, and $A^d (i \neq j)$ is the input coefficient matrix of the intermediate product produced by the national $i$ and $j$; i.e., the sub-matrix $A^d (i \neq j)$ depicts the intermediate product trade between the country and the country $j$. $Y^p$ is the national $i$ demand vector for final domestic products, i.e., domestic final use, fixed capital formation, and inventory growth. $Y^d (i \neq j)$ is the national $i$ demand vector for the final product produced by country $j$; i.e., the vector $Y^d (i \neq j)$ depicts the trade of the final product between country $i$ and country $j$. Equation (1) can easily be extended to a general model that contains $n$ countries.

Following the basic connotation of total production emission liability, the foreign emission component of a country’s total production emissions (e.g., a country 1) should include not only emissions (direct trade effects) caused by the direct import of intermediate products by one country but also foreign emissions (indirect trade effects) indirectly caused by the import of these intermediate products by the exporting country from other countries, as all these emissions are to meet the production and income generation of country 1.

$$P(\Delta E_d) = \frac{1}{2} (E^1_d - E^0_d) (X^0 + X^1) $$  \hspace{1cm} (7)

$$P(\Delta R) = \frac{1}{4} (E^1_d + E^0_d) (R^1 - R^0) (Y^0 + Y^1) $$  \hspace{1cm} (8)

$$P(\Delta Y_d) = \frac{1}{8} (E^1_d + E^0_d) (R^1 + R^0) (Y^1 + Y^0) $$  \hspace{1cm} (9)

$$P(\Delta Y_s) = \frac{1}{8} (E^1_d + E^0_d) (R^1 + R^0) (Y^1 - Y^0) (Y^0 + Y^1) $$  \hspace{1cm} (10)

$P(\Delta E_d)$ is an energy efficiency effect that indicates a change in CO$_2$ emission intensity due to changes in the energy structure and energy efficiency of the country, which in turn leads to a change in embodied carbon. $E^1_d$ and $E^0_d$ is an energy efficiency effect of industry $d$. $P(\Delta Y_d)$ is the structural effect, which means the change in embodied carbon caused by changes in the export structure. $P(\Delta Y_s)$ is the scale effect, which represents the embodied carbon change caused by the change in export scale. $P(\Delta R)$ is the input–output coefficient effect, which represents the embodied carbon change caused by the change of the input–output coefficient.
The Hypothetical Extraction Method (HEM) is adopted to further decompose the input-output coefficient.

\[ P(\Delta R) = P(\Delta M) + (\Delta M) + \Delta F + \Delta B \]  \hspace{1cm} (11)

\[ P(\Delta M) = \frac{1}{4} \left( E_d^1 + E_d^0 \right) \left( M^1 - M^0 \right) \left( Y^0 + Y^1 \right) \]  \hspace{1cm} (12)

\[ P(\Delta F) = \frac{1}{4} \left( E_d^1 + E_d^0 \right) \left( F^1 - F^0 \right) \left( Y^0 + Y^1 \right) \]  \hspace{1cm} (13)

\[ P(\Delta B) = \frac{1}{4} \left( E_d^1 + E_d^0 \right) \left( B^1 - B^0 \right) \left( Y^0 + Y^1 \right) \]  \hspace{1cm} (14)

\( P(\Delta M) \) is the domestic multiplier effect, which is the change in CO2 emissions caused by the change in the input ratio of intermediate products caused by domestic technological changes. \( \Delta F \) is the feedback effect caused by exports. \( \Delta B \) is the regional spillover effect (spillover effect), which reflects the changes in embodied carbon caused by the deepening of economic ties or industrial interdependence in the region.

**The carbon emission coefficient**

We calculate the carbon emission coefficient as

\[ G = \left\{ g^i_j \right\} = \left\{ \frac{g^i_j}{s^i_j} \right\} \]  \hspace{1cm} (15)

where \( g^i_j \) is the sectoral Production-Based Accounting (PBA) of emission and \( G \) is the diagonal matrix of \( G \). The country- and sector-level decomposition of the emission embodied in the final output can be written as

\[ \hat{G}B \hat{F} = \begin{bmatrix} g^1_1 & \cdots & g^1_n \ \\
\vdots & \ddots & \vdots \\
g^n_1 & \cdots & g^n_n \end{bmatrix} \begin{bmatrix} f^1_1 & \cdots & f^1_n \ \\
\vdots & \ddots & \vdots \\
f^n_1 & \cdots & f^n_n \end{bmatrix} \]  \hspace{1cm} (16)

To calculate the domestic production and intermediate trade flow, the diagonal block matrix of the domestic input coefficient \( A^d = \begin{bmatrix} A_{11} & \cdots & A_{1n} \\
\vdots & \ddots & \vdots \\
A_{n1} & \cdots & A_{nn} \end{bmatrix} \) should be used. We denote \( A' = A - A^d \). And the final product can be decomposed as the final production for domestic consumption \( F^d \) plus final production for export \( F^e \). For each country, there is \( E \) as the total exports, which consists of final export \( F^e \) and intermediate export \( A'X \); therefore, rearrange the gross output as

\[ X = (I - A^d)^{-1}F^d + (I - A^d)^{-1}E \]

\[ = LF^d + LE = LF^d + LF^e + LA'X \]  \hspace{1cm} (17)

As \( \hat{X} = B\hat{F} \), the matrix \( \hat{G}B\hat{F} \) can be decomposed as follows:

\[ \hat{G}B\hat{F} = \hat{G}LF^d + \hat{G}LF^e + \hat{G}LA'\hat{F} \]

\[ = \hat{G}LF^d + \hat{G}LA'\hat{F} + \hat{G}LA' \left( B\hat{F} + \hat{F}L\hat{F} \right) \]  \hspace{1cm} (18)

We further decompose \( \hat{G}B\hat{F} \) as

\[ \hat{G}B\hat{F} = \hat{G}LF^d + \hat{G}LF^e + \hat{G}LA'\hat{F} + \hat{G}LA' \left( B\hat{F} + \hat{F}L\hat{F} \right) \]  \hspace{1cm} (19)

According to the definition, the carbon emission (CE) of the \( i \) sector in country \( s \) can be decomposed as follows:

\[ CE_i = g^i_s \sum_{r \in \xi} \sum_{j \in \eta} b_{sij} f_{sj}^r = g^i_s \sum_{r \in \xi} \sum_{j \in \eta} \sum_{k \in \xi} \sum_{m \in \eta} a_{sik} a_{sjm} f_{sj}^r + g^i_s \sum_{r \in \xi} \sum_{j \in \eta} \sum_{m \in \eta} f_{sj}^r \]  \hspace{1cm} (20)

\section*{The shared responsibility calculation method}

In the following, vector \( \phi \) will be used to represent the weighting between production- and consumption-based responsibilities at the sector level. Mathematically, shared responsibility in a single-region model can be described as

\[ E^s = E^s\phi + E^s \left( I - \phi \right) \]

\[ = v^s\phi + v^s \left( I - \phi \right) = v^s\phi + v^s \left( I - \phi \right) \]  \hspace{1cm} (21)

The case of \( \phi = 1 \) means that the responsibility for carbon emissions contributed to sector \( j \) is exclusively determined according to the production-based principle. The case of \( \phi = 0 \) means that the responsibility for carbon emissions assigned to sector \( j \) follows the consumption-based principle. The case of \( \phi = 0.5 \) means that the responsibility for carbon emissions contributed to sector \( j \) is exclusively determined based on the shared responsibility. Therefore, the carbon emissions coming from domestic production to support domestic final demand will be the responsibility of the analyzed sector itself regardless of the value of \( \phi \). In calculating the shared responsibilities for sectors in country \( A \) that trade with sectors in country \( B \) (rest of the world), Eq. (22) could be expressed more clearly as

\[ CE_i^s = CE_i^s\phi + CE_i^s \left( 1 - \phi \right) \]

\[ = \text{some expression} \]  \hspace{1cm} (22)
The input–output table selected for the empirical study is the EORA database released by UNCTAD. The simplified dataset Eora covers the symmetric industry-by-industry IO tables and matching environmental accounts for 190 countries in a harmonized 26-sector classification from 1995 to 2019. The WIOT contains 27 members of the European Union and 13 main economies outside the EU, and all other countries were placed in the ROW region (Table 2). Due to the inconsistency of classification standards, this paper matches Eora, WIOD, World Bank, and IEA (International Energy Agency) into 35 sectors. Each country has 35 departments. The industry sectors are given in Table 3. The data of this paper are from British Petroleum, Eora, WIOD, World Bank, and IEA. The variables are shown in Table 2.

\[ E_{\text{AV}} = \psi^e(\tilde{Y} - \tilde{Z}) + \tilde{Y} \tilde{B} + \left[ \psi^w(\Lambda - \Lambda^e)^{-1}(\tilde{Y} - \tilde{Z}) + \psi^w(\tilde{I} - \tilde{G}_A) \right] \]  (22)

\section*{Data}

The input–output table selected for the empirical study is the EORA database released by UNCTAD. The simplified dataset Eora covers the symmetric industry-by-industry IO tables and matching environmental accounts for 190 countries in a harmonized 26-sector classification from 1995 to 2019. The WIOT contains 27 members of the European Union and 13 main economies outside the EU, and all other countries were placed in the ROW region (Table 2). Due to the inconsistency of classification standards, this paper matches Eora, WIOD, World Bank, and IEA (International Energy Agency) into 35 sectors. Each country has 35 departments. The industry sectors are given in Table 3. The data of this paper are from British Petroleum, Eora, WIOD, World Bank, and IEA. The variables are shown in Table 2.

\section*{Results}

\subsection*{Carbon emission coefficient}

The sectors in the WIOT Data are shown in Table 3, and the carbon emission coefficient of China and three other countries in 1995 and 2009 are shown in Table 4.

\subsection*{The embodied carbon emissions of imported trade}

From the perspective of the embodied carbon emissions in China’s imported trade, the embodied carbon emissions in China’s imported goods trade were 26.9 million tons in 1995, and the embodied carbon emissions in China’s imported goods trade were 227.7 million tons in 2018. In 24 years, the embodied carbon emissions in China’s imported goods trade increased by 200.7 million tons. The embodied carbon emissions of 2018 imported goods trade were 8.5 times that of 1995.

From the perspective of the embodied carbon emissions in the US imported goods trade, the embodied carbon
emissions in the US imported goods trade in 1995 were 366 million tons, and in 2018, the embodied carbon emissions in the US imported goods trade was 824 million tons. In the past 24 years, the embodied carbon emissions in the US imported goods trade increased by 458 million tons. The embodied carbon emissions of 2018 in the US imported goods trade were 2.3 times that of 1995.

The embodied carbon emissions of exported trade

From the perspective of the embodied carbon emissions in China’s export merchandise trade, the embodied carbon emissions in China’s export trade in 1995 were 314.7 million tons. The embodied carbon emissions in China’s export trade in 2018 were 1553.7 million tons. In 24 years, the embodied carbon emissions in China’s export merchandise trade have increased by 1239 million tons. The embodied carbon emissions of 2018 in China’s export trade were 4.9 times that of 1995.

From the perspective of the embodied carbon emissions in the US export merchandise trade, the embodied carbon emissions in the US export merchandise trade in 1995 were 170.7 million tons. The embodied carbon emissions in the U.S. export merchandise trade in 2018 were 255.3 million tons. In the past 24 years, the embodied carbon emissions of the US export merchandise trade increased by 84.6 million tons.

| Code | China 1995 | India 1995 | Japan 1995 | USA 1995 | China 2009 | India 2009 | Japan 2009 | USA 2009 |
|------|------------|------------|------------|----------|------------|------------|------------|----------|
| S1   | 0.44       | 0.29       | 0.15       | 0.26     | 0.13       | 0.18       | 0.10       | 0.15     |
| S2   | 1.65       | 2.98       | 0.44       | 0.89     | 0.42       | 2.63       | 0.68       | 0.32     |
| S3   | 0.65       | 0.34       | 0.04       | 0.11     | 0.09       | 0.53       | 0.03       | 0.08     |
| S4   | 0.53       | 0.27       | 0.05       | 0.15     | 0.08       | 0.12       | 0.05       | 0.15     |
| S5   | 0.16       | 0.13       | 0.04       | 0.09     | 0.03       | 0.04       | 0.03       | 0.06     |
| S6   | 0.45       | 0.12       | 0.04       | 0.20     | 0.07       | 1.07       | 0.04       | 0.18     |
| S7   | 1.13       | 0.65       | 0.11       | 0.19     | 0.22       | 0.43       | 0.10       | 0.14     |
| S8   | 1.54       | 0.90       | 0.33       | 1.42     | 0.39       | 0.43       | 0.16       | 0.39     |
| S9   | 2.71       | 1.49       | 0.21       | 0.43     | 0.33       | 0.54       | 0.18       | 0.22     |
| S10  | 0.66       | 0.17       | 0.03       | 0.05     | 0.07       | 0.11       | 0.02       | 0.03     |
| S11  | 4.55       | 4.55       | 0.87       | 1.61     | 1.77       | 2.46       | 0.94       | 1.20     |
| S12  | 1.99       | 1.14       | 0.24       | 0.51     | 0.48       | 0.76       | 0.22       | 0.21     |
| S13  | 0.55       | 0.12       | 0.03       | 0.07     | 0.06       | 0.11       | 0.01       | 0.06     |
| S14  | 0.17       | 0.07       | 0.02       | 0.04     | 0.01       | 0.07       | 0.02       | 0.02     |
| S15  | 0.34       | 0.08       | 0.01       | 0.05     | 0.05       | 0.15       | 0.01       | 0.03     |
| S16  | 0.96       | 0.07       | 0.06       | 0.07     | 0.07       | 0.01       | 0.07       | 0.03     |
| S17  | 29.92      | 14.26      | 0.96       | 7.69     | 6.90       | 12.49      | 1.23       | 5.25     |
| S18  | 0.11       | 0.12       | 0.04       | 0.08     | 0.05       | 0.04       | 0.04       | 0.04     |
| S19  | 0.00       | 0.08       | 0.02       | 0.06     | 0.00       | 0.04       | 0.01       | 0.03     |
| S20  | 0.17       | 0.03       | 0.03       | 0.07     | 0.01       | 0.01       | 0.02       | 0.03     |
| S21  | 0.26       | 0.08       | 0.06       | 0.14     | 0.06       | 0.03       | 0.05       | 0.07     |
| S22  | 0.21       | 1.72       | 0.04       | 0.17     | 0.08       | 0.43       | 0.04       | 0.08     |
| S23  | 0.96       | 0.67       | 0.15       | 0.70     | 0.36       | 0.17       | 0.15       | 0.56     |
| S24  | 3.64       | 2.40       | 1.28       | 2.47     | 0.92       | 1.75       | 1.05       | 1.66     |
| S25  | 2.45       | 4.43       | 1.23       | 1.64     | 1.79       | 0.83       | 0.57       | 1.17     |
| S26  | 0.25       | 0.73       | 0.02       | 0.24     | 0.28       | 0.29       | 0.02       | 0.29     |
| S27  | 0.11       | 0.28       | 0.02       | 0.06     | 0.03       | 0.08       | 0.02       | 0.05     |
| S28  | 0.06       | 0.01       | 0.01       | 0.04     | 0.01       | 0.01       | 0.01       | 0.01     |
| S29  | 0.25       | 0.03       | 0.01       | 0.01     | 0.01       | 0.00       | 0.00       | 0.00     |
| S30  | 0.24       | 0.15       | 0.03       | 0.10     | 0.06       | 0.05       | 0.02       | 0.04     |
| S31  | 0.30       | 0.07       | 0.04       | 0.25     | 0.08       | 0.01       | 0.03       | 0.09     |
| S32  | 0.72       | 0.07       | 0.03       | 0.15     | 0.07       | 0.03       | 0.02       | 0.07     |
| S33  | 0.30       | 0.04       | 0.04       | 0.13     | 0.09       | 0.02       | 0.03       | 0.05     |
| S34  | 0.88       | 0.29       | 0.09       | 0.21     | 0.15       | 0.12       | 0.08       | 0.05     |
| S35  | 0.04       | 0.03       | 0.06       | 0.07     | 0.03       | 0.02       | 0.05       | 0.04     |
The difference in embodied carbon emissions between import and export trade

A comparative analysis is used to explore the embodied carbon emissions in China’s import and export trade. The embodied carbon emissions of 1995 in China’s export merchandise trade were 287.8 million tons higher than that of import trade. The embodied carbon emissions of 2018 in China’s export merchandise trade were 1326.1 million tons higher than that of the import merchandise trade.

A comparative analysis is used to explore the embodied carbon emissions in the US import and export merchandise trade. The implied carbon emissions of 1995 in the US import merchandise trade were 195.3 million tons higher than that of the export merchandise trade. The embodied carbon emissions of 2018 in the US import merchandise trade were 568.7 million tons higher than that of the export merchandise trade.

According to Fig. 1, it can be found that from 1995 to 2018, the embodied carbon emissions in China’s imported goods trade grew slowly, and the increase was not large. However, from 1995 to 2018, the embodied carbon emissions in China’s export merchandise trade increased significantly, especially after China acceded to the World Trade Organization in 2001, and export trade rose rapidly, and embodied carbon emissions were noteworthy in China’s foreign exports. When the global financial crisis broke out in 2008, China’s embodied carbon emissions from foreign trade showed a downward trend.

According to Fig. 2, it can be found that from 1995 to 2018, the embodied carbon emissions in the US export merchandise trade grew slowly. However, from 1995 to 2009, the embodied carbon emissions of the US imported goods increased significantly. When the global financial crisis broke out in 2008, the embodied carbon emissions of imports in the US foreign trade showed a downward trend and continued to rise after 2010.

Consequently, from 1995 to 2018, the embodied carbon emissions of US imports of goods have been greater than the embodied carbon emissions of exports. The USA enjoys the benefits of economic globalization and international trade and is a major consumer of carbon emissions rather than a producer.

Production-Based Accounting and shared responsibility

According to producer and shared carbon emission responsibilities, using data provided by the WIOD and Eora, the MRIO model is employed to calculate the carbon emissions of 41 countries and regions worldwide in 2005, 2009, 2015, and 2019 as shown in Table 5 and Fig. 3.

Production-Based Accounting responsibility

In the viewpoint of the Production-Based Accounting (PBA) principle in 2005, the USA was the world’s biggest carbon emitter with 6019 million tons of carbon emissions and 1155 million tons higher than the rest of the world (ROW). China ranks second in the world with a carbon emission of 4636 million tons. Japan, India, and Russia were in the third, fourth, and fifth with 1351, 1203, and 1120 million tons of carbon emissions, respectively.

Based on the PBA method in 2019, China was the world’s biggest carbon emitter with 9965 million tons of carbon
emissions and 3881 million tons higher than the rest of the world (ROW). The USA ranks second in the world in 2019 with 5021 million tons of carbon emissions. India ranks third with 2563 million tons of carbon emissions. Russia ranks fourth in the world with 1417 million tons of carbon emissions in 2019. Japan ranks fifth with 1208 million tons of carbon emissions.

The shared responsibility

In the viewpoint of shared responsibility in 2005, the USA, with 5,302 million tons of carbon emissions, remains the world’s highest carbon emitter. China ranks second in the world with a total of 4050 million tons of carbon emissions. Japan, India, and Russia were in the third, fourth, and fifth with 1208, 1082, and 936 million tons of carbon emissions, respectively.

China’s carbon emissions reached 9714 million tons in 2019, according to the shared responsibility, making it the world’s highest carbon emitter. The USA ranks second in the world with 5742 million tons of carbon emission in 2019. India ranks third with 2319 million tons in shared carbon emissions responsibility in 2019. Japan ranks fourth in the world in 2019 with 1341 million tons of carbon emissions. Russia ranks fifth with 1296 million tons of carbon emissions.

The difference between Production-Based Accounting and shared responsibility

Comparing carbon emissions calculated based on producer and shared responsibility, we can see that, first of all, the top three countries for carbon emissions in 2005 were the USA, China, and Japan, and the top three countries for carbon emissions in 2019 were China, the USA, and India. The first place went from the USA to China and the third from Japan to India.

Secondly, the carbon emissions calculated based on producer responsibility are greater than those calculated based on shared responsibility for developing countries. Specifically, the PBA carbon emissions of China, India, and Russia in 2019 are 251,244,121 million tons higher than those calculated on shared responsibility, respectively.

Discussions

We employ the MRIO method to explore the embodied carbon of international trade, focus on analyzing China’s role in foreign trade, and investigate the embodied carbon emissions of China and the USA from an imports and exports perspective. The results show a prominent disparity between traditional production-based and shared responsibility accounting. First, the PBA principle does not take complete account of the historical emission responsibilities of developed countries and ignores the services and production of commodities satisfying final demand in developed countries. Moreover, the PBA principle is unfair to the developing countries with low historical emissions, which has prompted many scholars at home and abroad, especially from developing countries, to propose various carbon reduction programs that reject the PBA principle and integrate the responsibility for historical emissions (Fan et al. 2016; Harris et al. 2020; Zhang and Peng 2016).

Second, the Kyoto Protocol adopts the PBA principle in accounting for a country’s annual carbon emissions.
(Bohringer and Vogt 2003; Kander et al. 2015). Countries or regions are only responsible for emissions produced in their territories. The shortcomings of the principle are increasingly prominent. One is the principle of PBA that contributes to carbon leakage (Zhang and Fang 2019). Under this principle, to reduce emissions, developed countries can shift carbon-intensive products to developing countries, which are not constrained by emission reductions.

Table 5  Producer and shared carbon emission responsibility (unit: million tons)

| Countries/regions       | 2005 Production-Based Accounting | 2005 Shared responsibility | 2009 Production-Based Accounting | 2009 Shared responsibility | 2015 Production-Based Accounting | 2015 Shared responsibility | 2019 Production-Based Accounting | 2019 Shared responsibility |
|--------------------------|----------------------------------|----------------------------|----------------------------------|----------------------------|----------------------------------|----------------------------|----------------------------------|----------------------------|
| America                  | 6019                             | 5302                       | 5311                             | 4570                       | 5256                             | 6531                       | 5021                             | 5742                       |
| Australia                | 402                              | 376                        | 410                              | 382                        | 412                              | 429                        | 406                              | 416                        |
| Austria                  | 96                               | 81                         | 83                               | 70                         | 63                               | 68                         | 69                               | 72                         |
| Belgium                  | 152                              | 124                        | 144                              | 117                        | 118                              | 126                        | 125                              | 132                        |
| Brazil                   | 317                              | 250                        | 350                              | 285                        | 497                              | 469                        | 452                              | 441                        |
| Bulgaria                 | 43                               | 37                         | 43                               | 36                         | 39                               | 41                         | 35                               | 38                         |
| Canada                   | 529                              | 445                        | 516                              | 439                        | 582                              | 617                        | 591                              | 627                        |
| China                    | 4636                             | 4050                       | 6319                             | 5645                       | 9322                             | 9201                       | 9965                             | 9714                       |
| Cyprus                   | 10                               | 9                          | 10                               | 9                          | 8                                | 9                          | 9                                | 8                          |
| Czech Republic           | 116                              | 101                        | 107                              | 92                         | 107                              | 119                        | 104                              | 116                        |
| Denmark                  | 77                               | 66                         | 70                               | 62                         | 48                               | 51                         | 46                               | 49                         |
| Estonia                  | 17                               | 16                         | 14                               | 12                         | 17                               | 15                         | 16                               | 14                         |
| Finland                  | 72                               | 65                         | 68                               | 62                         | 47                               | 52                         | 45                               | 51                         |
| France                   | 547                              | 432                        | 489                              | 386                        | 318                              | 326                        | 315                              | 313                        |
| Germany                  | 1012                             | 820                        | 898                              | 730                        | 772                              | 791                        | 726                              | 741                        |
| Greece                   | 133                              | 123                        | 127                              | 114                        | 81                               | 89                         | 87                               | 93                         |
| Hungary                  | 79                               | 63                         | 61                               | 49                         | 47                               | 51                         | 53                               | 59                         |
| India                    | 1203                             | 1082                       | 1656                             | 1497                       | 2271                             | 2014                       | 2563                             | 2319                       |
| Indonesia                | 326                              | 260                        | 381                              | 317                        | 452                              | 431                        | 581                              | 547                        |
| Ireland                  | 66                               | 50                         | 59                               | 43                         | 39                               | 38                         | 41                               | 39                         |
| Italy                    | 616                              | 514                        | 532                              | 442                        | 347                              | 362                        | 351                              | 369                        |
| Japan                    | 1351                             | 1208                       | 1194                             | 1062                       | 1395                             | 1526                       | 1208                             | 1341                       |
| Korea                    | 553                              | 489                        | 550                              | 480                        | 599                              | 614                        | 617                              | 623                        |
| Latvia                   | 11                               | 10                         | 10                               | 9                          | 8                                | 7                          | 8                                | 8                          |
| Lithuania                | 20                               | 17                         | 18                               | 15                         | 13                               | 9                          | 14                               | 11                         |
| Luxembourg               | 8                                | 7                          | 7                                | 5                          | 9                                | 9                          | 10                               | 11                         |
| Malta                    | 3                                | 3                          | 3                                | 3                          | 2                                | 2                          | 2                                | 3                          |
| Mexico                   | 457                              | 392                        | 451                              | 375                        | 491                              | 475                        | 477                              | 452                        |
| Netherlands              | 233                              | 190                        | 222                              | 182                        | 223                              | 245                        | 216                              | 228                        |
| Poland                   | 314                              | 268                        | 310                              | 261                        | 306                              | 317                        | 314                              | 326                        |
| Portugal                 | 80                               | 72                         | 67                               | 59                         | 56                               | 59                         | 52                               | 57                         |
| Romania                  | 105                              | 90                         | 995                              | 80                         | 75                               | 76                         | 73                               | 77                         |
| Russia                   | 1120                             | 936                        | 1185                             | 1008                       | 1392                             | 1274                       | 1417                             | 1296                       |
| Slovak                   | 39                               | 35                         | 39                               | 36                         | 34                               | 32                         | 35                               | 34                         |
| Slovenia                 | 20                               | 15                         | 20                               | 16                         | 15                               | 13                         | 17                               | 14                         |
| Spain                    | 427                              | 360                        | 348                              | 287                        | 291                              | 317                        | 280                              | 299                        |
| Sweden                   | 85                               | 76                         | 74                               | 67                         | 52                               | 59                         | 53                               | 56                         |
| Taiwan                   | 262                              | 236                        | 231                              | 204                        | 287                              | 294                        | 291                              | 314                        |
| Turkey                   | 300                              | 254                        | 290                              | 246                        | 339                              | 327                        | 391                              | 382                        |
| United Kingdom           | 690                              | 569                        | 595                              | 476                        | 447                              | 468                        | 420                              | 449                        |
| Rest of the world        | 4864                             | 4088                       | 5486                             | 4637                       | 4962                             | 4531                       | 6084                             | 5937                       |
to reduce their carbon emissions responsibility and then import related products from developing countries to meet domestic demand. Such a shift could lead to a sharp increase in emissions from developing countries, resulting in carbon leakage, weakening emissions reduction policies, and even leading to a rise in global carbon emissions (Tan et al. 2018). The other one is that a large proportion of developing countries’ carbon emissions are the ultimate needs of developed countries, not themselves (Branger and Quirion 2014). Therefore, both producers and consumers are beneficiaries of carbon emissions and are responsible for them.

Third, the developed countries should take more shared carbon emission responsibility than the PBA. As China and other developing countries have greatly participated in the global value chains in the last 2 decades, there is a clear “carbon deficit” in the trade between developed and developing countries. Besides, in the context of international trade, embodied carbon emissions have been transferred from developed countries to developing countries. In fact, developing countries have consumed and imported plenty of energy-intensive goods from less developed countries, like China, India, Russia, and Mexico. The results indicate that the shared carbon emission responsibility is more reasonable and impartial to assign between developed and developing countries. Moreover, the developing countries should pay much attention to the ecological quantity for their long-term economic development.

The shared responsibility is mainly aimed at realizing the fairness of the allocation of carbon responsibility and the effectiveness of carbon emission reduction, thus enriching the essence of the principle of common but differentiated responsibility (Chang 2013; Jakob et al. 2021). PBA responsibility does not take into account the transfer of carbon emissions and consumer responsibility from international trade, which is not conducive to emission reduction and lacks equity (Zhu et al. 2018). And the principle of PBA cannot effectively guide low-carbon consumption and lifestyle (Zhou et al. 2020).

Conclusions

By employing the MRIO model, we calculate the carbon emission coefficient of China, India, Japan, and the USA with 35 industry sectors. We then assess the embodied carbon emission in imported and exported trade of China and the USA from 1995 to 2018 and analyze the producer and shared carbon emission responsibility of 41 countries or regions in 2005, 2009, 2015, and 2019, respectively. Our main findings follow.

(1) The shared responsibility enables producers and consumers to share carbon emissions in the production of traded goods. Empirical results show that promoting the reform of the traditional carbon liability accounting scheme based on the principle of PBA and adopting the principle of shared responsibility is necessary to improve the fairness and effectiveness of global carbon emission reduction and objectively reduce the pressure on developing countries such as China, India, and Russia. In the international climate negotiations, China and other developing countries should actively advocate the rights and interests of the developing countries that emphasize the historical emission responsibility and the difference in per capita emission levels.

(2) Addressing climate change needs the efforts of every country, especially China and the USA should cooperate closely in reducing emission transfers. And adopting shared responsibility can describe a more comprehensive picture of carbon leakage that has become significant due to international trade. Current researches pay close attention to either emission caused by the final
consumption of each country employing consumption-based accounting, such as final consumers, or direct emission of each country employing Production-Based Accounting, such as direct emitters (Liu and Fan 2017), but does not consider the embodied carbon emissions in import and export trade.

Limitations

There are several limitations in this paper as follows. First, this paper does not completely reflect the relationship between developed and developing countries on embodied carbon emissions in international trade, and further research is needed to investigate other factors that cause the embodied carbon emissions. Second, the world input–output tables have a lag and cannot offer the latest data. As the geographic range and database classification is different, we use the WIOD and EORA database to match the statistic range of the carbon emission data acquired from the IEA and World Bank database. Besides, not only the carbon emissions but also other pollutants, such as sulfur dioxide, are needed to be investigated. Finally, the global economy is suffering many new crises, such as the China-US trade dispute, the coronavirus pandemic, and the deglobalization, which make instability in international trade in the world.

Author contribution

Yulong Zhang: conceptualization, methodology, writing, original draft preparation.

Yulong Zhang and Binbin Pan: software, data, writing, reviewing, and editing.

Binbin Pan is responsible for ensuring that the descriptions are accurate and agreed by all authors.

Funding

This study was funded by (1) the 2021 Guizhou University of Finance and Economics Introduced Talents and Launched Scientific Research Project (grant number 2021YJ031), (2) the 2021 Guizhou University of Finance and Economics Special Scientific Research Project of Party Style and Clean Government Construction (grant number 2021DFL002), and (3) the 2021 Guizhou University of Finance and Economics Teaching Quality and Teaching Reform Project (grant number 2021JGZH40).

Data availability

The datasets generated and analyzed during the current study are available in the British Petroleum, Eora, WIOD, World Bank, and IEA, and the website are listed below.

https://www.bp.com/
https://worldmrio.com/
https://www.rug.nl/ggdc/valuechain/wiod/?lang=en
https://data.worldbank.org/indicator?tab=all.
https://www.iea.org/

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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