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Research on International Carbon Emission Responsibility Based on Tapio Decoupling Model

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Abstract

Based on the WIOD database, the article uses the MRIO model to analyze the production-based and consumption-based carbon emissions and transfer issues in international trade, measures the carbon emissions generated by the EU, China, India, Japan, Russia, and the US in 2014, uses the Tapio decoupling model to clarify the relationship between economic growth and carbon emissions, and determines the responsibility of carbon emissions in each country (region) using 2013 as the base period. The study found that: China and India are based on the production of carbon emissions. It is found that: production-based carbon emissions are higher than consumption-based emissions in China and India, and the opposite is true for EU, US, Japan, and Russia; developing countries are net exporters of trade-embodied carbon and developed countries are net importers of trade-embodied carbon; and a consumption-based accounting approach is used for EU and China, and a production-based accounting approach is used for India, Russia, Japan, and US.

Keywords

Embodied Carbon, Production-Based Carbon Emissions, Consumption-Based Carbon Emissions, MRIO, Tapio Decoupling, Carbon Emission Responsibility

1. Introduction

Global warming and climate change have become a common challenge for human society today, and reducing CO_2 emissions has become a unanimous development goal for all governments. In 2020, the European Union proposed the

"Green New Deal for Europe", which proposes to achieve net zero greenhouse gas emissions and decouple economic growth from resource consumption by 2050 (Dong, 2021). China announced to achieve "peak carbon" by 2030 and "carbon neutral" by 2060, setting off the largest carbon emission reduction action in human history. The clarity and sharing of responsibility for carbon emissions in the international arena is the key issue that needs to be addressed.

With the rapid development of international trade, trade embodied pollution has become the focus of academic attention. Inevitably, the trade process is accompanied by carbon emissions, and embodied carbon refers to the carbon dioxide emitted in the trade process along with the whole production chain, which can also be called carbon emissions generated in trade. Currently, there are two main ways to share the responsibility for emission reduction internationally: production-based and consumption-based. Production-based carbon accounting assumes that the responsibility for emission reduction lies with the place where the production takes place. This way of responsibility sharing is prone to carbon leakage (Han et al., 2018). Huang et al. (2018) introduced pollutant emission indicators and trade pollution conditions to analyze China's trade implied pollution transfer using the MRIO model, and concluded that China is an exporter of trade implied pollution and has become a "pollution haven" for developed countries. With the development and improvement of industrial division of labor and the development of international trade, the production and consumption of goods are separated, and the developed countries build factories of high-density carbon emission products in developing countries, which brings high carbon emissions, and the developed countries transfer carbon emissions to developing countries while gaining benefits. Consumption-based carbon emissions, on the other hand, believe that "who consumes, who bears", the final consumption-based products as the bearer of responsibility for emissions reduction, this accounting method is conducive to the fairness of international trade, especially for large exporting countries (Pan et al., 2008). With the deepening of global economic integration and the expansion of openness of developing countries, developing countries produce to meet the demand for their own products and then export the surplus to other countries, while consuming countries reduce the production of that part of the product in their own countries. This process of production transfer makes the producing countries bear the CO_2 emissions that should be borne by the consuming countries, and international trade makes the exporting countries generate trade implied carbon exports. Although a consumption-based approach to carbon accounting is more equitable, some scholars have pointed out that production-based emissions, although generating large amounts of carbon emissions, can lead to economic development in the region (Ma et al., 2015). Therefore, the adoption of production-based accounting or consumption-based accounting has become an urgent challenge to be solved.

The measurement of production-based carbon emissions is controversial. The Kyoto Protocol considers production-based carbon emissions as the carbon emissions emitted in the region under the territorial principle, and the data are directly available in the WIOD environmental accounts. Peter (2008) considers production-based carbon emissions as the domestic and foreign emissions resulting from the production of a country's final product. Eder & Narodoslawsky (1999) and Ferng (2003) define production-based emissions as the sum of territorial emissions and carbon emissions caused by imported products in other countries, however, Peng et al. (2016) argue that this approach contains double counting, so this paper adopts peter's production-based accounting approach when accounting for production-based carbon emissions.

For the measurement of consumption-based carbon emissions, scholars (Peter, 2008; Peng et al., 2015; Pang & Zhang, 2014) have used the MRIO model, defined as carbon emissions resulting from the use of final products in a country. Peter (2008) compared and analyzed the production-based consumption-based consumption under the EEBT and MRIO models, concluded that MRIO is more suitable for consumption-based studies, and argued that MRIO is more suitable for consumption-based studies. Yan (2013) constructed a consumption carbon emission system based on MRIO and measured the implied carbon transfer in eight regions of China, showing that the current carbon emission pattern in China is "west to central to east coast".

Several scholars have studied production-based and consumption-based carbon emissions separately. Sun et al. (2017) analyzed the carbon footprint of various sectors in India using the SRIO model, and the results showed a large gap between high-carbon sectors under different perspectives of production and consumption. Chen et al. (2016) studied the carbon emission responsibility in China and Japan under the equity perspective, and studied the equity of carbon emission in China and Japan under the perspective of producers, consumers and co-sharing with reference to the relative deprivation theory, and subdivided the carbon emission responsibility into sectors. Pang & Zhang (2014) analyzed the implied carbon of China-Europe trade using MRIO model, and measured CO_2 emissions based on production-based and consumption-based respectively, and concluded that there are differences based on the two carbon accounting methods, and such differences are especially obvious for outward-oriented economies. Peng et al. (2015) used the MRIO model to measure production-based and consumption-based carbon emissions in China, and considered production-based carbon emissions as the accounting method under the "Kyoto model", that is, carbon emissions generated in a country regardless of who produced them. Consumption-based carbon emissions, on the other hand, are considered as carbon emissions caused by the final demand of a particular country.

In summary, firstly, the existing studies using MRIO models to study carbon footprints have been common in the literature both at home and abroad, but in the current studies most of the inter-provincial or two-country comparisons have been conducted, no multi-country studies have been conducted, and comparisons between different trading partner countries are lacking. Secondly, multi-regional input-output (MRIO) models and the total bilateral trade method (EEBT) are generally used for the measurement of implied carbon. The bilateral aggregate trade method is based on the single-region input-output (SRIO) model, which does not distinguish the sources of intermediate goods and cannot model the trade linkages between sectors in each country, and compared with the bilateral aggregate trade method, the MRIO model can more accurately measure the interregional trade flows (Wang et al., 2021; Liu & Wang, 2017; Xue et al., 2020), so this paper uses MRIO to measure carbon emissions. Thirdly, scholars currently measure carbon emissions from production-based and consumption-based, and this paper, based on existing studies, accounts for international trade carbon emissions from production-based and consumption-based, respectively. Finally, scholars have used the tapio model to deal with carbon emissions-related problems, among which Liu et al. (2022) used the tapio model to study the relationship between electricity consumption and carbon emissions in more than 600 cities in China, and found that the decoupling effect in 2016 was stronger than in 2009. Chang et al. (2021) using the tapio decoupling model, the decoupling relationship between carbon emissions of China's power sector and technological effects, scale effects and income effects on the consumption side was analyzed. Wang & Yang (2015) combined with the two-level logarithmic average distribution index and the Tapio model, the relationship between carbon emissions and industrial development in the Beijing-Tianjin-Hebei region is explored. This paper uses the Tapio decoupling model to determine carbon emission responsibility accounting.

2. Materials and Methods

2.1. Selection of Data Sources and Regions

The input-output data in this article is from WIOD, select the latest input-output data in the latest version of the WIOD account 2016 version 2014, and the CO_2 data comes from the WIOD environmental account. There are 56 sectors in the 2014 version of the input-output data, and according to the International Standard Industrial Classification (ISIC Rev 4.0), this paper combines 56 sectors into 11 departments and departments of agriculture, forestry, animal husbandry and fishery, extractive industry, manufacturing, hydropower production and supply, construction, wholesale and retail trade, transportation industry, accommodation and catering industry, information and communication industry, financial industry and real estate, and service industry, and the specific consolidation is shown in **Table 1**.

This paper selects China, India, Russia, Japan, the United States, and the European Union. The EU in this article refers to the six founding countries of the European Union: Germany, Italy, France, Belgium, the Netherlands, and Luxembourg] for empirical analysis. China is the largest developing country with more frequent trade with other countries, in addition, China has a large CO_2 emission while its rapid economic growth, ranking first in 2005. As an economy, the EU trade closely with each other. India is the second largest developing country in the world and is well represented. Russia is one of the world's

Table 1. Consolidation of 56 departments into 11 departments.

Number	Original departments	Consolidated Departments
1	Crop and animal production, hunting and related service activities Forestry and logging Fishing and aquaculture	farming, forestry, animal husbandry and fishery
2	Mining and quarrying	Mining and quarrying
3	Manufacture of food products, beverages and tobacco products Manufacture of textiles, wearing apparel and leather products Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials Manufacture of paper and paper products Printing and reproduction of recorded media Manufacture of coke and refined petroleum products Manufacture of chemicals and chemical products Manufacture of basic pharmaceutical products and pharmaceutical preparations Manufacture of rubber and plastic products Manufacture of other non-metallic mineral products Manufacture of basic metals Manufacture of fabricated metal products, except machinery and equipment Manufacture of computer, electronic and optical products Manufacture of electrical equipment Manufacture of machinery and equipment n.e.c. Manufacture of motor vehicles, trailers and semi-trailers Manufacture of other transport equipment Manufacture of furniture; other manufacturing Repair and installation of machinery and equipment	Manufacture
4	Electricity, gas, steam and air conditioning supply Water collection, treatment and supply Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services	Electricity, gas, steam and air conditioning supply

Continued

5	Construction	Construction
6	Wholesale and retail trade and repair of motor vehicles and motorcycles Wholesale trade, except of motor vehicles and motorcycles Retail trade, except of motor vehicles and motorcycles	Wholesale and retail trade
7	Land transport and transport via pipelines Water transport Air transport Warehousing and support activities for transportation Postal and courier activities	transport
8	Accommodation and food service activities	Accommodation and food service activities
9	Publishing activities Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities Telecommunications Computer programming, consultancy and related activities; information service activities	Information and Telecommunications
10	Financial service activities, except insurance and pension funding Insurance, reinsurance and pension funding, except compulsory social security Activities auxiliary to financial services and insurance activities Real estate activities	Finance and Real estate activities
11	Legal and accounting activities; activities of head offices; management consultancy activities Architectural and engineering activities; technical testing and analysis Scientific research and development Advertising and market research Other professional, scientific and technical activities; veterinary activities Administrative and support service activities Public administration and defence; compulsory social security	Service

Continued

Education
Human health and social work activities
Other service activities
Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use
Activities of extraterritorial organizations and bodies

largest carbon emitters, rich in fossil fuels and zero-carbon energy resources (Safonov et al., 2020). According to the Economic Complexity Index, Japan is the most complex economy (Adedoyin et al., 2021), Japan has experienced a successful transition from high-carbon consumption patterns to low-carbon economy development with high economic growth and carbon emission growth, and China is currently in a similar stage. The United States is a technology-intensive developed country, but the CO_2 emissions in the United States have not risen sharply with the expansion of trade scale, but CO_2 emissions are in a state of slow reduction, which is typical. In summary, the above six regions or countries are selected for research.

2.2. MRIO Model

MRIO was proposed by Leontief and the current application has matured. This paper builds MRIO table based on WIOD input-output table in 2014. The MRIO model for M countries can be expressed as:

$$\begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} & \cdots & A_{1m} \\ A_{21} & A_{22} & \cdots & A_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ A_{m1} & A_{m2} & \cdots & A_{mm} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{pmatrix} + \begin{pmatrix} y_{11} + \sum_{i \neq 1} y_{1i} \\ y_{22} + \sum_{i \neq 2} y_{2i} \\ \vdots \\ y_{mm} + \sum_{i \neq m} y_{mi} \end{pmatrix}. \quad (1)$$

where x_i is the matrix of total output of each sector in country *i*; *A* matrix is the matrix of direct consumption coefficients, which is an $n \times n$ matrix composed of direct consumption coefficients a_{ij} responding to the direct inputs consumed by the country and other countries per unit of output in each sector of country Q. The sub-matrices A_{ii} on the diagonal represent the mutual demand of production sectors within each country, and the sub-matrix $A_{ij(i \neq j)}$ represents the direct consumption coefficients of intermediate inputs between different countries coefficient matrix, describing the activity of trade in intermediate goods in each country. Column matrix $Y_{ij(i \neq j)}$ represents the final product produced in sector *i* of country to meet domestic demand and 6 represents the final product produced in sector *i* of country to meet the demand of sector *j*. The above equation is rewritten in matrix form as

$$X = AX + Y. \quad (2)$$

Move the position of Equation (2) and swap it to:

$$X = (I - A)^{-1} Y . \tag{3}$$

where $X = (I - A)^{-1} Y$ is the Leontief inverse matrix with embedded elements L_{ij}^{rs} describing the complete consumption of products and services of sector *i* in country *r* for each additional unit of end use in sector *j* in country *s*. *I* is the unit matrix, the chunk matrix L_{ii} is the complete consumption coefficient matrix for country *i*, and $L_{ii(i \neq j)}$ denotes the complete consumption coefficient matrix for country *j* for country *i*.

1) Production-based and consumption-based carbon emission formulas

CO_2 direct emission factor:

$$c_i^s = \frac{q_i^s}{x_i^s} . \tag{4}$$

q_i^s represents the direct emissions of CO_2 in the *i* sector of the country, x_i^s represents the total output of the *i* sector in the country, and c_i^s represents the CO_2 emission intensity.

Converting (5) into matrix form as:

$$Q = CX \tag{5}$$

C represents the carbon emission intensity row vector, which represents the environmental impact per unit of output, substituting (3) into (5) yields:

$$Q = C(LY) = CLY \tag{6}$$

Then the embodied CO_2 emissions from end use in country *r* are:

$$Q^r = CLY = \begin{bmatrix} Q^{1r} \\ Q^{2r} \\ \vdots \\ q^{mr} \end{bmatrix} . \tag{7}$$

where $Q^{2r} \cdots Q^{mr}$ is the column matrix of *n**1, respectively. The sum of *n* elements in Q^{1r} represents the fraction from country 1 of the embodied pollution provided by all countries to country *r*. The sum of *n* elements in Q^{mr} represents the fraction from country *m* of the embodied pollution provided by all countries to country *r*. The difference between the embodied CO_2 input and output of any one country is the net implied CO_2 transfer of that country, and the transfer direction and amount of embodied pollution between trading countries is derived from the above equation.

The formula for carbon emissions based production of country *r* is

$$Q_p^r = c_r x_r = c_r L^W y^{r*} . \tag{8}$$

Among them, c_i is the carbon emission intensity row vector of country *i*, and it is written as a diagonal matrix to obtain the carbon emissions of each sector of *i*. L^W is the Lyontief matrix, in this paper there are 6 countries and the 56 departments are combined into 11 departments, so it is 66 × 66 departments.

$$y^{r*} = \begin{pmatrix} 0 \\ \vdots \\ 0 \\ y^{rr} + \sum_s y^{rs} \\ 0 \\ \vdots \\ 0 \end{pmatrix}. \tag{9}$$

The carbon emissions based production of the country r can be further decomposed:

$$Q_p^r = c_r x_r = c_r x_{rr} + c_r \sum_{s \neq r} x_{rs}. \tag{10}$$

where $c_r x_{rr}$ represents domestic demand emissions for domestic consumption, and $c_r \sum_{r \neq s} x_{rs}$ refers to external demand emissions, which represents the carbon emissions transferred to the country r by other countries through trade.

The formula of carbon emissions based consumption of country r is:

$$Q_c^r = c_r L^W y^{*r}. \tag{11}$$

where C is the carbon emission intensity line vector of the six countries, and y^{*r} is the final use column vector of country r.

$$y^{*r} = \begin{pmatrix} y^{1r} \\ y^{2r} \\ \vdots \\ y^{mr} \end{pmatrix}. \tag{12}$$

y^{*r} indicates the carbon emissions caused by the final demand of country r in other countries, and in the same way C is written as a diagonal matrix to obtain the carbon emissions of each sector in country r.

Decomposing national consumer carbon emissions into domestic emissions and foreign emissions, there are:

$$Q_c^r = c_r x_{rr} + \sum_{i \neq 1} f_i x_{i1}. \tag{13}$$

where $c_r x_{rr}$ represents domestic emissions for domestic use, and $\sum_{r \neq s} f_r x_{rs}$ represents foreign emissions.

2) Production-based and consumption-based carbon responsibility determination

In 2005, Tapio proposed a decoupling model using the change in growth rate to analyze the decoupling relationship between carbon emissions and economic growth in European transportation (Tapio, 2005). In this paper, Tapio decoupling model is introduced to construct a decoupling model of economic growth and carbon emissions, and if economic growth and carbon emissions show strong decoupling, it means that the economic growth of the region does not depend on carbon emissions, and the consumption-based accounting system is used at this time, otherwise the production-based accounting system is used. side Carbon emission accounting at the production end is easy to cause "carbon

Table 2. The degrees of coupling and decoupling of carbon emissions volume growth (ΔQ) from trade growth (ΔM).

	Internal demand emissions	$\%\Delta Q$	$\%\Delta M$	DI
negative decoupling	Strong negative decoupling	+	−	(−∞, 0)
	Weak negative decoupling	−	−	[0, 0.8)
	Expansion negative decoupling	+	+	(1.2, +∞)
coupling	Recessive coupling	−	−	[0.8, 1.2]
	Expansive coupling	+	+	[0.8, 1.2]
decoupling	Recessive decoupling	−	−	(1.2, +∞)
	Weak decoupling	+	+	[0, 0.8)
	Strong decoupling	−	+	(−∞, 0)

leakage" and is not conducive to major exporters such as China, but some scholars believe that if only the consumption side is accounted, it is not conducive to the growth of the region's economy, and the carbon emission accounting at the production end can drive the growth of a region's economy.

$$DI = \frac{\frac{Q_t - Q_{t-1}}{Q_t}}{\frac{M_t - M_{t-1}}{M_t}} = \frac{\Delta Q / Q_t}{\Delta M / M_t} = \frac{\%\Delta Q}{\%\Delta M}. \quad (14)$$

DI represents the decoupling elasticity coefficient, $\%\Delta Q$ represents the rate of change of carbon emissions, and $\%\Delta M$ represents the rate of change of trade. According to the research of Yu and Wang, the decoupling state can be divided as shown in **Table 2** (Yu et al., 2014; Wang et al., 2021).

3. Results and Discussion

The empirical analysis is mainly divided into four parts, firstly, based on WIOD's carbon emission data, the changes of carbon emission in each country (region) since 2000 are compiled, secondly, the MRIO model is used to measure the total carbon emission of each country (region) based on production and consumption, as well as the carbon emission of corresponding sectors and carbon emission of three industries. According to the national standard for dividing the industries, agriculture, forestry, animal husbandry and fishery are classified as the primary industry, extractive industry, manufacturing industry, water, electricity and gas supply industry and construction industry are classified as the secondary industry, and the remaining sectors are classified as the tertiary industry, and then decompose and analyze the production-based and consumption-based carbon emissions respectively. Again, according to the horizontal and vertical relationship of MRIO model, the net transfer between production-based and consumption-based is derived, and the net transfer is the input carbon emission minus the output carbon emission. Finally, the carbon emission responsibility is determined by combining the Tapio decoupling model.

3.1. Production-Based and Consumption-Based Accounting of Carbon Emissions

From the WIOD environmental account, the carbon emissions of each country (region) over the years can be obtained and sorted out, and it can be seen from Figure 1 that China's carbon emissions have been increasing significantly since joining the WTO, and have declined slightly since 2014, but they still far exceed those of other countries. Carbon emissions in the European Union, Japan, the United States, India and Russia have grown or declined slowly, either by much or at a small rate.

As shown in Figure 2, the final production-based and consumption-based carbon emissions for each country are derived using the MRIO model, which shows that production-based carbon emissions are higher than consumption-based carbon emissions for China and India. Japan, the United States, the European Union, and Russia have higher consumption-based carbon emissions than production-based carbon emissions.

According to Equations (8) and (11), the production-based consumption-based carbon emissions of each sector can be derived, as shown in Figure 3, where the difference between production-based and consumption-based carbon emissions of India and Russia is not significant. The difference between production-

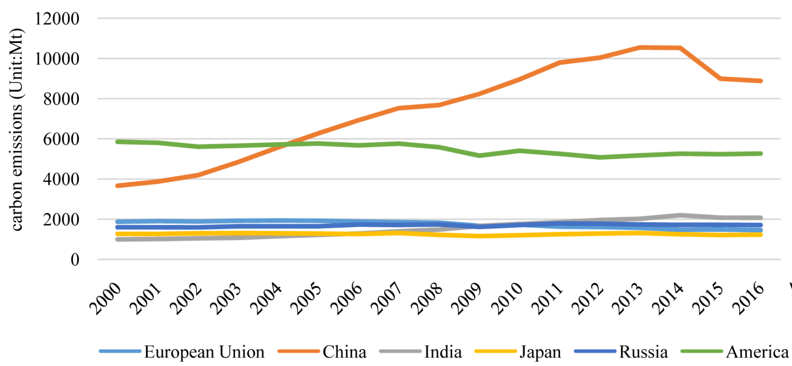
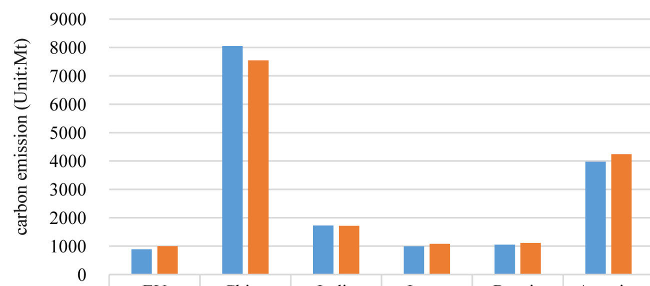


Figure 1. CO_2 emissions in six countries over the years (unit: Mt).



	EU	China	India	Japan	Russia	America
production-based carbon emissions	892.66	8048.60	1727.28	995.95	1054.26	3976.78
consumption-based carbon emissions	998.75	7542.19	1716.28	1083.91	1111.54	4242.85

Figure 2. Production-based and consumption-based carbon emissions in six countries in 2014.

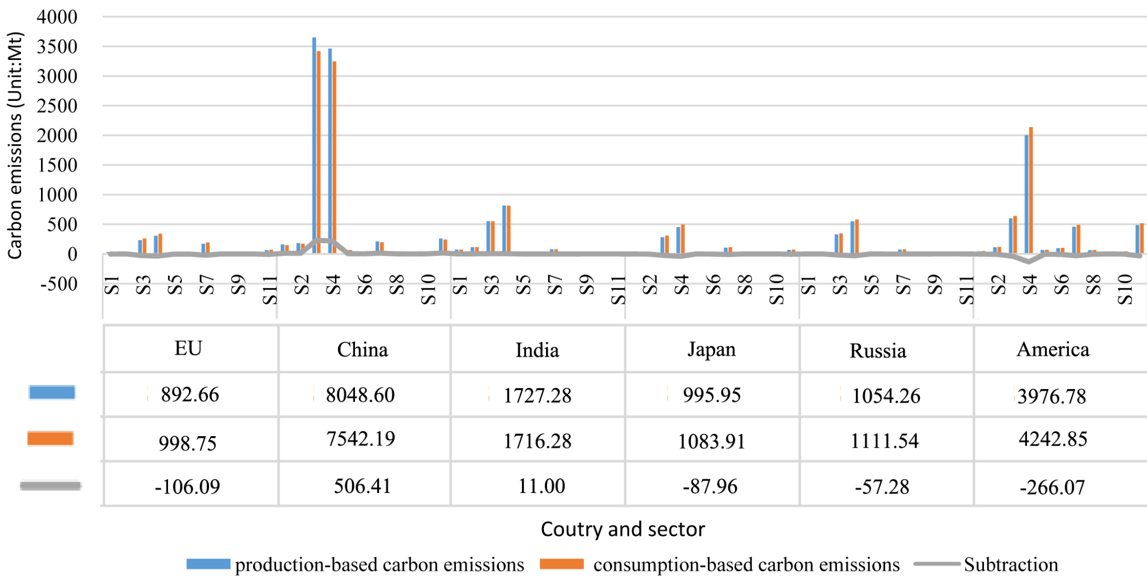


Figure 3. Production and consumption-based carbon emissions by sector by country in 2014 (unit: Mt).

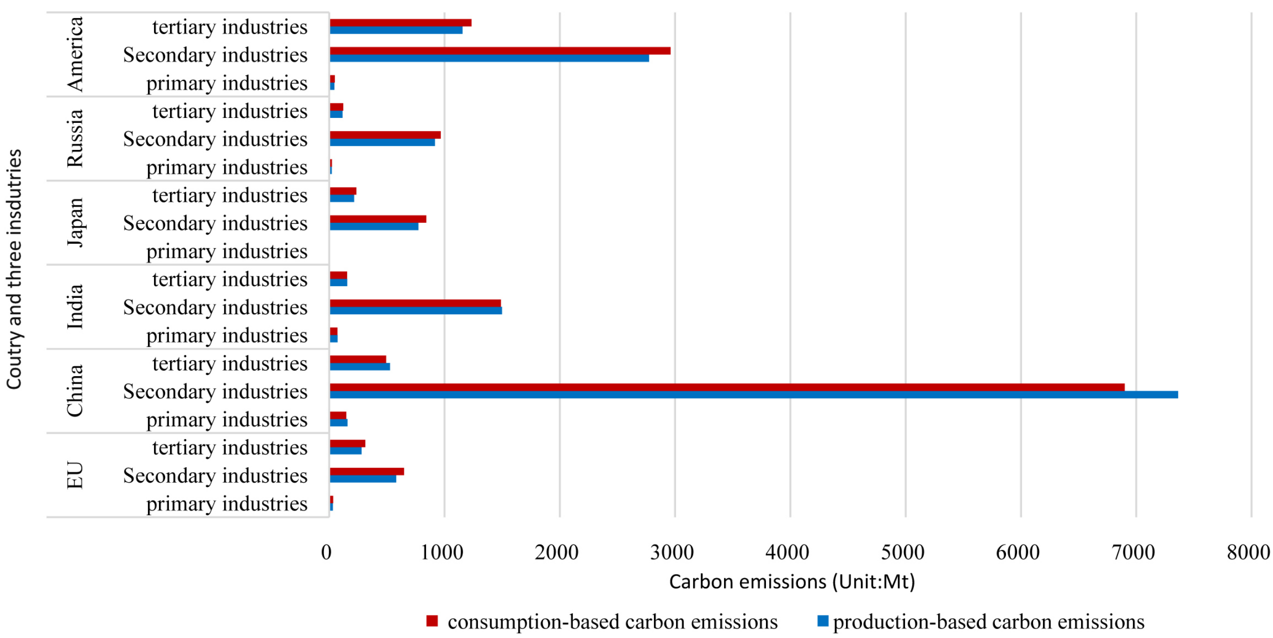


Figure 4. Carbon emissions from production and consumption in three industries in six countries (unit: Mt).

based and consumption-based carbon emissions is 11 Mt tons and 87.96 Mt tons, respectively, and it is within 100 Mt tons. China's production-based carbon emissions are significantly higher than consumption-based carbon emissions in the mining, manufacturing, and electricity, water, and gas production and supply sectors. The EU, the US, and Japan have higher consumption-based than production-based emissions in these sectors, with little difference in other sectors.

Combining the relevant departments in Figure 3 to obtain the carbon emissions of the production end and consumption end of the tertiary industry in each country (region) shown in Figure 4, it can be seen that the carbon emissions of the primary industry and the production end of the tertiary industry are not much different, mainly concentrated in the secondary industry. Among them, the carbon emissions of China and India on the production side of the secondary industry are greater than the carbon emissions at the consumer side, while the European Union, Japan, Russia and the United States are the opposite.

3.2. Decomposition of Production-Based and Consumption-Based Carbon Emissions

In this paper, we decompose production-based carbon emissions into internal demand emissions and external demand emissions, and consumption-based carbon emissions into domestic emissions and foreign emissions. The internal emissions and domestic emissions refer to the emissions caused by the final demand of a country in that country, the external emissions refer to the carbon emissions caused by the carbon emissions of other countries in a country, and the foreign emissions are the carbon emissions caused by the output of a country in other countries. According to the above definitions and MRIO model, the decomposition of carbon emissions at the place of production and consumption of each country is finally obtained, which is presented in a table in the form of percentages, as shown in Table 3.

As can be seen from Table 3, China's production-based emissions account for 6.88% of its external demand emissions, but its consumption-based emissions account for only 0.63% of its foreign emissions, which shows that China is at a disadvantage in international trade and is a processing plant for high-carbon products from other countries. India is the same, but the gap between its external demand emissions and foreign emissions is not as large as China's, which is caused by India's low degree of openness to the outside world. EU, Japan, Russia, and the United States have 14.54%, 12.68%, 6.23%, and 7.42% of foreign emissions and 4.38%, 4.49%, 1.14%, and 1.23% of external demand emissions, respectively,

Table 3. Carbon emission decomposition under production and consumption.

	Production-based carbon emissions		consumption-based carbon emissions	
	Internal demand emissions	External demand emissions	Domestic emissions	Foreign emissions
EU	95.62%	4.38%	85.46%	14.54%
China	93.12%	6.88%	99.37%	0.63%
India	97.81%	2.19%	98.44%	1.56%
Japan	95.03%	4.97%	87.32%	12.68%
Russia	98.86%	1.14%	93.77%	6.23%
America	98.77%	1.23%	92.58%	7.42%

and their foreign emissions are larger than external demand emissions, and these countries are in a dominant position through trade emissions in other countries where the embodied carbon imported is much larger than the embodied carbon exported by them. Especially, the EU is in an absolute dominant position.

3.3. Embodied CO_2 Transfer Analysis

As can be seen from Figure 5, the study concludes that the EU, the US, and Japan are the importers and China, India, Japan, Russia, and Russia are the exporters of embodied carbon by accounting for the export and import of embodied carbon by trade for each sector in the EU, China, Japan, Russia, and the US, and the net transfer of embodied pollution between countries.

In general, carbon transfer between countries is mainly concentrated in four sectors: mining and quarrying, manufacturing, water, electricity and gas production and application, and transportation, especially manufacturing.

As a major manufacturing country, China's CO_2 input in manufacturing far exceeds that of other sectors in other countries, and the main CO_2 input is concentrated in manufacturing. India and Russia have insignificant foreign trade, and the EU, Japan and the US have major trade concentration in manufacturing and water, electricity and gas production and application industries in international inter-trade. Overall China is in the most disadvantaged position in international inter-trade, with developed countries transferring large amounts of CO_2 to China through trade.

3.4. Determination of Carbon Emission Responsibility

In this paper, the decoupling elasticity index of carbon emissions under the production place principle is calculated with 2013 as the base period and 2014 as

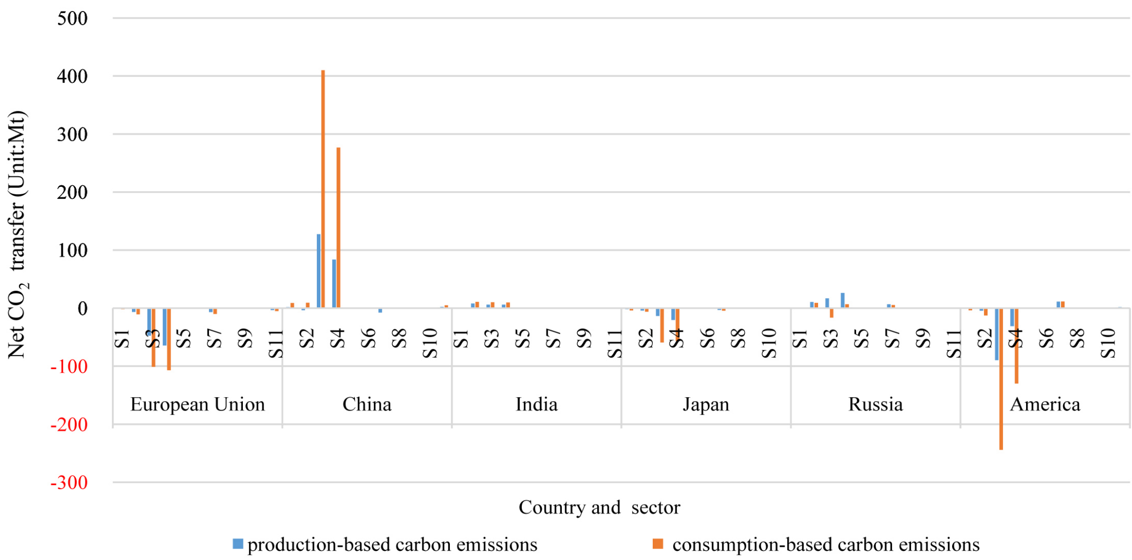


Figure 5. Net CO_2 transfer by sector internationally, 2014 (unit: Mt). Net CO_2 transfer = embodied CO_2 input minus embodied CO_2 output.

Table 4. Economic growth and carbon emission decoupling elasticity index based on production accounting.

Coutries	$\%\Delta Q$	$\%\Delta M$	Elastic decoupling index	Decoupling relationship
EU	−0.0466	0.0310	−1.5049	Strong decoupling
China	−0.0046	0.0859	−0.0539	Strong decoupling
India	0.1011	0.0536	1.8869	Expansion negative decoupling
Japan	−0.0554	−0.0757	0.7319	Weak negative decoupling
Russia	−0.0462	−0.0687	0.6719	Weak negative decoupling
America	−0.0466	0.0310	−1.5049	Strong decoupling

the current period, which is shown in Table 4.

As shown in Table 4, the decoupling elasticity indices and decoupling relationships for each country (region) are demonstrated, where the EU and China are in a strong decoupling state, i.e., the economic growth of this country (region) is not dependent on carbon emissions. Therefore, the consumption-based emissions approach is used for the EU and China. The production-based accounting method is applied to India, Japan, Russia, and the United States.

4. Conclusion and Countermeasures

This paper takes the EU, China, India, Japan, Russia, and the United States as research objects, and uses MRIO to measure production-based and consumption-based carbon emissions in each region respectively, and combines the Tapio decoupling model to determine the carbon emission accounting methods of each country (region), and the main conclusions are as follows.

1) In general, global carbon emissions are on an upward trend, with developing countries rising more rapidly and developed countries rising slowly. There are differences between production-based carbon emissions and consumption-based carbon emissions in each country (region), among which production-based carbon emissions are larger than consumption-based carbon emissions in China and India. The differences are mainly in the manufacturing and extractive industries sectors. The opposite is true for the EU, the US, Japan, and Russia. The differences between production-based and consumption-based emissions of the three sectors are mainly concentrated in the secondary sector.

2) A decomposition of production-based and consumption-based carbon emissions reveals that the EU, the US, Japan, and Russia have much larger offshore foreign emissions than external demand emissions, while the opposite is true for China and India, indicating that they are at a disadvantage in international trade.

3) Whether measured based on production or consumption: China, India, and Russia are the exporters of embodied carbon, while the EU, US, and Russia are the importers of embodied carbon.

The Tapio decoupling model shows that economic growth and carbon emissions are in a strong decoupling state in the EU and China, i.e., economic growth is accompanied by a decrease in carbon emissions. India is in an expansionary negative decoupling state, which is a worse state, where economic growth is slow while carbon emissions are increasing significantly. Japan and Russia are in a weak negative decoupling state, where the economy is in recession and carbon emissions are slowly declining. The US is in a weak decoupling state, where economic growth is accompanied by increasing carbon emissions.

The following recommendations are made in response to the study results.

First, under the production-based principle, China and India bear the carbon emissions from other countries and can request certain subsidies from the EU, the US, etc. The production-based and consumption-based differences among countries (regions) are mainly concentrated in manufacturing and extractive industries, so when conducting international trade, they can focus on these sectors and impose tariffs appropriately. Second, China, India, and Russia, as implicit carbon exporters, are at a disadvantage in international trade, especially China, which has become a "pollution factory" for developed countries and bears the carbon emissions of other countries. In the international climate negotiations, the carbon emissions transferred by developed countries to developing countries such as China through international trade should be taken into account, instead of only considering the responsibility of national emissions. Finally, how to determine the responsibility of carbon emission is the focus of scholars in recent years, countries can determine the responsibility of carbon emission reduction according to the state of economic growth and environmental pollution, and the effective combination of Tapio decoupling model and MRIO can provide a reference basis for carbon emission responsibility.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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