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Spatial-temporal Dynamics and Driving Forces of Provincial CO_2 Emission Responsibilities in China from Multiple Perspectives

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Abstract

A comprehensive analysis of the carbon emission profile of Chinese provinces from multiple perspectives is required to develop equitable and effective policies to reduce carbon emissions. This study estimates the carbon dioxide (CO_2) emission responsibilities of China's 30 provinces and 22 sectors from production, consumption, and income-based perspectives from 2012 to 2017. Structural decomposition analysis (SDA) is used to determine the driving forces of changes in CO_2 emissions in China from 2012 to 2017. The results indicate the following. (1) The dominant CO_2 emission sectors are the Electric Power, Steam, and Hot Water industry and the Smelting and Pressing of Metals industry. (2) The scale effect of the initial input is the dominant factor affecting the growth of CO_2 emissions, followed by the scale effect of the final demand from 2012 to 2017. (3) The structural effect of the production output is the primary carbon reduction factor, followed by the structural effect of the intermediate product input and the carbon intensity effect. Based on these results, recommendations are provided to reduce CO_2 emissions, such as developing green and low-carbon technologies, revising and optimizing the energy composition, accelerating the green transition, and a science-based approach to investment.

Keywords: Multiple perspectives, China's Provinces, Spatial-temporal evolution, MRIO model, SDA model.

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1. Introduction

Climate change poses a formidable challenge to humankind. Tackling it successfully is the combined responsibility of the Chinese nation and all other countries (Dai and Zhou, 2022). Climate change mitigation will significantly contribute to sustainable human existence and foster economic prosperity and ecological advancement (Wang et al., 2021; Li et al., 2020). Carbon dioxide (CO_2) emissions from burning fossil fuels and human activities are widely acknowledged as the predominant catalyst for global warming (Gao et al., 2021; Shan et al., 2021; Avcı et al., 2023; Han et al., 2023). Hence, the mitigation of CO_2 emissions constitutes a crucial environmental concern (Ma and Cai 2019; Chen et al., 2021). In 2006, China emerged as the foremost contributor to global CO_2 emissions (Mi et al., 2017), with a proportion of 24% (Li et al., 2021). China has implemented several policies, measures, and actions to mitigate increasing CO_2 emissions to reach peak CO_2 emissions before 2030 and achieve carbon neutrality before 2060 (Li et al., 2020; Yang et al., 2019; Liu et al., 2022). These actions are aimed at mitigating climate change by reducing CO_2 emissions and achieving sustainable development (Lv et al., 2021).

The conditions in the provinces must be known to meet the targets for mitigating increasing CO_2 emissions (Li et al., 2018). First, the vastness of China results in significant provincial disparities in the developmental stage, endowment of mineral resources, core industry, and eco-environmental resources (Liu et al., 2022a). Thus, the reduction of provincial carbon emissions is inconsistent with that at the national level, and progress toward climate targets differs in different regions (Wang et al., 2018). However, climate change research in China is commonly perceived as homogeneous in most studies (Fang et al., 2023; Jiang et al., 2023). Also, consistent CO_2 emission reduction policies and actions in regions and sectors do not result in economic sustainability, poverty alleviation, and common prosperity (Lee and Erickson 2017; Koondhar et al., 2021). The above statement emphasizes the scientific and practical imperative of formulating a robust, precise, and comprehensive accounting framework to guide provincial policies aimed at reducing CO_2 emissions. Second, the provinces are the fundamental administrative units to implement climate policies (Tian et al., 2022). The carbon emission statistics and accounting at the province level are critical for achieving the dual carbon goal. The findings could provide significant information for the comprehensive evaluation of the CO_2 emission reduction performance (Li and Wang, 2019). Assessing the emissions using producer responsibility alone results in a mismatch between the potential capability, and responsibility for carbon emission reduction at the province level. Further, there has been considerable debate on the rationalization of the producer responsibility (Meng et al., 2023). Thus, considering these reasons, a fair and rational accounting of the CO_2 emission responsibilities for the 30 provinces and 22 sectors is required to reach the national and provincial CO_2 targets.

Revealing the underlying factors of changes in CO_2 emissions is crucial to implementing effective carbon emission reduction policies. Many studies have analyzed the driving forces of CO_2 emission changes based on production or consumption. The producer responsibility approach accounts for emissions generated during production. Individual economies have been investigated, with an emphasis on energy use and policies, such as the adjustment of the economic structure, energy mix, and technological innovation (Zhang and Zhang, 2021). The consumer responsibility approach considers emissions generated in the supply. Individual or multiple economies have been researched, focusing on consumption needs and policies, such as the life-cycle management of CO_2 emissions and refining the obligations and responsibilities of CO_2 emission reductions (Wang et al., 2023; Xing, 2023). A few researchers calculated the proportion of producer and consumer responsibilities (Lenzen et al., 2007; Peng et al., 2015; Jakob et al., 2021). However, most studies on the driving forces of CO_2 emissions accounted only for emissions produced by producers and consumers, ignoring the CO_2 emissions based on income. Therefore, the underlying factors influencing changes in income-based CO_2 emissions, i.e., capital, labor, and material, were not considered (Cong et al., 2018). A comprehensive understanding of the driving forces of CO_2 emission changes is required to establish effective policies for emission reduction (Liu X et al., 2022a). Due to the limited applicability of single production-based accounting, we focus on multidimensional driving forces of CO_2 emissions and provide key information for policies and actions to mitigate CO_2 emissions (Zhang and Zhang, 2021).

We estimate the CO_2 emission responsibilities of China's 30 provinces and 22 sectors from production, consumption, and income-based perspectives from 2012 to 2017. A structural decomposition analysis (SDA) model is employed to explore the driving forces of changes in CO_2 emissions in China's domestic sector from 2012 to 2017. The results can be used to reduce CO_2 emissions by provinces and industries using targeted measures and influence the output and emissions in upstream and downstream supply chains. We provide supporting data to achieve the dual carbon goal and implement other reduction policies. Thus, this study serves as a valuable reference for decision-makers. Meanwhile, research on the impacts of a CO_2 accounting system in provinces and industries provides decision-makers with significant insights into critical issues, such as formulating effective adaptation strategies for changes in CO_2 emissions and identifying potential investment areas.

2. Literature Review

Examining CO_2 emissions from different perspectives is essential. An extensive body of literature exists regarding the potential impacts of producer and consumer CO_2 emissions. Three principal alternative approaches to emission accounting have been put forward in the literature: production, consumption, and income-based responsibilities. The producer responsibility is the perspective presumed in the Kyoto Protocol, where regions are held accountable for emissions generated within the boundaries of their respective territories. This approach is unambiguous and straightforward. Existing climate policies can be regarded as a production-based approach. However, carbon leakage can occur (Cong et al., 2018). In the consumer responsibility approach, the consumers (families, receivers of assets, the government as a consumer, and overseas importers) are responsible for emissions because they have a crucial role in driving the upstream sectors. The impact on these sectors would be significantly lower without the consumers' demand. From an income-based perspective, primary input providers (including workers, investors, and the government responsible for industry administration), contribute to production through their work, investments, or administrative roles and bear income-based responsibility. We reviewed the literature on this topic and found several prominent gaps despite previous advances in CO_2 emissions accounting based on producers or consumers.

First, most existing studies calculated CO_2 emission responsibilities solely based on producers or consumers or found a balance between them (Meng et al., 2023). However, few studies were conducted on income-based emissions. Multiple accounting methods should be used to clarify the CO_2 emissions of China's 30 provinces. Thus, it is unreasonable to ignore income-based accounting because it would underestimate the emission responsibilities of capital and resource-exporting provinces (Cong et al., 2021). Second, most previous studies considered static conditions, focused on assessments of a specific period, or examined solely temporal changes in one sector in a specific region (Chai et al., 2017; Liu et al., 2022b; Liu et al., 2023). Limited research has explicitly addressed the spatiotemporal heterogeneity and dynamics in the provincial-level CO_2 emissions. However, this information is of utmost importance in identifying hotspots for targeted policy interventions, comprehending the underlying factors contributing to spatial disparities in CO_2 emissions, and monitoring progress towards achieving emission reduction targets (Liang et al., 2017). Third, many studies have quantified the factors affecting CO_2 emission changes from production and consumption-based perspectives using the logarithmic mean division index (LMDI) model or SDA model (Deng and Chen, 2022; Li et al., 2020). In comparison, we assesses the driving forces including carbon intensity, the structure of the intermediate product input, the composition of the primary input categories, and the output structure et al. Investigating these factors is crucial for achieving comprehensive emission reduction, which requires prompt attention.

Due to the fragmented and static CO_2 emission accounting strategies, it is necessary to consider emissions based on production, consumption, and income at the provincial and sectoral levels across time and space. The new contributions of this study are as follows. (1) We analyze the provincial and sectoral CO_2 emissions based on production, consumption, and income perspectives in-depth, providing a new carbon accounting perspective that enables the development of effective policies to tackle CO_2 emissions. (2) A unified, correct, and comparable CO_2 emissions framework is developed to generate novel data insights with enhanced spatial and temporal resolution, enabling the implementation of effective emission reduction policies. (3) We conduct a decomposition analysis of the production input and product structure to gain a deeper understanding of products with the greatest impact on emissions and identify the key activities in their supply chains that contribute significantly to CO_2 release. Our study provides valuable information to improve coordinated climate action and formulate more effective carbon duction strategies in China.

3. Methodology and Data

3.1 China Multi-Regional Input-Output Table

Table 1 shows the framework of China's Multi-Regional Input-Output (MRIO) Table published by the China Emission Accounts and Datasets (CEADs). The table shows three quadrants: The matrix Z in Quadrant I represents a set of n × n transactions, where element x_{ij} in Z represents the total monetary purchases made by sector j from sector i. In the IO terminology, the consumption of goods and services by one industry as inputs to the production of another industry is referred to as intermediate consumption. Quadrant II represents an n × d final demand matrix Y, where d is the number of final consumption categories. The Z and Y columns comprise the sales of the sectors, enabling the derivation of a vector X representing the aggregate outputs by summing the values in the columns. Quadrant III represents a value-added matrix V, including each sector's non-industrial payments, such as wages, taxes, and profit. In a balanced IO system, the total payments of each sector equal its total sales, consequently, X can be derived by summing the values in columns Z and V.

Table 1: Framework of the China Multi-Regional Input-Output Table

<table>
<tr><th colspan="3" rowspan="3">Outputs
Inputs</th><th colspan="3">Intermediate Use</th><th colspan="3">Final demand</th><th rowspan="3">Export</th><th rowspan="3">Total Output</th></tr>
<tr><th>Province i</th><th>...</th><th>Province j</th><th rowspan="2">Province i</th><th rowspan="2">...</th><th rowspan="2">Province j</th></tr>
<tr><th>Sector i ... Sector j</th><th>...</th><th>Sector i ... Sector j</th></tr>
<tr><td rowspan="3">Intermediate Inputs</td><td>Province i</td><td>Sector i
...
Sector j</td><td>Z^{ii}</td><td></td><td>Z^{ij}</td><td>Y^{ii}</td><td>...</td><td>Y^{ij}</td><td>EX^{i}</td><td>X^{i}</td></tr>
<tr><td>⋮</td><td>...</td><td>...</td><td>⋱</td><td>...</td><td>...</td><td>⋱</td><td>...</td><td>...</td><td>...</td></tr>
<tr><td>Province j</td><td>Sector i
...
Sector j</td><td>Z^{ji}</td><td>...</td><td>Z^{jj}</td><td>Y^{ji}</td><td>...</td><td>Y^{jj}</td><td>EX^{j}</td><td>X^{j}</td></tr>
<tr><td rowspan="2">Intial inputs</td><td colspan="2">Import</td><td>M^{i}</td><td>...</td><td>M^{j}</td><td colspan="5" rowspan="3"></td></tr>
<tr><td colspan="2">Value-added</td><td>V^{i}</td><td>...</td><td>V^{j}</td></tr>
<tr><td colspan="3">Total input</td><td>X^{i}</td><td>...</td><td>X^{j}</td></tr>
</table>

3.2 Environmental input-output analysis

The IO theory is an analytical framework that utilizes economic data to establish a relationship between gross sectoral outputs or equivalent inputs and final demand (upstream or Leontief model) or primary inputs (downstream or Ghosh model). The environmental MRIO model is based upon the IO theory (Leontief, 1936), which has been extensively used for modeling in energy, CO_2 emissions accounting, and climate change studies. MATLAB (2022a) software was used for the calculations.
We used the Intergovernmental Panel on Climate Change (IPCC) emission coefficients and the Leontief MRIO and Ghosh MRIO models to calculate the CO_2 emissions associated with production, consumption, and income in each region as follows:

$$p_j = f x_j \tag{1}$$

$$c_j = f(I - A)^{-1} y_j \tag{2}$$

$$i_j = v\,(I - B)^{-1} f \tag{3}$$

where p_j, c_j, and i_j, respectively, represents the total CO_2 emissions based on production, consumption, and income.
In Eq. (1), f is the row vector of the region-specific CO_2 emissions per unit of output, and represents the carbon intensities of 22 sectors in 30 provinces. x_j is the total output of sector j. The element f_j^e in $f\ is\ given\ by$ Eq. (4):

$$f_j^e = e_j / x_j\ (j = 1, 2, 3\cdots n) \tag{4}$$

In Eq. (2), I is the identity matrix, and A is the direct consumption coefficient matrix (also known as the technical coefficient matrix).$(I - A)^{-1}$ is the Leontief inverse. y_j is the final demand in sector j. The element a_{ij} in $A\ is\ given\ by$ Eq. (5):

$$a_{ij} = x_{ij} / x_j \quad (i = 1, 2, 3 \dots n\ ;\ j = 1, 2, 3 \dots m) \tag{5}$$

In Eq. (3), v is a row vector of the primary inputs ; B is a matrix of direct sales, and $(I - B)^{-1}$ is the Ghosh inverse. The element h_{ij} in $B\ is\ given\ by$ Eq. (6):

$$h_{ij} = x_{ij} / x_i \quad (i = 1, 2, 3 \dots n\ ;\ j = 1, 2, 3 \dots m) \tag{6}$$

where x_i represents the row vector of the total input.

The responsibility accounting methods are summarized in Table 2.

Table 2: Responsibility accounting methods

Perspectives	Expressions	Methods
Production-based	$p_j = f_j^e x_j$	IPCC emission coefficient
Consumption-based	$c_j = f_j (I - A)^{-1} y_j$	Leontief MRIO model
Income-based	$i_j = v_i (I - B)^{-1} f_j^e$	Ghosh MRIO model

3.3 Structural decomposition analysis

The SDA model is a helpful medium for quantifying changes in the physical and economic factors based on the MRIO table and identifying latent determinants contributing to temporal changes in CO_2 emissions (Deng et al., 2023). Due to the advantages and wide application of SDA in carbon emissions and energy consumption, this approach was used to analyze the driving forces of the changes in CO_2 emissions.

We first assessed the determinants of changes in emissions based on consumption. The final demand, i.e., Y in Eq. (2), was broken down into Y_1 (the consumption structure of product), Y_2 (consumption structure), and Y_3 (the total consumption). f is the row vector of the carbon intensities, and L is the Leontief inverse matrix, which were defined in Eq. (2) and Eq. (4), respectively. Thus, the changes in consumption-based emissions ΔC can be decomposed into the following parts:

$$\Delta C = \Delta f L Y_1 Y_2 Y_3 + f \Delta L Y_1 Y_2 Y_3 + f L \Delta Y_1 Y_2 Y_3 + f L Y_1 \Delta Y_2 Y_3 + f L Y_1 Y_2 \Delta Y_3 \tag{7}$$

where Δ represents the variation in the driving force, and the items on the right of Eq. (7) represent the carbon intensity effect Δf, the production input structure effect ΔL, the product structure of the total final demand effect ΔY_1, the structure of the total final demand effect ΔY_2 and the total final demand effect ΔY_3. $y_{1(ij)}$, $y_{2(ij)}$, and $y_{3(ij)}$ in Y_1, Y_2, and Y_3, can be interpreted as:

$$y_{1(ij)} = \frac{q_{bk}}{\sum_1^n q_{bk}}, \quad y_{2(ij)} = \frac{\sum_1^n q_{kb}}{\sum_1^n \sum_1^d q_{kb}}, \quad y_{3(ij)} = \sum_1^n \sum_1^d q_{bk} \tag{8}$$

where q_{bk} represents elements in Y, d represents the number of categories of the final demand, n is the number of sectors, and k=1, 2, 3... d, b=1, 2, 3... n.

It should be noted that this equation performs complete decomposition without residual terms, but it is not the only decomposition method. In this study, we adopted the method used by Mi et al. 2017 and employed the average of two polar decompositions. The decomposition commences by sequentially altering each variable, starting with the first one, followed by subsequent modifications to the second and third variables, etc., resulting in the first polar form. Conversely, the second polar form is obtained through an inverse procedure. We then computed the arithmetic mean of the SDA results based on these two polar forms:

$$\begin{aligned}\Delta\mathrm{C} = &\left\{\left(\frac{1}{2}\right)\left[\Delta f L_{(t)} Y_{1(t)} Y_{2(t)} Y_{3(t)} + \Delta f L_{(t_0)} Y_{1(t_0)} Y_{2(t_0)} Y_{3(t_0)}\right]\right\} \\ &+ \left\{\left(\frac{1}{2}\right)\left[f_{(t_0)} \Delta L Y_{1(t)} Y_{2(t)} Y_{3(t)} + f_{(t)} \Delta L Y_{1(t_0)} Y_{2(t_0)} Y_{3(t_0)}\right]\right\} \\ &+ \left\{\left(\frac{1}{2}\right)\left[f_{(t_0)} L_{(t_0)} \Delta Y_1 Y_{2(t)} Y_{3(t)} + f_{(t)} L_{(t)} \Delta Y_1 Y_{2(t_0)} Y_{3(t_0)}\right]\right\} \\ &+ \left\{\left(\frac{1}{2}\right)\left[f_{(t_0)} L_{(t_0)} Y_{1(t_0)} \Delta Y_2 Y_{3(t)} + f_{(t)} L_{(t)} Y_{1(t)} \Delta Y_2 Y_{3(t_0)}\right]\right\} \\ &+ \left\{\left(\frac{1}{2}\right)\left[f_{(t_0)} L_{(t_0)} Y_{1(t_0)} Y_{2(t_0)} \Delta Y_3 + f_{(t)} L_{(t)} Y_{1(t)} Y_{2(t)} \Delta Y_3\right]\right\}\end{aligned} \quad (9)$$

Analogously, to ascertain the determinants of the income-based fluctuations in emissions, we decompose the value-added portion, i.e., V in Eq. (3), into V_3 (the total primary input), V_2 (the structure of the primary input), and V_1 (the category structure of the primary input). Thus, the changes in income-based emissions $\Delta\mathrm{I}$ can be decomposed as:

$$\Delta\mathrm{I} = \Delta V_3 V_2 V_1 G f + V_3 \Delta V_2 V_1 G f + \Delta V_3 V_2 \Delta V_1 G f + \Delta V_3 V_2 V_1 \Delta G f + \Delta V_3 V_2 V_1 G \Delta f \quad (10)$$

The items on the right side of Eq. (10) represent the total primary input effect ΔV_3, the structure of the primary input effect ΔV_2, the category structure of the primary input effect ΔV_1, the production input structure effect ΔG, and the carbon intensity effect Δf. $v_{3(ij)}$, $v_{2(ij)}$, and $v_{1(ij)}$ in V_3, V_2, and V_1 can be interpreted as:

$$v_{3(ij)} = \sum_1^d \sum_1^n p_{kb}, \;\; v_{2(ij)} = \frac{\sum_1^n p_{kb}}{\sum_1^d \sum_1^n p_{kb}}, \;\; v_{1(ij)} = \frac{p_{kb}}{\sum_1^n p_{kb}} \quad (11)$$

where q_{bk} represents the elements in V, d represents the number of specific primary input categories, n is the number of sectors, and $k = 1,\ 2,\ 3\ldots d,\ b = 1,\ 2,\ 3\ldots n$.

We recompute the arithmetic mean of the SDA results based on the two polar forms:

$$\begin{aligned}\Delta E = &\left\{\left(\frac{1}{2}\right)\left[\Delta V_3 V_{2(t)} V_{1(t)} G_{(t)} f_{(t)} + \Delta V_3 V_{2(t_0)} V_{1(t_0)} G_{(t_0)} f_{(t_0)}\right]\right\} \\ &+ \left\{\left(\frac{1}{2}\right)\left[V_{3(t_0)} \Delta V_2 V_{1(t)} G_{(t)} f_{(t)} + V_{3(t)} \Delta V_2 V_{1(t_0)} G_{(t_0)} f_{(t_0)}\right]\right\} \\ &+ \left\{\left(\frac{1}{2}\right)\left[V_{3(t_0)} V_{2(t_0)} \Delta V_1 G_{(t)} f_{(t)} + V_{3(t)} V_{2(t)} \Delta V_1 G_{(t_0)} f_{(t_0)}\right]\right\} \\ &+ \left\{\left(\frac{1}{2}\right)\left[V_{3(t_0)} V_{2(t_0)} V_{1(t_0)} \Delta G f_{(t)} + V_{3(t)} V_{2(t)} V_{1(t)} \Delta G f_{(t_0)}\right]\right\} \\ &+ \left\{\left(\frac{1}{2}\right)\left[V_{3(t_0)} V_{2(t_0)} V_{1(t_0)} G_{(t_0)} \Delta f + V_{3(t)} V_{2(t)} V_{1(t)} G_{(t)} \Delta f\right]\right\}\end{aligned} \quad (12)$$

Table 3 and Table 4 presents a summing-up of the driving forces analyzed in our study.

Table 3: Driving forces based on consumer responsibility

Factors	**Description**
Δf	the carbon intensity effect
ΔL	the production input structure effect
ΔY_1	the product structure of the total final demand effect
ΔY_2	the structure of the total final demand effect
ΔY_3	the total final demand effect

Table 4: Driving forces based on income responsibility

Factors	**Description**
ΔV_3	the total primary input
ΔV_2	the structure of the primary input
ΔV_1	the category structure of the primary input
ΔG	the production input structure effect
Δf	the carbon intensity effect

3.4 Data sources

The official IO data are compiled every five years, in this study, the 2012, 2015, and 2017 China MRIO tables were derived from the CEADs, the most up-to-date available IO data, which have been widely used for CO_2 emission analysis. To ensure comparability and facilitate the discussion, we selected the data from China's MRIO table and the CO_2 emission inventories for 2012, 2015, and 2017. Due to data difference, the accounting results were compared with those based on the IPCC emission coefficient, and the error was less than 10%. Thus, our calculations are accurate. Moreover, the economy is classified into 42 sectors in the MRIO table and the CEADs database, however, 45 sectors in the CO_2 emission inventories do not include rural and urban resident consumption. We adjusted the industry classification to obtain a match between the MRIO table and the CO_2 emission inventories using sector consolidation proposed by Wenzhi Wang 2022 and obtained 22 sectors. The research framework is illustrated in Figure 1.

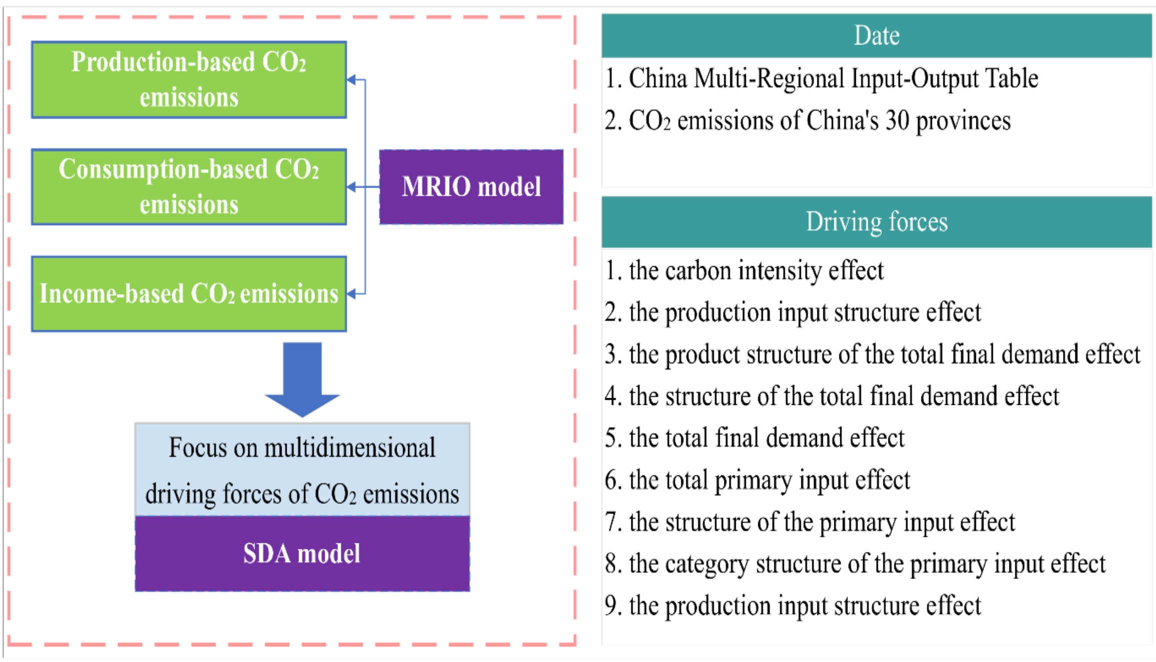

Figure 1: Outline of the research framework

4. Results and discussion

4.1 Spatial-temporal dynamics of provincial emission responsibilities

The region's responsibilities are shown in Figure 2. The CO_2 emission responsibilities differ significantly for different provinces.

The spatial evolution from 2012 to 2017 at the provincial scale indicates substantial differences between production, consumption, and income-based accounting methods. For instance, Shandong is the province with the highest production-based emissions in 2012, 2015, and 2017, followed by Hebei, Jiangsu, and Inner Mongolia. In contrast, the provinces with the lowest production-based emissions are primarily underdeveloped provinces in western regions, such as Qinghai, Ningxia and Gansu. Additionally, provinces with smaller populations like Hainan exhibit similar characteristics. The consumption-based results show that Guangdong had the highest CO_2 emissions in 2012 and 2017, and Shandong had the highest emissions in 2015. The income-based accounting results indicate that Shandong exhibited the highest domestic CO_2 emissions from 2012 to 2017, followed by Hebei, Jiangsu, and Inner Mongolia. Hainan, Qinghai, Beijing, Ningxia, Tianjin, and other provinces have lower carbon emissions for the three accounting methods. The results indicate that the 30 provinces can be divided into three categories. The first category includes the eastern and southern coastal provinces (including Shandong, Jiangsu, and Guangdong). They represent the most affluent regions in China. Their consumer responsibility is typically higher than their producer responsibility because their upstream carbon emissions in imports exceed that of the exports. This result is attributed to their well-developed industrial system and large economies. The second category includes resource-based provinces and those with large industries, represented by Hebei, Shanxi, Inner Mongolia, and Henan, whose economies primarily rely on the energy and raw materials industries. These provinces are the least developed region in China. They contribute to the economic development of the central and eastern regions by supplying products with high carbon intensity and low value-added. Therefore, they consistently have higher production and income-based responsibilities because they derive their income from exporting fossil fuels (or other goods that contribute to emissions downstream in the supply chain) and are responsible for emissions produced overseas when the fossil fuel is used. The other provinces fall into the third category. They have lower responsibilities for carbon emissions because of their small dependence on resources or the impact of economic scale and industrial structure.

The temporal evolution from 2012 to 2017 at the provincial scale shows that the largest increase in carbon emissions from the perspective of producer responsibility occurred in Xinjiang, followed by Jiangxi and Ningxia. From the perspective of consumer responsibility, Henan, Xinjiang, Zhejiang, Hunan, Guizhou, and Jiangxi exhibited the largest increase in carbon emissions. In these provinces, the increase in CO_2 emissions was the same for the income-based and production-based responsibility. On the other hand, the carbon emissions of the more economically developed provinces, such as Beijing, Tianjin, and Shanghai, decreased during this period. The results indicate that some economically underdeveloped provinces, such as the central and western parts of China, have been committed to investing in infrastructure and basic industrial development due to their development levels, resource endowment, and strategic positioning. As a result, the production capacity of resource-based industries and primary raw material industries have expanded rapidly, significantly increasing CO_2 emissions. In addition, the carbon emissions of key provinces along the Yangtze River Economic Belt, such as Hubei, Hunan, Sichuan, and Chongqing, increased significantly from the perspective of income-based responsibility during this period. The reason is a change in local factors due to the transfer of coastal industries along the Yangtze River. In addition, carbon emissions in relatively developed regions, such as Beijing, have continued to decrease, indicating that a few economically developed provinces will reach the carbon peak early.

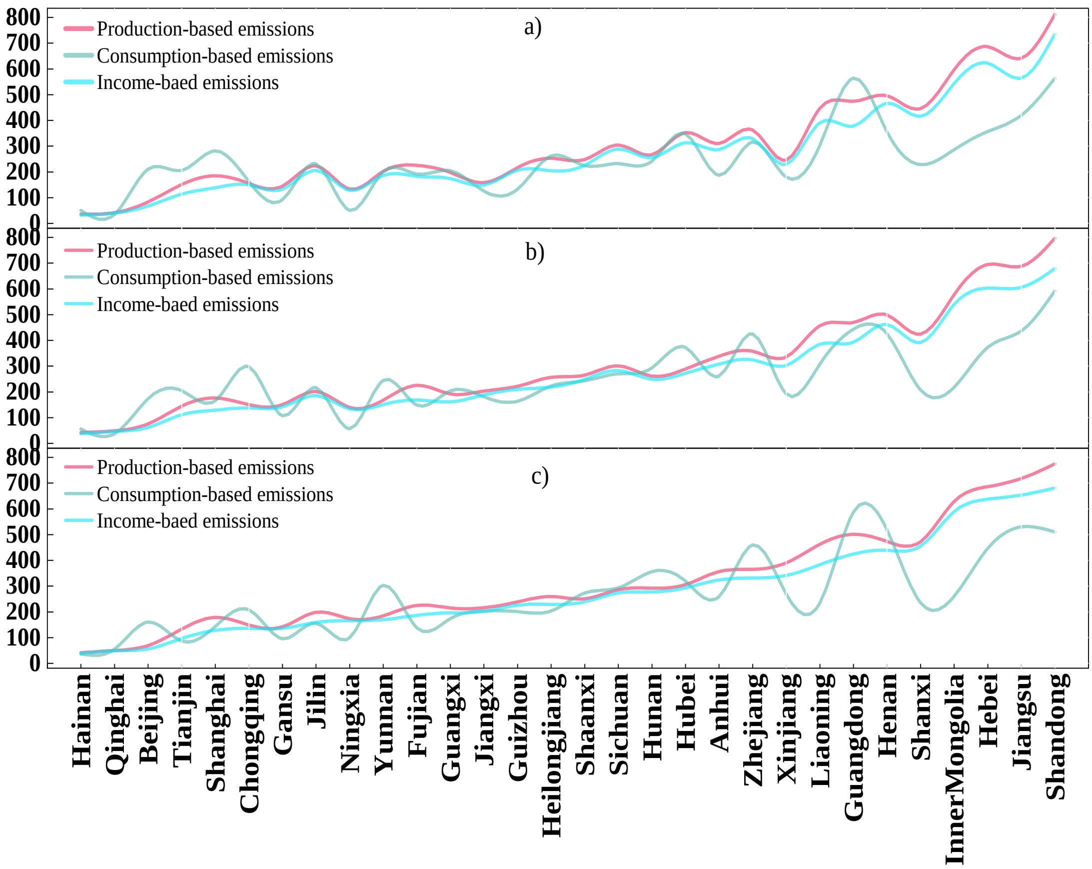

Figure 2: Provincial CO_2 emissions responsibilities derived from multiple emission accountings in 2012 (a), 2015 (b), and 2017 (c)

4.2 Dynamics of sectoral emission responsibilities

The findings indicate disparities in carbon emissions among China's provinces from different accountability perspectives. We conducted a comparative analysis of the carbon emission responsibilities in different provinces at the industrial sector level. For convenient presenting the results, we replaced the names of the 22 sectors with the letter S (as shown in Appendix Table 1).

Figure 3 presents the CO_2 emissions from 22 industrial sectors in 30 provinces in 2012, 2015, and 2017 from production, consumption, and income-based perspective. S17 (Production and Supply of Electric Power, Steam and Hot Water industry) and S11 (Smelting and Pressing of Metals industry) had the largest CO_2 emissions. The reason is that S17 is a critical sector supporting the operation of China's national economy and has a core position in China's industrial chain, resulting in an extensive amount of direct and indirect carbon emissions. In addition, China's large population and massive economic volume result in a significant demand for electricity and heat. Therefore, the emission responsibility of S17 had ranked first for a long time. Besides, S11 has a close relationship with the coal mining industry, thus, a relatively high responsibility for carbon emissions for the following two reasons. First, China has large quantities of coal but limited petroleum and natural gas. The proportion of coal consumption stays relatively high in most provinces of China. Second, coal is a primary input factor, indirectly causing a significant amount of CO_2 emissions in downstream industries. The downstream industries of S11 are mostly high-carbon emitters, such as the steel industry, resulting in high carbon emission responsibilities of this sector.

From a temporal perspective, the carbon emissions of the 22 sectors in 2012, 2015, and 2017 for different responsibility perspectives indicate that the key sectors contributing to CO_2 emissions remained relatively consistent in the 30 provinces. For instance, under production-based emissions, S11 in Hebei was the highest CO_2 emitter in 2012 (287.1 Mt), 2015 (325.2 Mt), and 2017 (329.28 Mt) and the sector with the largest carbon emission responsibility among the provinces. Following closely behind was S17 in Inner Mongolia (420 Mt in 2012, 415 Mt in 2015, and 467 Mt in 2017) and Jiangsu (392.6 Mt in 2012, 386.9 Mt in 2015, and 411.55 Mt in 2017). The limited scale of industrial structure adjustment and minimal changes in the provinces suggest a lack of substantial transformation in the country's industrial chain.

From a spatial perspective, diverse regions demonstrate different patterns in the major sectors contributing to CO_2 emissions. In economically advanced areas like Beijing, S17 was the primary carbon emitter. Conversely, resource-rich regions like Hebei, with substantial iron reserves, or Shanxi, with extensive coal deposits, experienced significant contributions from heavy industries and mining activities toward CO_2 emission levels. As a result, Shanxi's mining industry and Hebei's heavy industrial sector had higher accountability for carbon emissions during 2017.

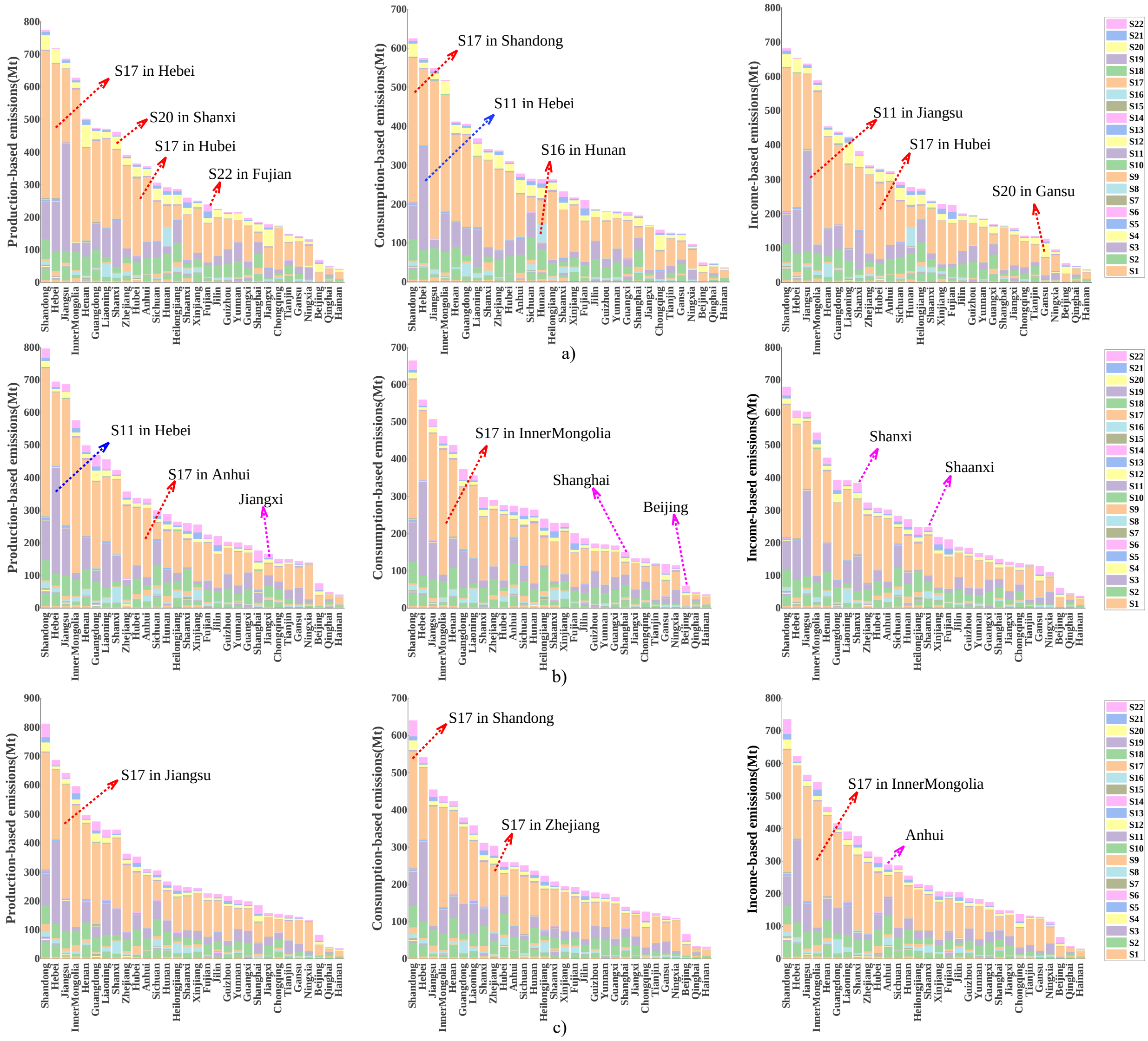

Figure 3: Production, consumption, and income-based CO_2 emissions of 22 sectors in 30 provinces in 2012 (a), 2015 (b), and 2017 (c)

4.3 Comparative analysis of provincial emission responsibilities

We ranked the carbon emissions of 30 provinces in descending order to clarify their responsibilities for carbon emissions. Since consumption and income-based responsibilities cover both ends of the supply chain with contrasting traceability directions, notable disparities were self-evident based on these two perspectives. Therefore, we did not conduct into an analysis or comparison between their responsibilities but focused on the comparison between production and consumption-based and between production and income-based responsibilities.

Figure 4 compares the carbon emission rankings of the provinces in 2012 (a), 2015 (b), and 2017 (c) for production, consumption, and income-based responsibilities.

The results provide a comprehensive understanding of the differences in carbon emission responsibilities between different accounting methods. The proximity of each data point to the red diagonal line indicates the similarity in the rankings for different perspectives and a smaller variation in carbon emission responsibilities and vice versa. Note that the "proximity" means the distance of the data point perpendicular to the red diagonal.

The results in Figure 4 show that few provinces are close to the red diagonal line, indicating that most provinces exhibit different rankings for different responsibility perspectives. Notably, the top-ranking provinces in terms of producer responsibility (Hebei, Inner Mongolia, Shanxi, and others) experience varying degrees of decline based on consumer responsibility. These provinces are positioned above the red diagonal line, indicating their dominant role as producers in the industrial chain and the relatively limited consumption of products from other provinces. Conversely, provinces that ranked lower in terms of producer responsibility (Shanghai, Beijing, and others) had a higher ranking based on consumer responsibility. These provinces are positioned below the red diagonal line, suggesting they do not directly contribute to significant CO_2 emissions but assume a more prominent role as consumers in the industrial chain. These provinces have low rankings from the perspective of production and income-based responsibilities. Shanghai and Jilin exhibit high rankings in terms of producer responsibility and low rankings regarding income-based responsibility. In contrast, Shanxi, Gansu, Ningxia, and other regions have higher rankings in terms of of income-based responsibility. This finding agrees with that of Cong et al. 2021. The reason is that Shanxi and other areas are resource-based regions, resulting in a higher proportion of carbon emissions for income-based responsibility due to energy-intensive production. On the other hand, Shanghai and similar locations consume significant energy during production, particularly in the petrochemical and fine chemical industries. Furthermore, these regions have relatively advanced tertiary industries where capital factors predominantly flow into high-tech industries, service sectors, and other industrial domains with high added value but low emissions. Hence, Shanghai does not rank highly for income-based responsibility.

Our results let us conclude that the diverse roles of different provinces in the industrial chain may cause some provinces to be overlooked regarding policies to mitigate CO_2 emissions. Also, several representative provinces produce high CO_2 emissions during production and the entire supply chain. Accordingly, formulating appropriate policies is pivotal to bolster productivity in these provinces and curtail the demand for intermediate inputs. Furthermore, provinces intersected by the two red dotted lines (e.g., Shandong, Hebei, and Jiangsu) should prioritize carbon emission control measures given their substantial contribution to carbon emissions for all three dimensions of responsibility.

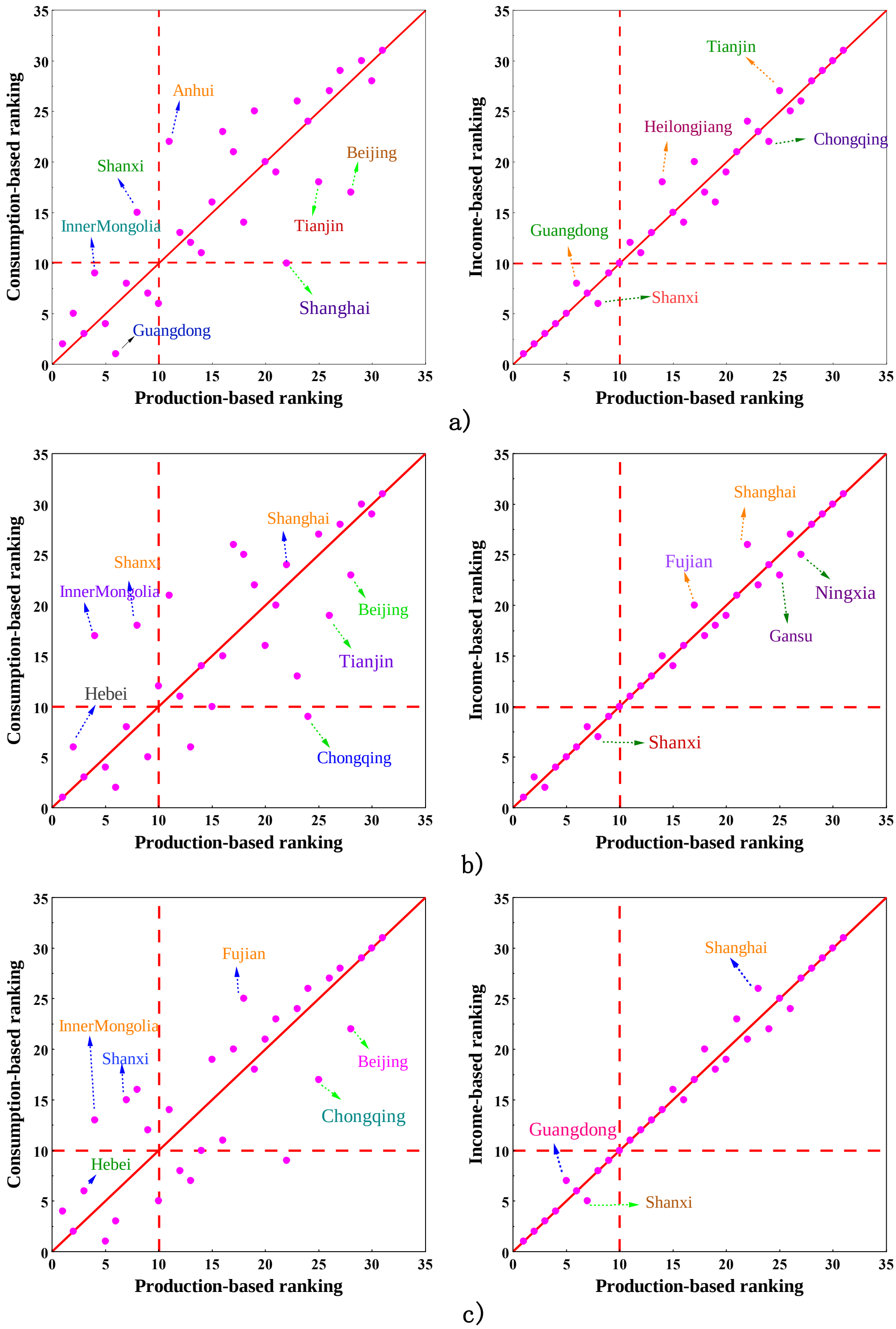

Figure 4: Carbon emission rankings of the provinces for different accounting methods in 2012 (a), 2015 (b), and 2017 (c)

4.4 The driving forces of carbon emission changes

After analyzing of the spatiotemporal evolution of CO_2 emissions, we investigated the underlying factors driving changes in carbon emissions. These changes are influenced by socio-economic and technological advancements and adjustments in the industrial structure. This study decomposed the changes in China's total CO_2 emissions for 2012, 2015, and 2017 from the consumption and income-based perspectives to analyze the contributions of different drivers (as illustrated in Figure 5). The results are shown in Figure 5. Since economic structural factors cannot be used to decompose production-based emissions, they are not analyzed here.

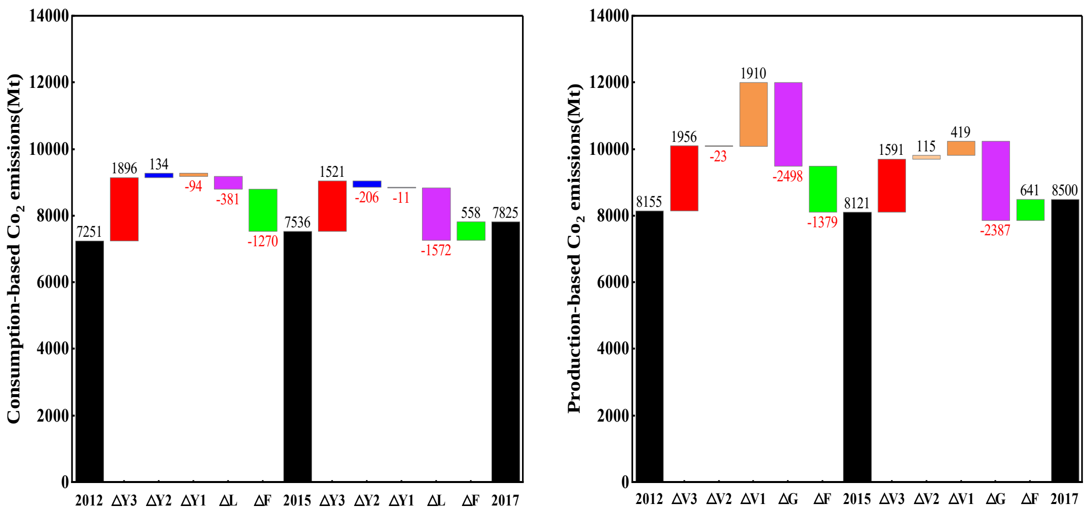

Figure 5: Changes in consumption and income-based emissions from 2012 to 2017

The dominant driver of CO_2 emissions is the scale effects of the final demand (ΔY_3) for consumption-based emissions. The carbon intensity effect (Δf) and the structural effect of the intermediate product input (ΔL) are predominant factors influencing the mitigation of increasing CO_2 emissions. For income-based emissions, the scale effects of the initial input (ΔV_3) and the product structure effect of the primary input (ΔV_1) are major factors contributing to an increase in carbon emissions. The carbon intensity effect (Δf) and the structure effect of the production output (ΔG) had crucial negative effects on mitigating the rise in carbon emissions. The SDA results reveal the driving forces of carbon emissions from the perspectives of consumption and income-based responsibilities. Two important conclusions were made based on the decomposition results. First, carbon emissions attributed to income-based responsibility exceed those attributed to consumption-based responsibility, indicating that production input factors have a greater multiplier effect than consumption, promoting industrial development and carbon emission growth. Second, the effects of carbon intensity and intermediate product input structure had significant negative effects on changes in carbon emissions from consumption and income-based perspectives. Therefore, it is necessary to prioritize improving technical levels. This finding shows that economic development can drive optimization and reform of economic structures while reducing the demand for low-level intermediate inputs. Conversely, less developed regions exhibit relatively lower levels of energy use; hence, each unit of output requires more energy consumption, resulting in increased carbon emissions. Additionally, we can conclude that the final demand scale effect significantly contributes to increased carbon emissions in all regions because goods and services are required to encourage local economic development.

5. Conclusions

In this article, we analyzed the provincial and sectoral CO_2 emissions based on production, consumption, and income-based perspectives using the MRIO model. Furthermore, the SDA model was employed to analyze the underlying factors driving changes in CO_2 emissions during the period from 2012 to 2017. The conclusions are as follows:

1. First, from a national perspective, carbon emissions exhibited an upward trend for difference dimensions during the study period. In terms of producer responsibility, China's carbon emissions increased from 9,098 Mt in 2012 to 9,425 Mt in 2017, representing a growth of 328 Mt. From the standpoint of consumer responsibility, national carbon emissions rose from 7,251 Mt in 2012 to 7,825 Mt in 2017, indicating an increase of 574 Mt. Regarding income-based responsibility, national carbon emissions grew from 8,155 MT in 2012 to reach approximately 8,500 Mt by the end of the study period, representing an increase of 346 Mt. Based on these findings, it can be concluded that consumption-based emissions contributed most significantly to the rise during this period, followed by income and production responsibilities. This result suggests that consumption-based emission activities were more active in China, input factors for production continued to increase, and policies germinating from producer responsibility have yielded positive results in emission reduction.
2. Second, from a multidimensional perspective, provinces with large industries and resource-based provinces, such as Shandong and Hebei, had the highest production-based responsibilities for CO_2 emissions. These provinces have heavy industry and rely substantially on fossil energy for mass production. In terms of consumer responsibility, economically developed regions like Guangdong and Jiangsu Province bore the main burden due to their significant carbon emissions exported to other provinces through the import of intermediate and final products. From the perspective of income-based responsibility, economically developed and resource-based provinces contributed more to production factors, resulting in a substantial increase in downstream carbon emissions in the industrial chain. A multidimensional perspective at the provincial level revealed that most provinces had different rankings for different types of responsibilities. Hebei, Inner Mongolia, and Shanxi Province ranked

high in terms of producer responsibility, low for consumer responsibility, and high for income-based responsibility. Shanghai and Beijing exhibited opposite trends, upward or downward, depending on the perspective. At an industrial sector level, electricity generation & supply, as well as metal smelting & rolling processing, were two sectors with significant carbon emissions. These sectors, which critically influence sustainable urban management, may not directly contribute significantly to environmental stress, but they are major conduits for substantial environmental pressures. Therefore, it is imperative to recognize these transmission centers to guide future environmental policies development.

3. Third, the total size effect of the primary input (ΔV_3) had the most substantial impact on CO_2 emission growth (2012-2017 total: 3,548 MT), followed by the scale effects of the final demand (ΔY_3) of 2012-2017 total: 3,417 Mt. The influence of the structure effect of the primary input categories (ΔV_2) on carbon emission growth increased from -23 Mt in 2015 to 115 Mt in 2017. Conversely, the product structure effect of the primary input (ΔV_1) on promoting carbon emission growth weakened, decreasing from 1,910 Mt in 2015 to 419 Mt in 2017.
4. Fourth, from the perspective of factors inhibiting carbon emissions growth, the structural effect of the production output (ΔG) contributed the most to reducing CO_2 emissions during the study period (2012-2017 total: -4,886 Mt). It was followed by the structural effect of the intermediate product input (ΔL) (2012-2017 total: -1,953 Mt). In contrast, the impact of the final demand product structure (ΔY_1) on inhibiting carbon emission growth weakened from -94 Mt in 2015 to -11 Mt in 2017. Furthermore, a shift occurred in the structural effect of the final demand (ΔY_2) from growth to inhibition, and a slight change occurred in the structure effect of the primary input categories (ΔV_2), which shifted from inhibiting carbon emission growth to promoting it. The combined effects of these two factors were -73 Mt and 92 Mt, respectively, during the study period.

6. Policy recommendations

To the best of our knowledge, most existing policies and actions for CO_2 emission reduction focused on production or consumption perspectives, resulting in the fragmented, isolated, and inconsistent implementation of CO_2 emission targets. Consequently, we provide a compelling incentive to supplement production and consumption-based environmental policy by incorporating income-related factors:

1. Develop low-carbon technologies, sustainable consumption, and science-based production factor strategies. From the producer responsibility perspective, it is imperative to prioritize the promotion of innovation and implementation of green and low-carbon technologies in major emitting provinces as well as key sectors, such as power plants and district heating facilities, with a continuous focus on reducing carbon intensity. For consumption-based emissions, eco-environmental protection should be prioritized to establish, industrial structures and production modes that facilitate resource conservation and environmental

protection while promoting a green and low-carbon lifestyle. For instance, guidance on green consumption should be strengthened to promote eco-friendly products, and industries should be provided with more support to focus on energy conservation, environmental protection, cleaner production, and renewable energy sources. From the income-based responsibility perspective, the supportive role of production factors should be leveraged to achieve the dual carbon goals by directing investments in capital and human resources towards low-carbon sectors. For instance, the carbon-reduction supporting tool can be utilized to provide low-cost loans to financial institutions, enabling them to independently make decisions and take risks while encouraging them to offer loans to firms operating in key carbon-reduction sectors, such as clean energy, energy conservation, and environmental protection. This approach ensures steady, orderly, targeted, and direct support for the development of these crucial fields. Additionally, increased mobilization of social funds can further facilitate the promotion of carbon emission cuts.

2. Optimize the energy mix, accelerate consumption upgrading, and strictly control the supply of high-carbon projects. Based on the producer responsibility, the emission priority areas and major industries should be defined to transform and upgrade the economic and industrial structure and energy mix through innovation. The prioritization of non-fossil fuel development should be encouraged while promoting the environmentally sustainable growth of hydropower and considering energy security and economic stability. From the perspective of consumer responsibility, it is necessary to speed up consumption upgrading and control the scale of consumption of high-carbon products. For income-based emissions, the constraints of production factors on the emission reduction target should be considered to ensure the stringent control of the expansion of energy-intensive and high-emission projects. For example, regarding capital factors, the disclosure of climate risk information for high-carbon investment projects should be encouraged. Additionally, investments in high-carbon projects, such as coal and thermal power, should be limited. It is necessary to curb the unregulated development of energy-intensive and high-emission projects. Conversely, green and low-carbon industries should receive more support to improve energy conservation, environmental protection, cleaner production, and cleaner energy.
3. Adjusting green and low-carbon spatial arrangements, making coordinated efforts in the supply chain, and decreasing CO_2 emissions. Provinces should focus on harmonized economic development and bridging the regional disparity between the eastern and western regions. Regardless of whether they are resource-based, consumption-oriented, or production factor supply provinces, it is imperative to enhance cooperation in emission reduction by implementing suitable measures to reduce CO_2 emissions. Furthermore, compensatory measures should be utilized to achieve China's dual carbon goal. Despite significant CO_2 emissions from the electricity, heat production, and supply sectors and the metal smelting and rolling processing sector, these sectors are

critical in the industrial chain. Therefore, it is crucial to consider the upstream and downstream interdependencies among various industrial sectors to mitigate CO_2 emissions. It is necessary to shut down outdated production facilities, reduce overcapacity at a faster pace, advance production technology, and establish transparent pricing mechanisms for production factors to lower the proportion of energy and carbon-intensive products in the entire supply chain.

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