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Analysis of Industrial Carbon Transfer in Beijing-Tianjin-Hebei City Cluster and Surrounding Areas

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To achieve the goal of carbon neutrality and win the blue-sky defense battle, the environmental situation in Beijing-Tianjin-Hebei and surrounding areas is still grim, and the optimization of its industrial structure and energy structure is imminent. With the rapid development of interregional trade in intermediate products, carbon emissions are transferred across regions with the trade. Due to the large differences in the technology, industrial structure, and economic development of cities, extending the environmental governance chain of Beijing-Tianjin-Hebei and surrounding areas is indispensable. In this article, based on the interregional input-output tables in 2002, 2007, and 2012, we establish the average propagation length (APL) model and the structural path analysis model Structural Path Analysis model for analyzing the carbon conduction relationship in Beijing-Tianjin-Hebei. And we also compare the situation of the Yangtze River Delta and the Pearl River Delta. The results show that: i) From perspective of the whole urban clusters, Beijing-Tianjin-Hebei has obvious characteristics of coal-fired urban clusters. More than 65% of the carbon-containing resources in Hebei's coal industry are transferred to the electricity and heat industry. In the carbon conduction chain, the carbon emissions caused by electricity and heat industry, which acts as an intermediary, account for more than 85% of the total emissions. ii) From the perspective of industrial structure transfer within the urban clusters, Hebei Province has an important resource support position. Its secondary industry can not only effectively alleviate the shortage of energy supply in other resource provinces, but also has great development potential in the improvement of economic benefits. iii) From the perspective of specific industry sectors, resource provinces such as Shanxi and Inner Mongolia have high carbon emission coefficients in the electricity and heat industry, which is the main reason for the high carbon emissions in the transfer chain.

Keywords: beijing-tianjin-hebei, carbon transfer, coordinated emission reduction, inputoutput, average propagation length model, structural path analysis model

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INTRODUCTION

The Beijing-Tianjin-Hebei regional plan was first proposed by the National Development and Reform Commission in 2004, and the plan involves 11 cities including Beijing, Tianjin and Hebei. It was not until 2011 that the Beijing-Tianjin-Hebei urban clusters included all cities in Hebei Province to achieve integrated and coordinated development. However, since the Beijing-Tianjin-Hebei urban clusters was proposed, its economic contribution has not been outstanding. From 2011 to 2019, the average contribution rate of Beijing-Tianjin-Hebei to economic growth was 7.52%, while the average contribution rates of the Yangtze River Delta and Pearl River Delta were 19.67 and 10.61%, respectively. The insufficiency of Beijing-Tianjin-Hebei economic drive is closely related to the positioning of its urban cluster. Compared with the maintaining growth in the central and eastern regions, Beijing-Tianjin-Hebei, as a new growth pole of the Chinese economy, is more rational in terms of economic growth. In terms of the general development strategy, government emphasizes the transformation of economic mode, improvement of economic quality, and emphasis on energy conservation and emission reduction while maintaining stable growth.

In order to achieve the goal of "stabilizing growth and adjusting structure", energy conservation and emission reduction must be the focus of improving the quality of regional economic growth. The current international situation is becoming more and more complex, China's export-oriented economy has been seriously affected, and the role of the core engine of the regional economy has become increasingly prominent. How to play the role of regional clusters and take into account of their ecological benefits is also the focus and difficulty of future development. In recent years, despite of the positive changes in the coordinated development of Beijing-Tianjin-Hebei, environmental issues have always been a major pain point. Due to the unbalanced regional development, the Beijing-Tianjin-Hebei has obvious urbanization gap. And the influx of population into the economically developed cities, namely Beijing and Tianjin, has caused huge pressure on the two cities' resources, environment, electric power transportation, etc. The positioning and development of Beijing's "Four Centers" faces greater challenges. As the hinterland of Beijing and Tianjin, Hebei's functional status has always been relatively clear, that is, as a resource support area for Beijing-Tianjin-Hebei economic development and an experimental area for industrial transformation and upgrading. However, at present, Hebei Province still has problems such as the insufficient supply of its own energy, unreasonable energy consumption structure, and low energy efficiency. With the proposal of the Beijing-Tianjin-Hebei coordination strategy and the establishment of the Xiongan New Area, higher requirements have been placed on the environmental conditions and pollution emissions of Hebei. Hebei is also facing the dual dilemma of energy conservation, emission reduction, and increased resource use.

How to meet the higher requirements of the national strategy on regional environmental conditions and energy conditions while ensuring the resource needs of economic development in the Beijing-Tianjin-Hebei is the focus of this study. Based on this, we first analyze the Beijing-Tianjin-Hebei urban cluster as a whole, compare the carbon transmission chain and industry linkages in the Yangtze River Delta and the Pearl River Delta, and study the focus of the overall emission reduction of the urban cluster. Secondly, based on the main resource provinces identified by the overall carbon transmission chain of the urban cluster, we further study the carbon transfer of industries in the Beijing-Tianjin-Hebei and other resource provinces. Finally, considering the current situation of insufficient self-sufficiency of some resources and the increasing proportion of external energy in Hebei, we focus on the key industries in Hebei and explore the characteristics of carbon transfer docking with industries in other provinces.

LITERATURE REVIEW

At the end of the 20th century, many scholars studied energy consumption and carbon emissions, and they found that with the increasing frequency of international trade and inter-regional trade, changes in the demand for products or resources often resulted in energy consumption and total carbon emissions in the areas where the resources were provided. Usually, the carbon emission in the consumption area is very small, but the resource supply area is limited by the production technology and cost, and the total carbon emission may be very large (Williams et al., 1987; Xie and Chen, 2007; Zhu et al., 2018). Since then, more and more scholars have carried out a lot of research on the transfer of carbon emissions from domestic and foreign trade.

From the perspective of foreign trade, most scholars mainly focus on global and national alliances to study the impact of carbon transfer. As early as the end of the 20th century, Burniaux and Oliveira Martins (2012) discussed the key mechanisms behind the scale of carbon leakage based on three types of fossil fuels (coal, oil, and low-carbon energy), international trade and capital flows. Subsequently, Baker et al. (2007) used a static equilibrium model to estimate that the carbon leakage in the EU from 1995 to 2005 was generally within 5–20%, but the technology spillover effect in some regions alleviated the "carbon leakage" to a certain extent. Essandoh et al. (2020) studied the relationship between CO_2 and trade in developed and developing countries. The study found that with the increase in trade and foreign direct investment, the emissions were transferred from developed to developing countries. Barker et al. (2007) and Muhammad et al. (2020) verified the conclusion from the perspectives of trade and embodied carbon emissions in the Belt and Road countries and ASEAN five countries, respectively. These findings confirm the long-term and widespread impact of international trade-induced carbon emissions shifts on global carbon emissions totals and patterns.

From a domestic point of view, there are also many scholars taking Chinese provinces and cities as examples to measure the scale of carbon emissions across regions. Feng et al. (2020) studied the implied carbon emissions in China in 2010, and the results showed that the inter-provincial trade increased the national carbon emissions by 247t, and the four trillion stimulus plan promoted a large amount of carbon growth in energy-related trade. Wang and Chen (2016) calculated the amount of pollutant transfer in eight regions in China and pointed out that the phenomenon of implied pollution transfer was detrimental to the interests of late-developing regions. Once the threshold of the ecological environment was exceeded, it would damage the achievement of coordinated regional development. Liao and Xiao (2017) found that there was a phenomenon of carbon emission reduction in the northern and southern coastal areas, while the "carbon leakage" effect was more serious in the southwestern region. Mi et al. (2019) analyzed the carbon emissions of 11 cities in Hebei from the perspective of consumer responsibility, and found that 50% of the carbon emissions in these cities were imported from external regions, and believed that policy cooperation between carbon-consuming and carbon-producing regions should be strengthened to effectively mitigate climate change. Based on the pollutant discharge and development levels of Hebei and Beijing, Zhao and Wu (2020) also found that there was serious transfer pollution in Hebei. Shen and Huang (2015) pointed out that Guangdong was still a "pollution refuge" for international pollution-intensive industries, but with the strengthening of environmental control, pollution-intensive industries have gradually shifted from the Pearl River Delta to non-Pearl River Delta regions. Shao et al. (2020) analyzed the changes and driving forces of carbon emissions on the urban consumption side by taking Shanghai as an example and found that the consumption-based carbon emissions in Shanghai increased by 32.82% since 2007, which was much higher than the production-based carbon emissions, and technological changes had greatly reduced carbon leakage.

The transfer of carbon pollution usually did not only depend on area transfer, but the industrial transfer was the main body of carbon transfer (Liao and Xiao, 2017). Most studies were also based on this, focusing on the carbon ripple effect inside and outside the region, and studying the characteristics of carbon transfer in industries. Wei et al. (2020) quantified the environmental inequality behind regional trade and believed that electricity-related carbon emissions are closely related to more than 40% of China's carbon emissions, and 20–80% of electricity-related carbon emissions in developed provinces and 15–70% of the added value were outsourced to other provinces. Sun et al. (2010) used the IPCC inventory method to explore the carbon footprint characteristics of Chinese foreign trade and domestic industrial sectors, and found that the electricity and heat industry was highly dependent on carbon emissions. The total emissions from the electricity and heat industry, agriculture and manufacturing industry account for more than 80% of the total emissions. Yang (2015) focused on the carbon emissions of 23 industrial sectors in China and found that the carbon transfer between sectors constituted the main part of the complete carbon emissions of the industrial sector. Li J. et al. (2019), Zhang Y. et al. (2016) focused on Beijing-Tianjin-Hebei and pointed out that among the three regions, Hebei was the main energy producer, Beijing and Tianjin were the consumers, and electricity and heat, coal, and aquatic products were the most important high-carbon industries (Shen and Huang, 2015).

To sum up, the articles about carbon pollution transfer and carbon leakage mostly explores international trade, China's inter-provincial and eight major regional levels. There are few research on typical urban clusters (such as Beijing-Tianjin-Hebei and the Yangtze River Delta). Most of the research focused on the direction and total amount of carbon transfer unilaterally in regions and industries, but there were few studies about the dual effects of regions and industries on carbon emissions. Among the research methods, the input-output method could more comprehensively reflect the regional and industrial linkages. However, limited by the data, few studies started from the inter-regional input-output table with multiple industries to screen the key paths of carbon transfer. Thus, we would use the inter-regional input-output table in 2002, 2007, and 2012, focus on the research inside and outside the Beijing-Tianjin-Hebei region, compare the two major urban clusters in the Pearl River Delta and the Yangtze River Delta, study their carbon transfer characteristics and try to give policy recommendations for reducing total regional carbon emissions.

METHODOLOGY

Interregional Input-Output Model

The inter-regional input-output model connects every region's input-output models and systematically reflects the connection of goods and services. Compared with the traditional tabular representation of the input-output relationship between sectors, it divides the input-output table according to the region and industry, and more fully reflects the economic relationship between regions and industries. In the study of the relationship between trade and environmental pollution, through combining the interregional input-output model with relevant data, the interregional input-output model clearly clarifies the resource consumption and pollution transfer problem (Zhang B. et al., 2016).

The basic structure of the input-output table between regions is roughly the same as the general input-output table, but it further divides products and services between regions in the final use and final demand parts. The specific structure is shown in **Supplementary Table S1**:

Average Propagation Lengths

The Average Propagation Lengths (APL) model was proposed by Dietzenbacher and Romero (2007). This model explores the interrelationship between regional sectors from the perspective of the production chain and reveals their inputs sequence of output impacts. We introduce the carbon coefficient into the APL model.

$$L^c = CL = C(I - A)^{-1} = C(I + A + A^2 + \ldots) \quad (1)$$

$$G^c = CG = C(I - R)^{-1} = C(I + R + R^2 + \ldots) \quad (2)$$

Where C is a diagonal matrix formed by the carbon emission intensity of each industrial sector in each region, and the diagonal element is c_i. A is the direct consumption coefficient matrix, $a_{ij} = \frac{x_{ij}}{x_j}$. R is the direct distribution coefficient matrix, $r_{ij} = \frac{x_{ij}}{x_i}$, and $R = X^{-1}AX$. L^c and G^c are complete carbon consumption coefficient matrix and complete carbon distribution coefficient matrix respectively. L^c reflects the impact of the final demand of an industry in a certain area on the direct or indirect carbon emissions of each unit. **Eq. 1** can also be understood as the emissions caused by an increase in the final demand of the industrial sector by one unit. It means that L^c includes the direct impact on its own department C, the direct impact on all departments CA^2, the indirect impact of the second step CA^3.

Simarly, G^c reflects the impact of the initial investment on the carbon emissions of other industrial sectors by one unit, which can also be decomposed into the initial impact C, which directly affects CR of other sectors. In order to obtain the impact and spread of carbon emissions, we take the impact of each round as a weight, and get the average round, that is, APL. Based on the influencing factors, APL can be divided into backward and forward APL, and the calculation formulas are **3–6**.

$$U_{ij} = \frac{\left(1 \times c_i \times a_{ij} + 2\Sigma c_i a_{ik} a_{kj} + \ldots\right)}{l_{ij}^c}, \; i \neq j \tag{3}$$

$$U_{ij} = \frac{\left(1 \times c_i \times a_{ij} + 2\Sigma c_i a_{ik} a_{kj} + \ldots\right)}{l_{ij}^c - c_i}, \; i = j \tag{4}$$

$$V_{ij} = \frac{\left(1 \times c_i \times r_{ij} + 2\Sigma c_i r_{ik} r_{kj} + \ldots\right)}{g_{ij}^c}, \; i \neq j \tag{5}$$

$$V_{ij} = \frac{\left(1 \times c_i \times r_{ij} + 2\Sigma c_i r_{ik} r_{kj} + \ldots\right)}{g_{ij}^c - c_i}, \; i = j \tag{6}$$

c_i is the intensity of carbon emissions. U_{ij} is the backward APL value, which represents the average backward distance of the impact of a change in the final demand of sector j on the carbon emissions of sector i. V_{ij} is the forward APL value, which represents the forward carbon distance of sector j's initial investment to change the impact of one unit on the carbon emissions of industry sector i. The smaller the carbon APL, the stronger the carbon ripple effect between the two sectors. May wish $H = A + 2A^2 + 3A^3 + \ldots = \sum_{n=1}^{\infty} nA^n$, $\bar{H} = R + 2R^2 + 3R^3 + \ldots = \sum_{n=1}^{\infty} nR^n$. Knowing that $R = X^{-1}AX$, $\bar{H} = R(R - I) = X^{-1}L(L - 1)X = X^{-1}HX$, we can get $\overline{h_{ij}} = h_{ij}/x_i$ and $R = X^{-1}AX$, that is $U_{ij} = V_{ij}$. Then the forward APL is equal to the backward APL, collectively called APL (Li Y. et al., 2019).

Before calculating the APL value, in order to screen industries and regions with a greater degree of correlation, it is necessary to calculate the degree of correlation between industries (Ma et al., 2018) as the threshold for carbon chain identification, namely:

$$F = \frac{1}{2}\left(L^c + G^c\right) \tag{7}$$

Structural Path Analysis

Structural Path Analysis (SPA) was proposed by Defourny and Thorbecke (2014). It is mainly based on input-output technology to identify the main production chain and is mostly used for energy, water resources, and other physical quantities in the economy (Lenzen, 2003; Wood and Lenzen, 2003; Peters and Hertwich, 2006).

In the calculation process, the SPA model expands the Leontief inverse matrix by Taylor and multiplies the corresponding carbon intensity coefficient to quantify the direct or indirect carbon conduction effects of other sectors caused by the final demand of the sector and the initial investment. In this way, it clearly reveals the carbon conduction relationship. It is calculated as formula **8**:

$$\hat{S} = C(I - A)^{-1}\hat{F} \tag{8}$$

In **Eq. 8**, S represents the total carbon emissions caused by the path, C represents the diagonal matrix composed of carbon emission intensity vectors and $\hat{F}$ represents the final demand vector. Decomposing **Eq. 8** into conduction paths at all levels can be written as **Eq. 9**:

$$\hat{S} = C\left(I + A + A^2 + A^3 + \ldots\right)\hat{F} \tag{9}$$

In **Eq. 9**, the first $C\hat{F}$ represents the total direct carbon emissions of each sector brought by the final demand, which is called the zero-order effect and $CA\hat{F}$ represents the total indirect carbon emissions brought by the final demand shift, which is called the first-order influence, and so on.

The APL model can effectively identify the main carbon conduction chain, and the SPA model can calculate the carbon emissions in the carbon conduction chain. Therefore, we combine the two models. We use the APL model to identify the carbon conduction chain of high-dimensional data, and obtain the main carbon-sweeping provinces and cities in a certain area and their sequential positions, and then combine formula **9** in the SPA model to obtain the total amount of carbon transfer in each step. The formula for calculating the total amount of carbon transfer in each step is **Eq. 10**.

$$S_{i_n j_n} = C_{i_0} a_{i_0 j_0} \ldots a_{i_n j_n} \widehat{F_{j_n}} \tag{10}$$

In **Eq. 10**, i_n and j_n represent the transfer-in and transfer-out parties in the carbon conduction chain, and i_0 and j_0 represent the initial transfer-in and transfer-out parties in the conduction chain. The absolute amount of specific carbon transfer in the carbon chain can be calculated by **Eq. 10**.

EMPIRICAL ANALYSIS

This paper mainly uses the multi-regional input-output (MIRO) model proposed by Xia and Tang (2017) and Wu et al. (2017), and the regional social accounting matrices (SAMs) of China in 2002, 2007 and 2012. The carbon emission factor is calculated according to the IPCC method based on the energy balance sheet. Subsequently, based on the Average Propagation Length Model (APL) and the Structural Path Analysis Model (SPA), using the IRIO table and the calculated carbon emission coefficients, we first study the overall carbon emissions of the Beijing-Tianjin-Hebei urban clusters and compare it with the Yangtze River Delta and Pearl River Delta. Further, we explore the carbon transfer relationship of the industrial structure in the Beijing-Tianjin-Hebei urban clusters and its surrounding areas. Finally, we study the carbon correlation of major resource transfer industries in the cluster.

Beijing-Tianjin-Hebei Total Carbon Emission and Carbon Emission Coefficient

The proportions of total emissions of the Beijing-Tianjin-Hebei region are shown in **Supplementary Figure S1**. From 2002 to 2012, the total carbon emissions in the Beijing-Tianjin-Hebei region accounts for about 11.03% of the total carbon emissions in 30 provinces and cities across the country. Among the urban clusters, Hebei has the highest total carbon emissions, accounting for 72.15% of the total carbon emissions, while Tianjin and Beijing account for 16.12 and 11.74% respectively. Affected by resource endowment and economic development levels, Hebei undertakes many high-carbon emission industries in Beijing and Tianjin and bears most of the carbon emission pressure. This is the main reason why Hebei's carbon emissions are much higher than the other two places.

To achieve the coordinated development of the Beijing-Tianjin-Hebei, Hebei's resource support is indispensable, but how to reduce the pressure of regional emissions while ensuring the complementarity of its industries is the focus of this study. In this regard, we first compare the industries and carbon emissions of the other two major urban clusters to explore their reference points. Then, we calculate the direct carbon emission coefficients (unit: tCO2/10,000 yuan) of the three industrial sectors in the Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta regions from 2002 to 2012, as shown in **Supplementary Table S2**:

It can be seen from **Supplementary Table S2** that from 2002 to 2012, the carbon emission coefficient of the three major industries in the three major urban clusters in China shows an overall downward trend. Among the three major urban clusters, the secondary industry has the highest carbon emission intensity, followed by the tertiary industry and primary industry. Comparing the three major urban clusters, it can be seen that the three major industries in the Pearl River Delta have relatively low carbon emission coefficient and high efficiency, followed by the Yangtze River Delta and Beijing-Tianjin-Hebei.

In terms of the primary industry, from 2002 to 2012, the proportion of the added value of the primary industry in the three major urban clusters is almost maintained at about 5% of their total added value. The volume of the primary industry in the Beijing-Tianjin-Hebei and Pearl River Delta are similar, and it accounts for 2/3 of the Yangtze River Delta. Due to the strong support for the secondary and tertiary industries in Beijing, Tianjin, and the Pearl River Delta, large amounts of labour and land are separated from agriculture, and the scale of the primary industry is gradually shrinking. However, the agricultural policy support is strong in the Yangtze River Delta, with an annual investment of about 300 million yuan to build farmland infrastructure. And it also develops tourism and other related industries in the corresponding agricultural chain, and the scale of the primary industry is relatively high. Zhang and Wang (2014) mentioned that the scale expansion of the primary industry will accelerate the growth of total carbon emissions at a certain stage, which may be the main reason for the relatively low carbon efficiency of the primary industry in the Yangtze River Delta. As for the Beijing-Tianjin-Hebei and the Pearl River Delta, they are similar in the size of the primary industry, but there is a certain gap in carbon emission efficiency. The main reason is that the added value of the primary industry in the Beijing-Tianjin-Hebei accounts for more than 90%. Compared with the Pearl River Delta, the agricultural industry structure of Hebei is relatively simple, the degree of specialization is not enough, and the rural financial system is relatively backward, resulting in a relatively low carbon emission efficiency.

In terms of the secondary industry, the carbon emission efficiency of Beijing-Tianjin-Hebei is lowest among three clusters. The Pearl River Delta has always been known as the "world's factory", and its labor-intensive manufacturing industry has always occupied an absolute advantage. Limited to the local energy situation, the total carbon emissions of high-carbon industries in the Pearl River Delta, such as coal mining and oil processing, are not high, accounting for only about 5% of the high-carbon industries in the three major urban clusters. And its total added value is relatively low. Additionally, the secondary industry in the Yangtze River Delta strongly leads the economic growth. During the study period, nearly 50% of its economic growth is contributed by industrial growth. Beijing-Tianjin-Hebei is dominated by heavy chemical and capital-intensive industries. It is the industrial base of Chinese heavy chemical industry and equipment manufacturing industry. Most of these industries are carbon-intensive industries. Although the three major urban clusters have different priorities for the development of the secondary industry, the Beijing-Tianjin-Hebei region has the lowest degree of regional cooperation. Hebei, as an important supporting hinterland for agricultural resources and industrial energy in Beijing and Tianjin, has always been in a state of weakness. Lack of industrial supporting service and the weak technical radiation of universities in Beijing and Tianjin are the main reasons for the falling gap.

In terms of the tertiary industry, the carbon emission efficiency of Beijing-Tianjin-Hebei has a slight advantage. The main reason is that 46.9% of the added value of the tertiary industry in Beijing-Tianjin-Hebei from 2002 to 2012 was contributed by Beijing, and Shanghai contributed 25.6% in the Yangtze River Delta. As the center of "scientific and technological innovation", Beijing has 61 colleges and universities, 1/3 of the national scientific research institutions, and the density of technical personnel is the highest in China. The penetration of new technologies into the tertiary industry has significantly improved the technological content of the tertiary industry, and the service methods have become increasingly electronic and low-carbon. However, although Hebei's tertiary industry contributes about 30% to the tertiary industry of the Beijing-Tianjin-Hebei, its carbon emission coefficient is about 1.5 times that of Beijing. Beijing's technological radiation effect on Hebei's tertiary industry is not significant.

Regional Carbon Conduction in Beijing-Tianjin-Hebei

In order to further explore the implied carbon emissions of inter-regional trade, we use the APL model to identify the transfer-in and transfer-out parties in the carbon conduction relationship in Beijing-Tianjin-Hebei through the forward and backward APL values. We take the transfer-in direction of carbon emission as the direction of the arrow, identify the carbon ripple relationship, and calculate the total carbon emissions (tCO_2/10,000 yuan) along the chain based on the carbon chain relationship based on the SPA model. The result is shown in **Supplementary Figure S2**:

It can be seen from **Supplementary Figure S2** that during the study period, the carbon conduction relationship brought about by the foreign trade links between the Beijing-Tianjin-Hebei and other provinces is always relatively stable, and the provinces with the strongest carbon spread are always Shanxi and Inner Mongolia. The carbon chain in the Yangtze River Delta is not stable. Except for the close carbon sweep effect with Anhui, most of the regions in the carbon chain are in flux. The carbon sweep cities in the Pearl River Delta are mainly concentrated in the southwest and southeast.

Using the main related provinces and cities of Beijing-Tianjin-Hebei and other urban clusters revealed in **Supplementary Figure S2**, we study the degree of carbon correlation between these provinces and cities based on the industrial correlation index proposed by Ma et al. (2018). Specific as formula **11**:

$$\xi_{ij} = \frac{\frac{APL_{ij}}{F_{ij}}}{\frac{\overline{APL}}{\bar{F}}} \tag{11}$$

In **Eq. 11**, the APL value measures the economic distance between regions and industries with the average step length of the conduction chain, and the F value can be used to measure the degree of correlation between industries at the same level. The smaller the industry correlation index, the closer the relationship between the region (industry) and other regions (industry) is.

We use 0.05 as the threshold of the industrial correlation index to identify the main related industries of the three major urban clusters. Beijing-Tianjin-Hebei, as a coal-based emission city cluster, also has similar characteristics in its cross-provincial and municipal industry linkages. During the study period, electricity and heat industry in the carbon conduction chain of Beijing-Tianjin-Hebei is the main carrier industry for carbon transfer. For example, during the period from 2002 to 2007, Beijing-Tianjin-Hebei is the carbon transfer-in party of Shanxi, and the main carbon transfer-in industries is electricity and heat. Until 2012, that the transfer industries of Beijing-Tianjin-Hebei changed, which included electric and heat, non-metallic mining and transportation industry. In summary, we further identify the main chains of carbon transfer in Beijing-Tianjin-Hebei and other resource provinces, and calculate that the implied carbon emissions during the transfer of electricity and heat account for more than 85% of the total carbon emissions. Different from the Beijing-Tianjin-Hebei carbon transmission chain, in the Yangtze River Delta, most of the industrial linkages are related to the resource extraction industry and related manufacturing industries, such as metal product manufacturing, boiler manufacturing, motor manufacturing and metallurgical industries. Electricity and heat industry does not play a pivotal role in industry transfer.

In order to further explore the characteristics of the electricity and heat industry in the Beijing-Tianjin-Hebei, we further compare the carbon emission coefficients of the industry in the three major urban clusters. The results show that Beijing-Tianjin-Hebei has obvious characteristics of coal-fired carbon emission urban clusters. The carbon emission coefficients of electricity and heat industry and coal mining industry are not only far higher than other industries in the region, but also significantly higher than the other two major urban clusters. The average carbon emission coefficient of the Beijing-Tianjin-Hebei electric power industry is 18.25tCO2/10,000 yuan, which is about 2 times that of the Pearl River Delta and 2.5 times that of the Yangtze River Delta. In the process of carbon transfer in the coal industry in Hebei, more than 65% of the resources are transferred to the electricity and heat industry in Hebei and then to the electricity and heat industry in Beijing and Tianjin. It is true that the Beijing-Tianjin-Hebei is limited by the input of factors and the consumption structure. Unlike the Yangtze River Delta or the Pearl River Delta, Beijing-Tianjin-Hebei cannot almost completely avoid the intermediary role of electricity and heat from the perspective of carbon transfer. However, it is one of the key points of emission reduction whether to reduce carbon leakage in the electricity and heat industry while ensuring the supply of resources in Beijing and Tianjin. In order to reduce the overall carbon emissions in the region, improving the electric and heating efficiency in the Beijing-Tianjin-Hebei may be a good starting point. The Yangtze River Delta belongs to the East China Power Grid and is one of the models of cross-provincial and cross-regional power cooperation in China. Although it is difficult for Beijing Tianjin Hebei region to realize the mutual assistance and mutual protection of energy similar to the Yangtze River Delta, it is feasible to optimize the power grid structure and develop new energy technologies.

Internal Carbon Conduction Paths in Beijing-Tianjin-Hebei

We aim to further explore the internal correlation of carbon spillover in the three regions of Beijing-Tianjin-Hebei and other provinces with close spillover effects, such as Shanxi, Inner Mongolia, etc. Thus, we consolidated the IRIO table into a whole at the provincial level, set the threshold as 0.1, and take Beijing-Tianjin-Hebei as the center of investment and demand. The relationship between them is identified as shown in **Supplementary Figure S3**:

It can be seen from **Supplementary Figure S3** that the relationship between the transfer-in and transfer-out parties in Beijing-Tianjin-Hebei and other places basically remains unchanged. During the study period, Beijing and Tianjin have been the transfer-in sources of carbon emissions from Hebei, Shanxi, and Inner Mongolia, and Shanxi is mainly the transfer-out party. In terms of the total amount of direct carbon transfer, from 2002 to 2012, the amount of carbon emission transfer in the region continued to increase. The total amount of carbon transfer in Beijing was always the largest, and the total amount transferred from Hebei to Beijing dominated, increasing from 2.26×10^5 t in 2002 to 1.56×10^6 t in 2012.

It can be seen from **Supplementary Figures S2, S3** that the dependence of Beijing-Tianjin-Hebei on resource provinces like Shanxi and Inner Mongolia is strong, and the total amount of carbon transfer within the urban cluster gradually decreases. To further analyze the carbon transfer changes in the industrial structure of the urban clusters, we take Shanxi, Inner Mongolia and Hebei as carbon transfer-out parties, take Beijing and Tianjin as carbon transfer-in parties, and calculate the total carbon transfer changes of the three industries. The calculation formula is **Eq. 12**:

$$\widehat{S_{ij}} = C_i (I - A)_{ij}^{-1} \hat{F}_j \quad (12)$$

Through calculation, it is found that whether it is resource provinces outside the urban cluster (such as Shanxi and Inner Mongolia) or the main energy hinterland within the urban cluster (Hebei), the total carbon transfer-out of the three major industries is basically increasing year by year. The resource status of Hebei Province is also highlighted year by year and the proportion of its total carbon transfer has increased from 47.8% in 2002 to 62.10% in 2012. From the perspective of the structural proportion of industrial carbon transfer, the direct support of the secondary industry in resource provinces to Beijing and Tianjin showed a trend of rising first and then decreasing. The proportion of the secondary industry first increased from 71.73% in 2002 to 81.34% in 2007, and finally fell to 54.81% in 2012. The main reason for the decline in 2012 is that Shanxi has always had a "coal-based" industrial structure (Hu et al., 2016). In 2012, the growth rate of domestic coal demand declined, coal prices plummeted, and most coal enterprises fell into a state of cessation of production. Its economy experienced a "cliff-like" decline (Jiang et al., 2014). But for Hebei, the support structure of its three major industries has been relatively stable, and the proportion of the secondary industry and the tertiary industry has always been about 3:1. And in 2012, although the coal price drop had a greater impact on the coal mining enterprises in Hebei, unlike the overall economic weakness in Shanxi, the coal mining enterprises and power plants in Hebei showed a trend of ebb and flow. The "coal fullness" of power plants in Hebei completely compensated for the reduction in carbon transfer caused by the reduction in the proportion of secondary industries in resource provinces, especially for Shaanxi.

In Summary, it is known that Hebei plays an important role in resource security, and the secondary industry can effectively alleviate the pressure of insufficient supply in resource provinces. So, can the economic benefits of Hebei be improved while ensuring the total supply of resources in Beijing and Tianjin? In response to this problem, we further calculate the carbon productivity of Hebei, that is, the change in value-added per tCO2 emitted (Pan and Zhang, 2011). During the study period, the carbon productivity of the secondary and tertiary industries in Hebei was 6,300 yuan and 48,700 yuan respectively, of which the carbon productivity of the secondary industry was 43.52% lower than the national average, and the tertiary industry was 26.72% higher than the national average. It can be seen that the carbon productivity of the secondary industry in Hebei Province still has a large room for growth. When Hebei meets the energy needs of Beijing and Tianjin, it can improve the economic benefits and achieve the goal of economic growth by optimizing the production structure and energy efficiency of the secondary industry.

Major Industrial Carbon Conduction Paths in Beijing-Tianjin-Hebei

The mismatch between energy pressure and efficiency upgrades in Hebei makes its energy supply more dependent on foreign transfers. From the analysis of carbon transfer inside and outside the Beijing-Tianjin-Hebei urban cluster, we can see that the electricity and heat industry in Hebei Province plays an important intermediary role in the introduction of resources from other provinces. Based on this, we take Hebei electricity and heat as the center to explore the situation of related industries outside the province under the situation of resource transfer.

It can be seen from **Supplementary Figure S4** that when Inner Mongolia, Hebei, and Shanxi transfer carbon resources to Beijing and Tianjin, most of them are transferred through the electricity and heat industry in each province. For example, in 2002, when Hebei metallurgy's resources are transferred to Beijing Metallurgical, it is mainly transferred to Beijing metallurgy through Shanxi electricity and heat industry and Hebei electricity and heat industry, and then Beijing metallurgy is transferred to other industries in the city. Judging from the absolute amount of carbon emissions transferred in each step, the carbon generated by the electricity and heat industries in Inner Mongolia and Shanxi accounts for more than 95% of the entire carbon conduction chain. To further explore the causes of high carbon production in Inner Mongolia and Shanxi, we compare the direct carbon emission coefficients of Beijing-Tianjin-Hebei and major resource provinces such as Shanxi and Inner Mongolia, as shown in **Supplementary Table S3**:

It can be seen from **Supplementary Table S3** that compared with the carbon emission coefficients of the electricity and heat industry in the three places of Beijing, Tianjin and Hebei, Shanxi and Inner Mongolia, especially for Shanxi, are obviously at a higher level. Based on this, it is not difficult to propose that when Beijing-Tianjin-Hebei electricity is transferred out, if the transmission efficiency of the power grid in Shanxi and Inner Mongolia can be optimized to a certain extent, the overall carbon emissions of the region can be reduced. However, as far as the actual situation is concerned, Shanxi has long used coal as its pillar industry. In recent years, the domestic demand for coal, including coal from Shanxi, has not been strong, resulting in greater financial pressure in Shanxi and other places. The upgrading of the structure may lead to a long-term fiscal deficit, which will have a greater negative impact on its economic development (Jiang et al., 2014). Therefore, when reducing the carbon emissions caused by the consumption side in the Beijing-Tianjin-Hebei, it is necessary to include Shanxi, Inner Mongolia and other places into the scope of collaborative governance and share their emission reduction costs.

CONCLUSION

Based on the input-output methodology, the APL model, and the SPA model, combined with the regional input-output tables in 2002, 2007 and 2012, we explore the carbon spillover effect and industrial evolution inside and outside the Beijing-Tianjin-Hebei. The main conclusions drawn are as follows:

First, from the perspective of the internal urban cluster, the electricity and heat industry plays a key role in the main carbon transmission chain, and the carbon emissions brought by it as an intermediary account for more than 85% of the total carbon emissions in the transmission chain. The carbon emission coefficient is relatively high, and the characteristics of coal-fired power are obviously the main characteristics of the electricity and heat structure in the Beijing-Tianjin-Hebei. When considering reducing the total amount of carbon emissions in the region as a whole, due to the limitation of resource endowment, external energy transfer is inevitable, but the development of the power grid in the Yangtze River Delta still has strong reference significance. The Beijing-Tianjin-Hebei, as a national science and innovation base, can make full use of its technological advantages. In terms of new energy development, vigorously developing the abundant wind and solar energy resources in northern Hebei to expand power varieties is essential. In terms of improving energy efficiency, gradually promoting the UHV transmission grid could reduce the coal consumption in Hebei and improve the power receiving capacity outside the area.

Second, from the perspective of the transfer of industrial structure, the secondary industry in Hebei can alleviate the pressure of insufficient supply in resource provinces to a certain extent, and the economic benefits brought about by its emissions have a large room for development. The average carbon productivity of the secondary industry in Hebei is 6,300 yuan, which is only 56.47% of the national average. One of the strategic orientations of Hebei is to ensure the energy supply between Beijing and Tianjin, so given the total amount of resources that Hebei needs to provide to Beijing and Tianjin, its economic benefits still have a lot of room for growth. Therefore, gradually transforming the energy structure dominated by coal, accelerating the development of clean energy, and dealing with "zombie enterprises" in industries such as steel and cement can reduce carbon costs. Increasing carbon productivity could also maximize economic benefits when ensuring resource supply.

Third, from the perspective of major industries, compared with Beijing, Tianjin and Hebei, resource provinces such as Shanxi and Inner Mongolia have high carbon emission coefficients in the electricity and heat industry, which is the main reason for the high carbon emissions in the main transmission chain. Although Hebei has provided energy support for the development of Beijing and Tianjin, the external resource transfer is inevitable. If the total regional carbon emissions are reduced from the perspective of external resource allocation, it is more difficult to rely solely on resource provinces outside the urban cluster, which is likely to lead to conflicts caused by long-term local fiscal deficits. Therefore, when considering the reduction of carbon emissions caused by external resource transfer. Shanxi, Inner Mongolia and other resource provinces should be included in the scope of coordinated governance, and the funds for the implementation of the power transfer strategy should be reasonably apportioned and multi-sourced, and provide them with improved energy efficiency and technical support for clean energy.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: https://www.ceicdata.com/zh-hans/china/energy-balance-sheet Name: Energy Balance Sheet.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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SUPPLEMENTARY MATERIAL

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