Environmental Science and Pollution Research (2020) 27:23281–23300
https://doi.org/10.1007/s11356-020-08911-0

RESEARCH ARTICLE

# Analyzing carbon emission transfer network structure among provinces in China: new evidence from social network analysis

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Received: 20 January 2020 / Accepted: 16 April 2020 / Published online: 26 April 2020


**Abstract**

Domestic trade plays a key role in China's rapid economic progress. However, the increased domestic trade causes significant variations in carbon emission transfer among provinces. This study adopted the multi-region input-output (MRIO) model and social network analysis (SNA) to estimate the carbon emission transfer. Furthermore, the carbon emission transfer network characteristics among 30 provinces and 27 sectors were analyzed by using interprovincial input-output tables for 2007, 2010, and 2012. The results showed that (1) Large differences exist in carbon emission transfer flow and its network characteristics between provinces. (2) The three industrial sectors of metal smelting and pressing sector, power, heat production, and supply sector, petroleum processing, coking, and nuclear fuel processing sector have high carbon emission transfer and pose a strong influence on the carbon emission transfer network. (3) Provinces of the eastern region have a "bidirectional spillover" role, while those of the western region have a mediating role as an "agent." Provinces of the central region have a "main inflow" role. Finally, useful policy implications and suggestions of this study are summarized.

**Keywords** Carbon emission transfer · Multi-region input-output model · Social network analysis · Overall network characteristics · Individual network characteristics · Inter-province

## Introduction

In 1978, China initiated an opening-up and reform policy, and its economy has witnessed remarkable economic growth since then, following an average annual growth rate of 9.5%. This ranks China as the second-largest economy across the globe (Chen 2018). However, China's rapid economic progress is enabled by the extensive use of energy resources, which has ultimately increased carbon emissions; as a result, China is the top carbon emitter in the world (Lin and Chen 2019; Tian et al. 2018; Ma et al. 2019). Consequently, China is facing increasing pressure by the international community to address the environmental concerns associated with this increased economic growth. In 2015, to decrease the growing threat to human health and the ecosystem as a result of environmental pollution, while simultaneously addressing the increasing international pressure, the government of China submitted its "intended nationally determined contribution" (INDC) to the United Nations. This was followed by great determination toward reducing $CO_2$ emissions per unit of gross domestic product by up to 60–65% by 2030 (relative to 2005 emissions levels). This should be achieved through an increase in the share of renewable energy use by up to 20% as primary energy utilization. The highest emission level would be reached by 2030, following the targets of the 2015 Paris treaty. Therefore, the Chinese government proposed several plans, such as the 11th Five-Year Plan, which outlines measures to be adopted to lower energy use. The government plans to decrease the total energy use by 15% and abate $CO_2$ emissions per unit of GDP

Responsible Editor: Philippe Garrigues

**Electronic supplementary material** The online version of this article (https://doi.org/10.1007/s11356-020-08911-0) contains supplementary material, which is available to authorized users.

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by 18% during the 12th Five-Year Plan period (ending 2015) (Wang et al. 2020). Similarly, during the 13th Five-Year Plan period (ending 2020), the government suggested the implementation of a "double-control" strategy on both the overall energy use and intensity. Furthermore, the Chinese government implemented a national emissions trade system (ETS) in 2017 (de Souza et al. 2018).

With regard to the environmental problems related with increased trade in China, carbon emission transfer within China's trade has become a hotly-debated topic among both scholars and policy makers. In general, China's trade can be segmented into international trade and domestic trade. This paper focuses on the latter: China's domestic trade. In recent years, carbon emission transfer as a result of China's domestic trade has exceeded the international trade (Shi et al. 2012). As the world's third-largest country by area, Chinese provinces show significant heterogeneity in various socioeconomic indicators such as energy and industrial structures, population density, economic development level, and people's life standards (Feng et al. 2012; Xu et al. 2017). Because of disparities in resource distribution and economic strategies, coastal provinces act as the backbone of China's economic development, whereas the northern provinces lead the production industry of the country. This is because China's coastal regions have enforced stringent environmental protocols and optimized both their industrial and energy structures. Consequently, they have gradually transferred their emission-intensive industries to central and western regions which are relatively less developed, offer cheaper labor force, more energy resources, and have a low prerequisite for undertaking industrial transfer (Liu 2016; Tian et al. 2017). Moreover, the transferred industries are always marginal, which either lag technologically, or are characteristically human capital intensive, energy intensive, and heavy pollution emitters (Yin et al. 2016; Zhao et al. 2020). This often leads to different degrees of carbon-emission transfer. Simply put, the carbon transfer with products and services as carrier forms a complex carbon-transfer relationship within provinces, and builds a provincial carbon-transfer network.

To determine the relationship, characteristics, and changes of this transfer of carbon emissions in the process of industrial transfer, this study focused on carbon-emission transfer networks and their characteristics among 30 provinces of China in 2007, 2010, and 2012 by adopting multi-region input-output (MRIO) and social network analysis (SNA) methods. Therefore, this paper poses three important research questions: (1) What was the current status of carbon-emission transfer across the 30 investigated provinces of China for 2007, 2010, and 2012? (2) What are the characteristics of the carbon-emission transfer network that formed by the carbon-emission transfer relationship of these 30 provinces? (3) What are the characteristics of the carbon-emission transfer network among these 30 provinces for each sector? To answer these questions, identifying the carbon emission transfer network can improve the general understanding of the economic development and industrial transfer of the provinces within the intertwined economy and environment. Therefore, this approach provides a reference for the formulation of provincial targets to achieve the overall national carbon emission reduction target, and further expands the research content of carbon-emission transfer. This study is structured as follows: "Literature review" section provides a brief literature review. "Methodology and data" section introduces both the methodology and data. "Results and discussion"section presents the obtained results and discusses them. "Conclusions and policy implications" section provides a conclusion and policy implications.

## Literature review

The concept of the "regional carbon footprint" can be translated as the overall $CO_2$ emissions caused by fulfilling the final demand, including direct and indirect interprovincial $CO_2$ emissions, emissions confined in domestic trade, and $CO_2$ emissions embodied in exports and imports of an economy, a province, or a city (Munoz and Steininger 2010). In addition, Wiedmann (2009) defined "embodied carbon" as the $CO_2$ emissions generated during the process of procurement of raw materials to the production and transportation of goods purchased by customers. These concepts have been extensively adopted by various studies to measure embodied carbon emissions in both international as well as inter-regional trade.

With respect to China's domestic trade, previous studies have assessed the embodied carbon transfer from three major perspectives: regions, provinces, and industries. From the perspective of regions, Su and Ang (2014) decomposed the 30 provinces of China into industrialized and emerging regions and further claimed that the embodied carbon emissions were directed from industrialized regions to emerging regions in 1997. Zhang et al. (2014) divided Chinese provinces into coastal, central, and western regions and argued that regional spillover of $CO_2$ emissions occurred from coastal regions toward western and central regions. A similar argument was presented in the study of Liu et al. (2015) who reported that the embodied carbon emission spillover of China was mainly higher in regions with low development that are enriched with fossil fuel resources during 1997–2007. Zhou et al. (2018) concluded that the embodied $CO_2$ emissions are largely transferred from northwest (less developed regions) to east coastal regions (developed regions). In addition, Ning et al. (2019) analyzed $CO_2$ emission spillover and feedback effects across 30 provinces and accordingly classified these into eight regions. The results of a MRIO approach confirmed that the spillover effects caused by other regions ranked top in the northeastern region, southwestern region, and western region. Ning et al. (2019) further argued that the magnitude of this spillover effect was observed to be higher in geographically closer regions. Moreover, the feedback effects were mainly caused by the regions themselves.

The second strand of research focused on the embodied carbon transfer at the provincial level. Guo et al. (2012) evaluated the flow of embodied carbon transfer at the provincial level and claimed that in 2002, the carbon transfer flowed from eastern provinces to central provinces. In addition, Meng et al. (2011) claimed that eastern coastal provinces mainly transferred their high emissions to central provinces in China in 2007. In contrast, Xie et al. (2017) conducted an input-output analysis and examined embodied $CO_2$ emissions among various Chinese provinces during 2007–2010. The results indicated that the embodied carbon outflow was directed from the central and western provinces to industrialized eastern coastal provinces. Furthermore, Lv et al. (2019) combined a MRIO model with a SNA method to explore the direction of carbon emission transfer among provinces in China over the period of 2002–2012. The results showed that the flow of embodied carbon transfer remained inconsistent. For example, it was observed that the carbon transfer was directed from energy-rich northern provinces to advanced central and eastern provinces in 2002. However, in 2012, this direction changed to emerging southern and southwestern provinces.

The third group of studies focused on embodied carbon transfer at the industry level. Zhou et al. (2013) stated that industries are key contributors to the embodied carbon transfer in the interregional trade of China. In addition, Chang (2015) argued that industries are held responsible for both direct and indirect carbon transfer in interregional trade. Du et al. (2018) analyzed the flow of indirect $CO_2$ emissions among 41 industries during 2005–2014 using an indirect carbon emission flow network approach. The results showed that for most industries, indirect $CO_2$ emissions contribute 70% of overall carbon emissions in China. Zhou et al. (2018) examined the carbon transfer of manufacturing industries across both developed and less developed regions of China. The authors claimed that the direction of embodied $CO_2$ emissions flow caused by manufacturing industries was largely a transfer from less developed regions to more developed regions. Meng et al. (2016) applied an input-output approach to measure both the direct and indirect $CO_2$ emissions of the Chinese tourism industry. These empirical results confirmed that tourism industry was accountable for 2.48%, 2.42%, 2.43%, and 2.44% of the overall $CO_2$ emissions of all industries during 2002, 2005, 2007, and 2010, respectively. These results further indicated that indirect $CO_2$ emissions as a result of the tourism industry were 3–4 times higher than direct $CO_2$ emissions. Wu et al. (2017) implemented an interprovincial input-output method to estimate carbon emission transfer caused by heavy industries among 30 provinces of China. Based on these results, the authors confirmed that in 2007, carbon transfer was directed from southern to northern provinces and from coastal to inland provinces. Zhao et al. (2020) employed a gravity model to explore variations in emission-release patterns of the manufacturing industry in the Pan-Yangtze river delta, China, during 2005–2015. These empirical findings showed that the manufacturing industrial transfer caused significant disparities in emissions release patterns, in which the gravity center of pollution and the overall discharge transferal were from east to west. Furthermore, they concluded that the regional economic status and strict environmental policies can transfer emissions-intensive industries from developed regions to emerging regions.

Recently, several scholars have studied the carbon emission transfer network between Chinese provinces and industries. In contrast to previous studies that used the total output to calculate carbon emission transfers, the present paper uses added value to calculate carbon emission transfers. The added value of each sector constitutes the added value of the primary, secondary, and tertiary industries, and the sum of the added values of each industry constitutes the gross domestic product (GDP). Therefore, the added value of each sector forms the basis of the GDP. The GDP reflects the total scale and level of production activities (NBSC 2020). In simple words, the GDP represents the sum of the final products of a community as a whole. The added value from a MRIO table is based on 27 sectors of 30 provinces. Therefore, the main purpose of this study was to analyze the carbon emission transfer and its carbon emission transfer network characteristics in the value-added chain.

In addition, based on previous studies, this article expands the analysis of carbon emission transfer network characteristics in 27 sectors among 30 provinces. Therefore, this study analyzed China's carbon transfer between provinces by combining MRIO and SNA methods. Motivated by the facts and figures presented above, this paper contributes to the existing literature in multiple ways. First, MRIO tables from 30 provinces and 27 sectors in China for 2002, 2007, and 2012 were used to estimate carbon emission transfers. Second, the SNA method was used to evaluate China's inter-provincial carbon transfer networks and to further investigate the spatial distribution characteristics of carbon emission transfer in trade, including overall network characteristics, individual characteristics, and block-model clustering. Third, the characteristics of carbon emission transfer networks were analyzed in various industries in various provinces and main carbon-emission transfer paths of various sectors.

## Methodology and data

### Multi-region input-output model

This paper focuses on the inter-provincial carbon emission transfer problem in China based on the MRIO model. When dividing a country into several regions, MRIO provides a useful tool with which to investigate the interconnection among regions (Su and Ang 2014; Zhao et al. 2016; Wang et al. 2017). Furthermore, it preciously assesses the impact of carbon emissions on interregional socioeconomic systems and provides an appropriate approach for the combination of carbon emissions with economic activity and demonstrates how intermediate trade and final demand trigger carbon trade between regions (Duan et al. 2018; Wen and Wang 2020). Using the MRIO model enables the accurate calculation of regional carbon emission transfer and can comprehensively reveal the interregional relationships between different sectors in different regions (Wiedmann 2009; Peters and Hertwich 2008). The most basic input-output relationship between regions is presented in Table 1, which contains $m$ provinces and $n$ sectors. According to the row direction in the input-output table, the total output can be divided into intermediate use and final demand. Then, the total output of the province $i$ can be expressed as follows:

$$X_i^r = \left(X_{i1}^{r1} + \ldots + X_{\mathrm{in}}^{r1}\right) + \ldots + \left(X_{i1}^{\mathrm{rm}} + X_{\mathrm{in}}^{\mathrm{rm}}\right) + Y_i^{r1} + \ldots + Y_i^{\mathrm{rm}} = \sum_{s=1}^{m}\sum_{j=1}^{n} X_{\mathrm{ij}}^{\mathrm{rs}} + \sum_{s=1}^{m} Y_i^{\mathrm{rs}} \tag{1}$$

$X_i^r$ represents the total output of province $r$ sector $i$, $Y_i^{\mathrm{rs}}$ represents the final product provided by sector $i$ in province $r$ for province $s$, and $X_{\mathrm{ij}}^{\mathrm{rs}}$ represents the intermediate input of sector $i$ in province $r$ to sector $j$ in province $s$. Using Leontief's method (Leontief 1970), the direct consumption coefficient from province $r$ sector $i$ to province $s$ sector $j$ is: $\alpha_{\mathrm{ij}}^{\mathrm{rs}} = X_{\mathrm{ij}}^{\mathrm{rs}} \big/ X_j$. This signifies that the value of goods or services in sector $i$ is directly consumed by the unit output of sector $j$ during the production and operation process. Then, Eq. (1) can be written as:

$$X^r = \sum_s A^{\mathrm{rs}} X^s + \sum_s Y^{\mathrm{rs}} \tag{2}$$

Equation (2) can be extended in matrix form as follow:

$$\begin{bmatrix} X^1 \\ X^2 \\ \vdots \\ X^m \end{bmatrix} = \begin{bmatrix} A^{11} & A^{12} & \cdots & A^{1m} \\ A^{21} & A^{22} & \cdots & A^{2m} \\ \vdots & \vdots & \ddots & \vdots \\ A^{m1} & A^{m2} & \cdots & A^{mm} \end{bmatrix} \begin{bmatrix} X^1 \\ X^2 \\ \vdots \\ X^m \end{bmatrix} + \begin{bmatrix} Y^{11} + \cdots + Y^{1m} \\ Y^{21} + \cdots + Y^{2m} \\ \vdots \\ Y^{m1} + \cdots + Y^{mm} \end{bmatrix} \tag{3}$$

$[X^1, X^2, \cdots X^m]^{\mathrm{T}}$ is mn × 1 the total output vector, $[A^{rs}]_{m\times m}$ is the mn × mn matrix of intermediate consumption coefficients, $[Y^{1s}, Y^{2s}, \cdots Y^{\mathrm{ms}}]^{\mathrm{T}}$ is the mn × 1 final demand vector of province $r$ for each province and sector. Equation (3) can be abbreviated as Eq. (4):

$$X = \mathrm{AX} + Y \tag{4}$$

Equation (4) is transformed into a demand-oriented formula as follows:

$$X = (I - A)^{-1} Y \tag{5}$$

$X$ is the total output and $Y$ is the final demand. $(I-A)^{-1}$ is the Leontief inverse matrix (Leontief 1970). This means that

**Table 1** Inter-regional input-output model

| Output<br>Input | | | Intermediate demand | | | | | | | Final demand | | | Total output |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Province 1 | | | … | Province $m$ | | | Province 1 | … | Province $m$ | |
| | | | Sector 1…Sector $n$ | | | … | Sector 1…Sector $n$ | | | | | | |
| Intermediate input | Province 1 | Sector 1 | $X_{11}^{11}$ | … | $X_{1n}^{11}$ | … | $X_{11}^{1m}$ | … | $X_{1n}^{1m}$ | $Y_1^{11}$ | … | $Y_1^{1m}$ | $X_1^1$ |
| | | … | … | … | … | … | … | … | … | … | … | … | … |
| | | Sector $n$ | $X_{n1}^{11}$ | … | $X_{\mathrm{nn}}^{11}$ | … | $X_{n1}^{1m}$ | … | $X_{\mathrm{nn}}^{1m}$ | $Y_n^{11}$ | … | $Y_n^{1m}$ | $X_n^1$ |
| | … | … | … | … | … | … | … | … | … | … | … | … | … |
| | Province m | Sector 1 | $X_{11}^{m1}$ | … | $X_{1n}^{m1}$ | … | $X_{11}^{\mathrm{mn}}$ | … | $\mathrm{X}_{1n}^{\mathrm{mm}}$ | $Y_1^{m1}$ | … | $Y_1^{\mathrm{mn}}$ | $X_1^m$ |
| | | … | … | … | … | … | … | … | … | … | … | … | … |
| | | Sector $n$ | $X_{n1}^{m1}$ | … | $X_{\mathrm{nn}}^{m1}$ | … | $X_{n1}^{\mathrm{mm}}$ | … | $X_{\mathrm{nn}}^{\mathrm{mm}}$ | $Y_n^{m1}$ | … | $Y_n^{\mathrm{mm}}$ | $X_n^m$ |
| Value added | | | $V_1^1$ | … | $V_n^1$ | … | $V_1^m$ | … | $V_n^m$ | | | | |
| Total input | | | $X_1^1$ | … | $X_n^1$ | … | $X_1^m$ | … | $X_n^m$ | | | | |

$X_i^r$ represents the total output of sector $i$ in province $r$. $Y_i^{\mathrm{rs}}$ represents the final product provided by sector $i$ in province $r$ to province s. $X_{ij}^{rs}$ represents the intermediate input of sector $i$ in province $r$ to sector $j$ in province $s$, and $V_i^r$ represents the added value of sector $i$ in province $r$

when the unit final demand of a certain sector is increased, the total input provided by each sector is required. The final demand $Y$ includes the consumption by rural residents, the consumption by urban residents, governmental consumption, gross fixed capital formation, and increased inventory. To calculate the amount of carbon emissions transferred between provinces, the carbon emission intensity $D$ needs to be calculated, which is the carbon emissions per unit value added:

$$D = \begin{bmatrix} D^1 & 0 & \cdots & 0 \\ 0 & D^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & D^m \end{bmatrix}, D^r = \begin{bmatrix} d_1^r & 0 & \cdots & 0 \\ 0 & d_2^r & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & d_n^r \end{bmatrix} \quad (6)$$

Here, $d_i^r = C_i^r / V_i^r$ represents the unit value-added ($V$) carbon emissions ($C$) of sector $i$ in province $r$, which can be written as $L$. The carbon-emission transfer matrix can be written as:

$$CT = \begin{bmatrix} CT^{11} & CT^{12} & \cdots & CT^{1m} \\ CT^{21} & CT^{22} & \cdots & CT^{2m} \\ \vdots & \vdots & \ddots & \vdots \\ CT^{m1} & CT^{m2} & \cdots & CT^{mm} \end{bmatrix} = \begin{bmatrix} L^{11} & L^{12} & \cdots & L^{1m} \\ L^{21} & L^{22} & \cdots & L^{2m} \\ \vdots & \vdots & \ddots & \vdots \\ L^{m1} & L^{m2} & \cdots & L^{mm} \end{bmatrix} \begin{bmatrix} Y^{11} & Y^{12} & \cdots & Y^{1m} \\ Y^{21} & Y^{22} & \cdots & Y^{2m} \\ \vdots & \vdots & \ddots & \vdots \\ Y & Y^{m2} & \cdots & Y^{mm} \end{bmatrix} \quad (7)$$

where $\mathrm{CT}^{rs}$represents the amount of carbon emission transfer from province $r$ to province $s$ that is embodied in the interprovincial trade. $\mathrm{CT}^{rr}$represents the embodied carbon emissions of products and services produced by province $r$ that are eventually consumed in province $r$.

Therefore, the total carbon emission transfer import for province $r$ from other provinces is the embodied carbon emissions of products produced in province $r$ but consumed in province $s$, which can be calculated with Eq. (8):

$$\mathrm{CT_{in}}^{r*} = \sum_{s,s\neq r} \mathrm{CT}^{rs} \quad (8)$$

The total carbon emission transfer export from province $r$ to each of the other provinces is equal to the embodied carbon emissions of products produced in province $s$ that are consumed in province $r$, according to Eq. (9):

$$\mathrm{CT_{out}}^{*r} = \sum_{s,s\neq r} \mathrm{CT}^{sr} \quad (9)$$

The net carbon emission transfer $\mathrm{NT}^r$) of province $r$ is the difference between the carbon emission transfer import and export, according to Eq. (10):

$$\mathrm{NT}^r = \mathrm{CT_{in}}^{r*} - \mathrm{CT_{out}}^{*r} \quad (10)$$

## Social network analysis

A social network is a collection of social actors and their relationships. It is a powerful model for integrating social structures. Actors can be individuals, groups, organizations, or even entire countries. SNA can identify influential actors on the basis of their relationships and analyze the structure of the resulting network (Yustiawan et al. 2015). Examples are overall network features, individual network features, and cluster analysis (Huang et al. 2019). When applied to the provinces of China, SNA can connect different provinces that interact in space through multiple factors such as social, economic, and carbon emissions (Xia et al. 2018). This paper uses the SNA theory to further understand the relationships within the carbon emission transfer among 30 provinces in China.

### Overall network characteristics

Network density is a measure of the closeness of inter-provincial links in a carbon emission transfer network. The higher the density of the overall network, the closer the connections between the members of the network, and the stronger the impact this network may have on the attitudes and behaviors of its actors. A tightly connected overall network not only provides various social resources for its members, but also becomes an important limiting force of its development. According to the definition of Freeman (1978), if the actual number of relations included in the network is $L$, the density of the network is the number of actual relations, divided by the theoretical maximum number of relations. The carbon emission transfer network studied in this paper is a directional network with a total of $N$ nodes. The theoretical maximum possible number of relationships included in the network is $N \times (N-1)$. The network density of the directional network is$D_n$.This can be calculated according to Eq. (11):

$$D_n = \frac{L}{N \times (N-1)} \quad (11)$$

Network efficiency is an indicator of the extent to which the entire carbon transfer network contains excess lines. The lower the network efficiency, the more redundant lines the network members will contain, and the lower its efficiency will be. However, more redundant lines represent more communication paths between provinces, which results in a more stable network. The network efficiency GE can be calculated as follows:

$$\mathrm{GE} = 1 - \frac{R}{\max(R)} \quad (12)$$

where $R$ represents the number of redundant lines in the overall network, and max $(R)$ represents the maximum number of possible redundant lines.

Network relevance is an indicator of the vulnerability and robustness of the overall network. If a direct or indirect connection path exists between any two nodes in an overall network, the entire network has a high degree of correlation, and thus, the network is robust and relevant. The degree of network association $C$ can be calculated as follows:

$$C = 1-\left[\frac{V}{N(N-1)/2}\right] \tag{13}$$

where $N$ represents the number of nodes in the network, and $V$ represents the number of unreachable point pairs in the overall network.

The network hierarchy is used to measure the dominance and hierarchical status of each province in the carbon-emission transfer network, and reflects the extent to which provinces can be reached asymmetrically. A higher the network hierarchy indicates a stricter hierarchy in the carbon transfer network. The network grade degree GH can be calculated with Eq. (14):

$$\mathrm{GH} = 1-\frac{V}{\max(V)} \tag{14}$$

where $V$ represents the number of symmetrical reachable points in the network, and max($V$) represents the maximum number of possible symmetrical reachable points.

## Individual network characteristics

Centrality is an indicator of the importance of each province in the carbon emission transfer network. The identity at the center of the network has greater power and influence. Centrality can be assessed by degree centrality and betweenness centrality.

Degree centrality directly reflects the status of each province in the network. The higher this degree of centrality, the more important the province's status or role in the overall carbon transfer network will be. If a network is directed (i.e., one edge points in one direction from one node to another node), then this node has two different degrees: an out-degree, which is the number of carbon emission transfer import edges, and an in-degree, which is the number of carbon emission transfer export edges. The degree centrality of a directed graph uses standardized centrality to compare data for 3 years. The out-degree and in-degree can be calculated according to Eq. (15):

$$D_i^{\mathrm{out}} = \sum_{i=1(i\neq j)} x_{\mathrm{ij}} \text{ and } D_i^{\mathrm{in}} = \sum_{i=1(i\neq j)} x_{\mathrm{ji}}. \tag{15}$$

The betweenness centrality of a point is an index that describes the degree to which a network node controls the network resources. A greater betweenness centrality indicates a stronger control of the province over other provinces in the carbon transfer network. $g_{\mathrm{jk}}$ represents the number of shortcuts that exist between points $j$ and $k$. The third point $i$ can control the communicative ability of both points, and indicates the probability that $i$ is on the shortcut between point $j$ and $k$. The third point $i$ can control the communication ability of both points and is represented by $b_{\mathrm{jk}}(i)$, i.e., the probability that $i$ is on the shortcut between point $j$ and point $k$. The number of shortcuts passing through point $i$ (between point $j$ and point $k$) is represented by $g_{\mathrm{jk}}(i)$, thus, $b_{\mathrm{jk}}(i) = g_{\mathrm{jk}}(i)/g_{\mathrm{jk}}$. Then, the betweenness centrality $C_{\mathrm{ABi}}$ can be calculated with Eq. (16):

$$C_{\mathrm{ABi}} = \sum_{j}^{\mathrm{n}}\sum_{k}^{n} b_{\mathrm{jk}}(i), j\neq k\neq i \tag{16}$$

## Block model

Block model analysis was originally proposed by White et al. (1976) and Smith and White (1992) and was extensively adopted to study the role of network nodes, with the overall goal to better display the characteristics of the spatial clustering of each province. This paper divides the 30 provinces into different plates, i.e., actors in this plate have relatively strong, direct, close, regular, or positive relationships. Consequently, the number of plates and the province each plate contains can be identified, and the relationships and connections between the plates can be analyzed. This enables to examine the development of the carbon emission transfer network in each province from a new dimension, and reveals and characterizes the internal substructure status of the plates. This paper adopts the CONCOR iterative method, selecting a maximum segmentation depth of 2 and a convergence standard of 0.2. This method divides China's provinces into four categories, which have the corresponding role of "bidirectional spillover," "main inflow," "net spillover," and "agent" according to Wasserman and Faust (1994). The specific location classification index system is shown in Table 2, where $g$ represents the number of actors at the location, and $n$ represents the number of members in the entire network.

The actual internal proportional relationship between the bidirectional spillover and the main inflow is stronger than the expected internal proportional relationship. The members of the bidirectional spillover plate extend more relationships to other plate members, and at the same time also extend more relationships to the inside of the plate; however, they do not have many external relationships. The main inflow plate has a large proportion of internal relationships and a small proportion of external relationships. The internal members of the net spillover plate extend more relationships to other plate

**Table 2** Classification of economic growth in block model

| Relationship ratio within location | Percentage of relationships received by location | |
|---|---|---|
| | ≈ 0 | > 0 |
| ≥$(g-1)/(n-1)$ | Bidirectional spillover | Main inflow |
| ≤ $(g-1)/(n-1)$ | Net spillover | Agent |

*n* represents the 30 provinces, and *g* represents the number of provinces in the plates. The role of each plate was determined based on the data and relationships presented in Table 7

members, but extend less relationships to the inside of the plate, and also have fewer external relationships. The internal members of the agent plate extend and accept external relationships, but there are fewer links among internal members.

### Data sources

The 2007, 2010 input-output tables required for this study were obtained from the National Bureau of Statistics (NBSC). The input-output tables for both years were compiled by the Institute of Geography and Natural Resources of the Chinese Academy of Sciences. The input-output table and carbon dioxide emissions data for 2012 were obtained from a study by Mi et al. (2017) and were downloaded from http://www.ceads.net/. To unify the input-output sector data of 2007, 2010, and 2012 with the carbon emission sector data of the corresponding years, this paper merges the 30 sectors of the input-output table and the 45 sectors of carbon dioxide emissions into 27 sectors. In this way, each province has data for 27 sectors. In fact, the research objects in this paper are related to 22 provinces, 4 municipalities, and 4 autonomous regions. Hong Kong, Macau, Taiwan, and Tibet were excluded because of missing data. For simplicity and clarity, this paper uses "province" to represent all of the abovementioned provinces, municipalities, and autonomous regions (Wang et al. 2018).

## Results and discussion

### Carbon transfer

According to the carbon transfer calculation method described above, the carbon emission transfer between provinces in 2007, 2010, and 2012 was obtained. The results of carbon emission transfer import, carbon emission transfer export, and net carbon emission transfer in each province are shown in Table 3.

From 2007 to 2012, the carbon emission transfer import and carbon emission transfer export of most provinces followed an increasing trend. The total carbon transfer over all three investigated years was 7734 (2007), 10,212 (2010), and 13,665 (2012) million tons of carbon dioxide ($MtCO_2$). After the financial crisis of 2008, China still maintained its rapid economic growth. There is no doubt that the overall carbon transfer has continued persistently as a result of booming trade.

From the perspective of carbon emission transfer import, in 2007, 2010, and 2012, the carbon emission transfers of Hebei, Henan, Jiangsu, Inner Mongolia, and Liaoning increased every year, and these were the top five provinces with the highest carbon transfer. Except for Jiangsu, the other provinces are located in the less developed areas of northern China, but Jiangsu is rich in energy resources and is highly industrialized. Jiangsu provides a large number of products for eastern coastal cities that meet the needs of their consumption and industrial development. Jiangsu is an important province with regard to the old-fashioned manufacturing industry. Many private enterprises drive the export of goods.

From the perspective of carbon emission transfer export, Jiangsu, Henan, Guangdong, Hebei, Zhejiang, and Shandong are the provinces with the highest carbon emission transfer. These provinces share two characteristics: On the one hand, their population is huge, and they need to import goods from other provinces to meet the needs of their inhabitants. Guangdong has a population of over 100 million and is the most populous province in China, while Shandong and Henan, each has close to 100 million inhabitants. On the other hand, these provinces have secondary traditional processing and manufacturing industries.

The gap in net carbon emission transfers between provinces is large. From 2007 to 2012, Hebei, Shanxi, Inner Mongolia, Liaoning, Henan, Guizhou, Gansu, and Ningxia have been net carbon emission transfer provinces. These provinces are all underdeveloped regions in the north and west. They mainly rely on processing and manufacturing as well as energy output to maintain their economic growth. The provinces with the most net carbon emission transfers are mainly Guangdong and Zhejiang. For both carbon emission transfer import or carbon emission transfer export, Qinghai is the province with the least carbon emission transfer. Ningxia has the highest energy intensity (2.279 tons of standard coal/104 yuan in 2011), and its large output of coal resources led to a rapid increase in carbon emissions transfer in 2012 (Guan et al. 2017). Hainan's transportation lines have gradually

**Table 3** Results of carbon transfer for 2007, 2010, and 2012

| Province | Import (Mt) | | | Export (Mt) | | | Net inflow (Mt) | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2007 | 2010 | 2012 | 2007 | 2010 | 2012 | 2007 | 2010 | 2012 |
| Beijing | 109 | 100 | 326 | 348 | 395 | 560 | − 239 | − 295 | − 233 |
| Tianjin | 159 | 268 | 298 | 285 | 447 | 495 | −126 | −179 | −197 |
| Hebei | 978 | 1294 | 1679 | 441 | 639 | 742 | 537 | 655 | 937 |
| Shanxi | 339 | 367 | 821 | 118 | 216 | 391 | 221 | 150 | 430 |
| Inner Mongolia | 532 | 665 | 1141 | 127 | 351 | 516 | 404 | 314 | 624 |
| Liaoning | 488 | 514 | 962 | 236 | 365 | 602 | 252 | 149 | 360 |
| Jilin | 264 | 286 | 323 | 435 | 516 | 468 | − 171 | − 230 | − 145 |
| Heilongjiang | 286 | 291 | 405 | 285 | 359 | 550 | 1 | − 68 | − 145 |
| Shanghai | 183 | 302 | 478 | 512 | 603 | 405 | − 329 | − 301 | 73 |
| Jiangsu | 707 | 746 | 1005 | 527 | 754 | 1036 | 181 | −9 | −31 |
| Zhejiang | 333 | 373 | 392 | 717 | 718 | 696 | −384 | −346 | −305 |
| Anhui | 231 | 311 | 606 | 246 | 296 | 494 | − 15 | 15 | 113 |
| Fujian | 73 | 112 | 148 | 152 | 205 | 140 | − 80 | − 93 | 8 |
| Jiangxi | 70 | 177 | 210 | 249 | 246 | 287 | −179 | −69 | −77 |
| Shandong | 521 | 903 | 447 | 496 | 594 | 703 | 24 | 309 | − 256 |
| Henan | 625 | 1045 | 1028 | 383 | 585 | 907 | 243 | 460 | 121 |
| Hubei | 137 | 206 | 142 | 156 | 180 | 237 | − 19 | 26 | − 94 |
| Hunan | 147 | 229 | 312 | 183 | 259 | 538 | − 35 | − 30 | − 226 |
| Guangdong | 346 | 443 | 314 | 547 | 729 | 793 | − 201 | − 287 | − 480 |
| Guangxi | 109 | 180 | 189 | 135 | 228 | 353 | − 26 | − 47 | − 164 |
| Hainan | 9 | 14 | 62 | 12 | 17 | 107 | − 2 | − 3 | − 45 |
| Chongqing | 85 | 116 | 222 | 146 | 160 | 480 | − 61 | − 45 | − 257 |
| Sichuan | 127 | 248 | 139 | 204 | 199 | 292 | − 77 | 48 | − 153 |
| Guizhou | 222 | 217 | 391 | 96 | 126 | 201 | 126 | 91 | 190 |
| Yunnan | 164 | 178 | 280 | 141 | 213 | 403 | 23 | − 35 | − 122 |
| Shaanxi | 152 | 244 | 427 | 228 | 395 | 631 | − 77 | − 151 | − 204 |
| Gansu | 94 | 145 | 244 | 86 | 102 | 200 | 8 | 43 | 44 |
| Qinghai | 41 | 42 | 23 | 42 | 58 | 55 | − 1 | − 17 | − 32 |
| Ningxia | 71 | 98 | 306 | 53 | 81 | 74 | 18 | 17 | 232 |
| Xinjiang | 133 | 99 | 344 | 149 | 172 | 310 | − 16 | − 73 | 34 |

$MtCO_2$ represents million tons of carbon dioxide

increased, and the number of imported goods from other provinces has also increased.

## Carbon transfer network construction

The regional input-output data of 2007, 2010, and 2012 indicates that import and export trade exist between 30 provinces, which also have a carbon emission transfer relationship. If the carbon emission transfer relationships of all 30 provinces are displayed, it will be difficult to highlight the key characteristics of provinces. To better analyze the characteristics of carbon emission transfer networks, this paper uses the average carbon emission transfer in 2007, 2010, and 2012 according to Lv et al. (2019) (see Table 4) as a threshold and filter for the network. If the amount of carbon transfer exceeds the average, the carbon emission transfer relationship is retained. As shown in Table 4, during the study period, China's economic growth accompanied the increase in carbon emissions transfer. However, less than one-third of the carbon transfer relationship exceeded the average,

**Table 4** The characteristics of overall network for 2007, 2010, and 2012

| Year | 2007 | 2010 | 2012 |
|---|---|---|---|
| Average (Mt) | 8.8892 | 11.7377 | 15.7068 |
| Remain lines | 233 | 242 | 270 |
| % | 27 | 28 | 31 |

*Mt* million tons

which indirectly reflects the uneven level of China's economic development. As a result, the carbon emission transfer relationship is complex.

To better reflect the inter-provincial carbon transfer relationship of China, this paper uses SNA, with 30 provinces as nodes and the carbon emission transfer relationship between provinces as edges. Consequently, carbon emission transfer network diagrams are built for 2007, 2010, and 2012 (Figs. 1, 2, and 3). The blue lines in the figures represent the relationship between two provinces if they only have carbon emission transfer import or export. The red lines represent two provinces that have both carbon emission transfer import and export. For example, in Fig. 3, the blue line from Ningxia to Hebei represents the carbon emission transfer from Hebei to Ningxia.

The size of the nodes in the network figures (Figs. 1, 2, and 3) are divided according to the values of the degree centrality. A larger degree centrality indicates a larger node. The thickness of the lines is based on the amount of carbon emission transfer between provinces. The larger the amount of carbon transferred, the thicker the line. In 2007, 2010, and 2012, the carbon emission transfers of both Qinghai and Hainan with other provinces were below average. After filtering the network by the average, Qinghai and Hainan had no carbon emission transfer relationship with the other provinces. Therefore, in the 3-year carbon emission transfer networks, Hainan and Qinghai have become isolated. Qinghai belongs to the northwestern region of China. Its low population density, underdeveloped infrastructure, and weak industrial foundation classify Qinghai's economic development as insufficient. Hainan is an island, located at the southern tip of China. The lack of convenient transportation to the inland causes high trade and transportation costs with inland provinces. Hainan has a low population and a low level of industrialization. Thus, consumption-oriented import trade or production-oriented export trade did not form.

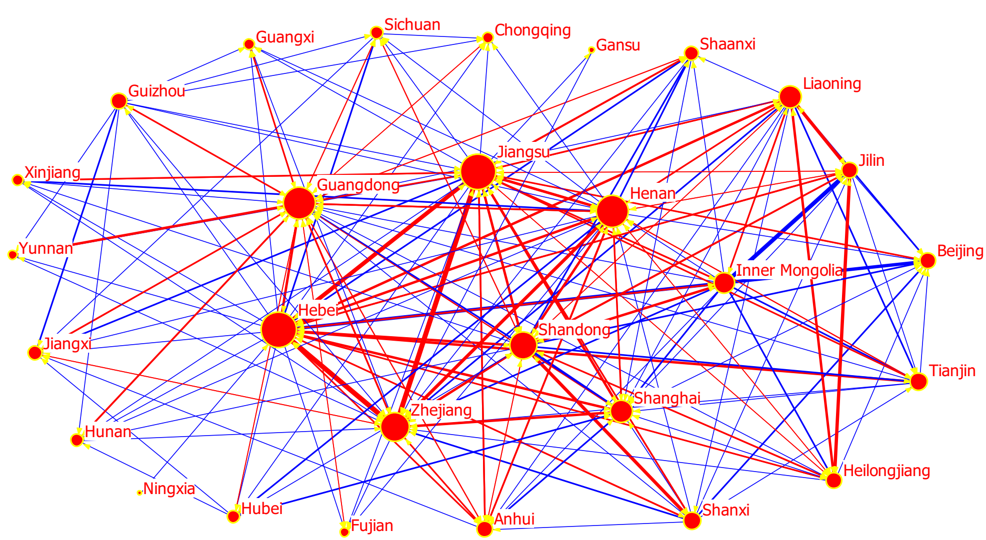
In 2007, the carbon emission transfer network was centered around Jiangsu and Hebei. Henan was the center in 2010, and Hebei was the center in 2012. These provinces formed a radiation network. First, the amount of carbon emission transfer as a result of economic development in 2007, 2010, and 2012 has gradually increased. The denser the carbon emission transfer network, the more complicated the carbon emission transfer relationship between provinces will be. Second, a number of the 30 provinces exert a very important influence in the carbon emission transfer network, such as Jiangsu, Henan, Hebei, Guangdong, and Zhejiang. The influence of these provinces has not changed significantly from 2007 to 2010 and 2012, and these provinces remain an important force for economic development. Finally, in 2012, several provinces have experienced rapid economic development and thus exerted increasing influence, such as Inner Mongolia and Shanxi. These provinces delivered energy for China's infrastructure.

## Overall network characteristics

Overall network research specifically focuses on the entire carbon emission transfer network structure, to identify its inherent characteristics from the perspectives of network density, network efficiency, network hierarchy, and network relevance. In this study, Ucinet software (version 6.186) was used to binarize the carbon emission transfer matrix. According to Eqs. (11–14), the overall network characteristic values were obtained.

As shown in Table 5, slight fluctuations were found in the network density, network relevance, network hierarchy, and network efficiency of the carbon emission transfer network between 2007, 2010, and 2012. However, overall, network

**Fig. 1** Carbon transfer network in 2007



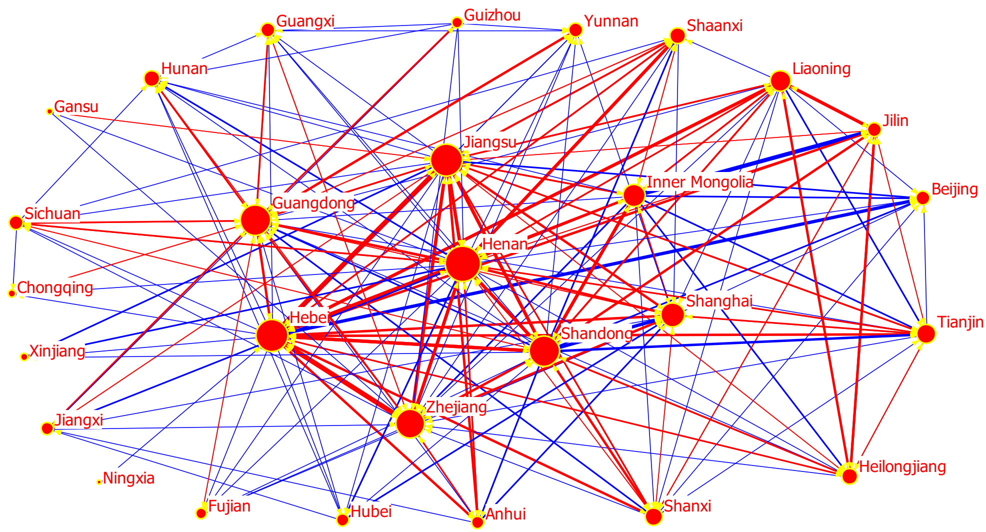



**Fig. 2** Carbon transfer network in 2010

density has not changed considerably. During the studied years, the overall carbon transfer network remained in a stable state of development. First, the network density increased gradually, but the overall network density was low. The carbon emission transfer links between provinces were getting closer and closer; resources were complementary, and commodity circulation was becoming more frequent; however, there was no mutual restriction or monopoly. Second, although the degree of network correlation is declining, the overall network correlation remains high. The carbon emission transfer network has a uniform structure and is not susceptible to the influence of individual provinces. Many channels exist for trade links between provinces. Third, the network hierarchy is low. The network hierarchy for 3 years is below 0.1. No hierarchical structure exists within carbon emission transfer networks. Trade between provinces is free and competitive. Finally, the overall carbon emission transfer network is inefficient, which indirectly identifies the existence of a carbon emission transfer link between provinces, and the carbon emission transfer network has good liquidity. In summary, the carbon transfer network structures of 2007, 2010, and 2012 remained stable and highly correlated.

## Individual network characteristics

Centrality measures the status and role of each province in the carbon emission transfer network and mainly includes degree centrality and betweenness degree. According to Eqs. (15) and (16), and using Ucinet software, the degree centrality of the carbon emission transfer network for 2007, 2010, and 2012 was calculated and the results are reported in Table 6.

The outdegree represents the number of carbon emission transfer import relationships, while the indegree represents the number of carbon emission transfer export relationships. For 2007, 2010, and 2012, the outdegrees of Jiangsu, Henan, and Hebei all exceeded 20, and the outdegrees of Jiangsu were 25,

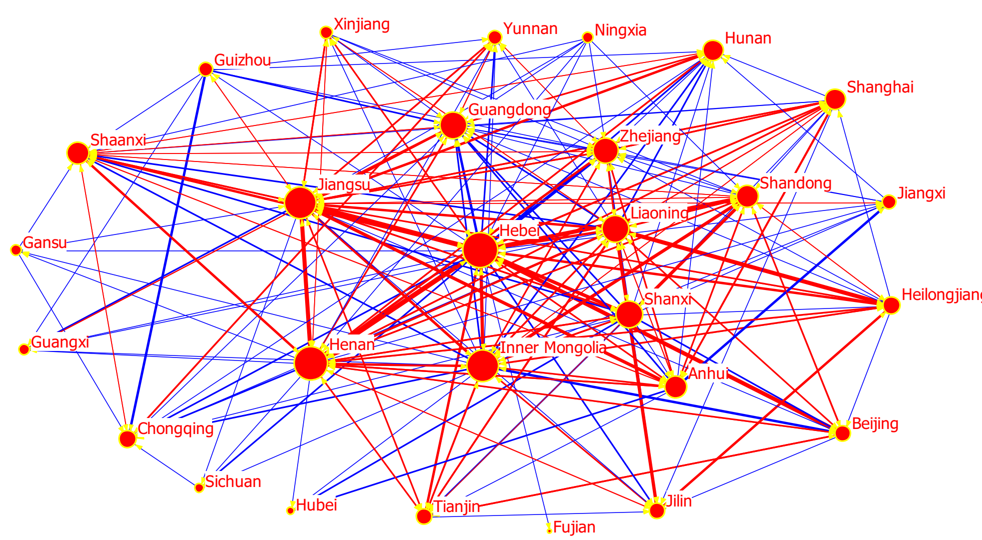



**Fig. 3** Carbon transfer network in 2012

**Table 5** Characteristics of the overall network of 2007, 2010, and 2012

| Indicators (year) | Network density | Network relevance | Network level | Network efficiency |
|---|---|---|---|---|
| 2007 | 0.2678 | 0.8092 | 0.0739 | 0.3917 |
| 2010 | 0.2782 | 0.7494 | 0.0798 | 0.3650 |
| 2012 | 0.3103 | 0.7540 | 0.0854 | 0.2819 |

24, and 22, respectively. The outdegrees of Henan were 25, 23, and 25, and the outdegrees of Hebei were 21, 25, and 24, respectively. Provinces with higher outdegree are mainly export-oriented, providing goods for most provinces in China. The indegrees of both Guangdong and Zhejiang should receive further attention. The high indegree of both provinces during the studied years implies that they imported a large number of goods from other provinces across China to meet their own needs. However, in 2007, 2010, and 2012, the outdegree and indegree of Qinghai and Hainan were both 0; therefore, both provinces became isolated points in the carbon emission transfer network diagram. In addition, Ningxia has an indegree of 0. Ningxia is an underdeveloped province in the northwest region. Its unfavorable geographical location,

**Table 6** Centrality of the carbon emission transfer network for 2007, 2010, and 2012

| Province | | Outdegree | | | Indegree | | | Nrmdegree | | | Betweenness | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2007 | 2010 | 2012 | 2007 | 2010 | 2012 | 2007 | 2010 | 2012 | 2007 | 2010 | 2012 |
| 10 | Jiangsu | 25 | 24 | 22 | 17 | 16 | 20 | 89.7 | 82.8 | 82.8 | 17.3 | 10.8 | 15.5 |
| 3 | Hebei | 25 | 23 | 25 | 14 | 15 | 14 | 89.7 | 82.8 | 89.7 | 11.2 | 9.5 | 8.3 |
| 16 | Henan | 21 | 25 | 24 | 14 | 15 | 18 | 82.8 | 89.7 | 86.2 | 5.7 | 9.5 | 10.7 |
| 15 | Shandong | 18 | 21 | 13 | 12 | 11 | 14 | 65.5 | 75.9 | 55.2 | 5.3 | 3.7 | 1.2 |
| 19 | Guangdong | 16 | 14 | 6 | 23 | 22 | 20 | 79.3 | 75.9 | 69.0 | 20.4 | 16.2 | 5.6 |
| 6 | Liaoning | 15 | 14 | 20 | 7 | 7 | 14 | 51.7 | 48.3 | 69.0 | 0.4 | 0.3 | 2.7 |
| 5 | Inner Mongolia | 14 | 14 | 24 | 4 | 8 | 12 | 48.3 | 51.7 | 82.8 | 0.0 | 1.5 | 3.5 |
| 4 | Shanxi | 11 | 10 | 19 | 4 | 8 | 6 | 41.4 | 41.4 | 65.5 | 0.0 | 0.1 | 0.3 |
| 24 | Guizhou | 10 | 7 | 8 | 2 | 1 | 2 | 37.9 | 24.1 | 31.0 | 0.0 | 0.0 | 0.0 |
| 8 | Heilongjiang | 10 | 8 | 11 | 7 | 8 | 8 | 37.9 | 34.5 | 41.4 | 0.0 | 0.1 | 0.3 |
| 7 | Jilin | 9 | 8 | 4 | 8 | 9 | 10 | 37.9 | 31.0 | 34.5 | 0.1 | 0.2 | 0.1 |
| 11 | Zhejiang | 9 | 10 | 9 | 20 | 20 | 17 | 72.4 | 72.4 | 62.1 | 9.0 | 5.6 | 1.9 |
| 12 | Anhui | 8 | 7 | 14 | 9 | 5 | 10 | 37.9 | 27.6 | 51.7 | 0.1 | 0.1 | 1.0 |
| 2 | Tianjin | 7 | 9 | 8 | 8 | 10 | 9 | 41.4 | 44.8 | 34.5 | 0.0 | 0.2 | 0.1 |
| 9 | Shanghai | 6 | 11 | 12 | 15 | 14 | 9 | 55.2 | 58.6 | 48.3 | 0.7 | 2.0 | 0.2 |
| 17 | Hubei | 5 | 5 | 0 | 4 | 3 | 4 | 27.6 | 27.6 | 13.8 | 0.1 | 0.0 | 0.0 |
| 23 | Sichuan | 4 | 7 | 1 | 6 | 5 | 4 | 27.6 | 31.0 | 17.2 | 0.1 | 0.2 | 0.0 |
| 26 | Shaanxi | 4 | 7 | 9 | 7 | 8 | 16 | 31.0 | 34.5 | 55.2 | 0.0 | 0.2 | 5.0 |
| 30 | Xinjiang | 3 | 0 | 7 | 4 | 4 | 5 | 20.7 | 13.8 | 27.6 | 0.0 | 0.0 | 0.0 |
| 20 | Guangxi | 2 | 3 | 1 | 5 | 8 | 7 | 20.7 | 31.0 | 24.1 | 0.0 | 0.1 | 0.0 |
| 18 | Hunan | 2 | 4 | 6 | 7 | 9 | 12 | 27.6 | 37.9 | 48.3 | 0.0 | 0.3 | 0.4 |
| 25 | Yunnan | 2 | 2 | 4 | 4 | 8 | 9 | 17.2 | 31.0 | 31.0 | 0.0 | 0.0 | 0.8 |
| 14 | Jiangxi | 2 | 4 | 4 | 9 | 6 | 6 | 31.0 | 27.6 | 31.0 | 0.1 | 0.1 | 0.0 |
| 27 | Gansu | 1 | 2 | 3 | 1 | 2 | 3 | 6.9 | 10.3 | 20.7 | 0.0 | 0.0 | 0.0 |
| 22 | Chongqing | 1 | 1 | 3 | 6 | 4 | 11 | 20.7 | 13.8 | 41.4 | 0.0 | 0.0 | 3.3 |
| 13 | Fujian | 1 | 1 | 0 | 5 | 7 | 1 | 17.2 | 24.1 | 3.4 | 0.0 | 0.0 | 0.0 |
| 1 | Beijing | 1 | 0 | 6 | 11 | 9 | 9 | 37.9 | 31.0 | 34.5 | 0.0 | 0.0 | 0.0 |
| 29 | Ningxia | 1 | 1 | 7 | 0 | 0 | 0 | 3.4 | 3.4 | 24.1 | 0.0 | 0.0 | 0.0 |
| 28 | Qinghai | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 21 | Hainan | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

low economic development, large gaps between urban and rural areas, and low per capita income have led to low imports from other provinces.

From the perspective of degree centrality, for 2007, 2010, and 2012, Jiangsu, Hebei, and Henan were the top three provinces with the highest centrality, and had an output ratio of more than 80. These provinces not only have a large population, but also form important pillars of China's economic development, followed by Guangdong, Zhejiang, Shandong, and Shanghai. Jiangsu, Zhejiang, and Shanghai belong to the Yangtze River Delta and represent the largest economic zones in China. They have developed sea and land transportation networks and a strong economic status. Guangdong belongs to the Pearl River Delta region and is one of the first provinces in China to implement the reform and opening up. For more than 40 years, the road of reform and opening up has made Guangdong one of China's most important and economically strongest provinces. Hebei, Henan, and Shandong all belong to the Bohai Rim Economic Circle. These provinces are rich in energy resources, have developed transportation infrastructure, and coordinated city development. In addition, Inner Mongolia, Liaoning, and Shanxi also had a high degree centrality in 2012. These three provinces are rich in mineral resources and provide coal, oil, and natural gas to the other provinces. They belong to the extended region of the Bohai Rim Economic Belt and play an increasingly important role in the economic development of China. It can be seen that provinces with higher degree centrality are all strategically important areas for the regional economic development of China. The ongoing western development strategy and the northeast revitalization strategy have gradually injected new vitality into the less developed regions in the west and the three northeastern provinces.

Guangdong had the highest betweenness centrality in 2007 (20.4), followed by Jiangsu (17.3), Hebei (11.2), and Zhejiang (9.0). These provinces have apparent intermediary functions and are "resources and information transit stations" or "control centers." which in turn affect the availability of resources and information for other provinces. However, among the abovementioned provinces, only Jiangsu maintained a high betweenness centrality in 2010 and 2012. The betweenness centrality of the other provinces followed a decreasing trend, which means that the control capacity of these provinces gradually weakened, and it is thus difficult for them to maintain their intermediary status. Jiangsu is a large manufacturing and processing province in China. It must not only meet the processing needs of intermediate products from other provinces, but must also meet the consumer demand for final products in other provinces. Guizhou, Xinjiang, Gansu, Fujian, Beijing, Ningxia, Qinghai, and Hainan all had a betweenness centrality of 0. With the exception of Beijing, the other provinces are geographically remote, making it difficult to establish smooth transportation networks and attract external capital for the establishment of factories to develop large-scale industries. Therefore, these provinces cannot exert a controllable influence on other provinces.

## Analysis of major sectors

The amount of carbon emission transfer by the sector between provinces cannot be underestimated (Sun et al. 2017). Over the past 10 years, local governments have adopted GDP as their economic development goal, launched a fierce investment model, and provided favorable policies that simplify the entry of industries and enterprises. However, they have neglected both the high pollution and high energy consumption caused by such a development model. Based on the results of carbon emission transfer calculations across provinces, this study analyzed the degree centrality characteristics of carbon emission transfer networks and its main paths (Figs. 4, 5, and 6) in 27 sectors (Appendix Table 9). This section attempts to analyze the influencing factors of carbon emission transfer in various provinces for 2007, 2010, and 2012 from the perspective of the sector. This provides further suggestions for the formulation and implementation of carbon emission reduction policies.

In 2007, 2010, and 2012, the metal smelting and pressing sector, as well as the power, heat production, and supply sector had high degree centrality, occupying an important position among the 27 sectors. These are the two sectors with the highest carbon emission transfer of all provinces, which belong to high energy consumption and high pollution industries. In the metal smelting and calendaring sector, Hebei has maintained the highest degree centrality and is far ahead of other provinces. Hebei is China's heavy industry base. Its traditional processing and forging processes have yielded economic benefits, while at the same time also causing a large amount of carbon dioxide emissions and air pollution.

The power, heat production, and supply sector is the leading and global sector that reflects the country's economic development. This sector provides the power source for the overall economic development through the consumption and conversion of three major energy sources: coal, oil, and natural gas. In 2007, Jiangsu had the highest degree centrality, which was replaced by Henan in 2010, and Inner Mongolia in 2012. Jiangsu and Henan are provinces with large population, and residents require a lot of electricity and heat to support their lives and consumption. Inner Mongolia is a resource of coal. In 2012, the coal production of Inner Mongolia reached 1.06 billion tons and the sales volume reached 1.07 billion tons. Until 2012, Inner Mongolia's cumulative proved coal reserves exceeded 800 billion tons. China's use of coal resources accounts for about 75% of the total national energy production, and coal is the main source of electricity for production and living. The entire petroleum processing industry, coking, and nuclear fuel processing had high degree centrality. In 2007,

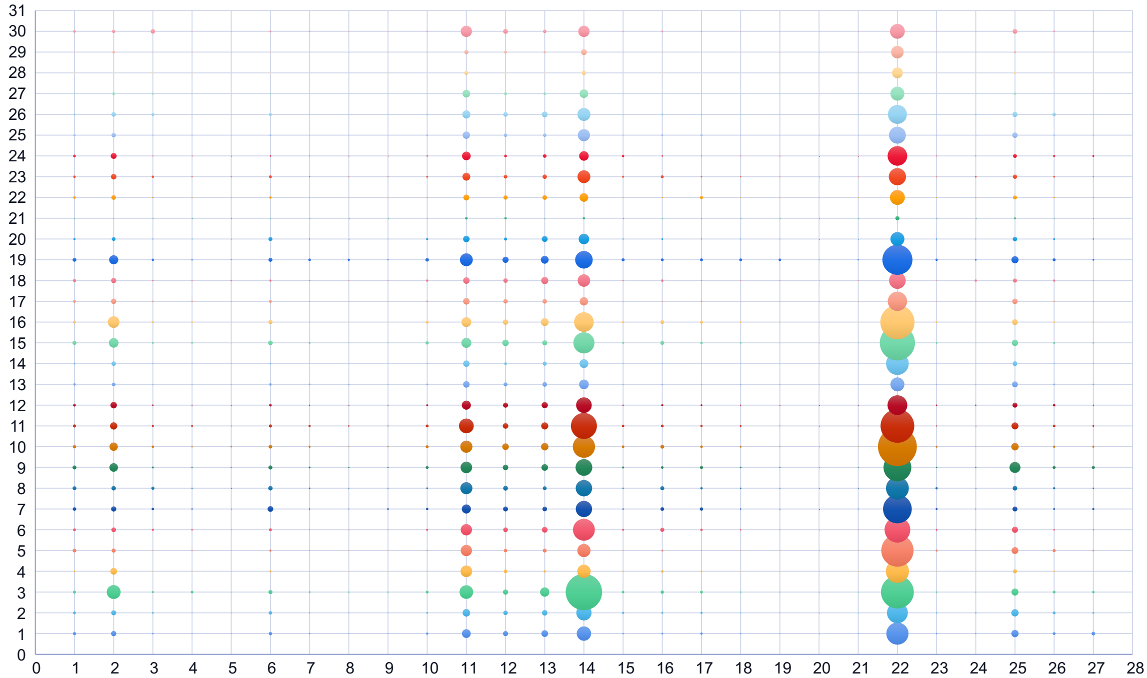



**Fig. 4** Sector degree centrality in 2007

Zhejiang had the highest degree centrality, which was replaced by Heilongjiang in 2010, and Shanxi in 2012. Oil is the "blood" of the economy and still the main source of energy for factory production and residential life.

In addition, in 2012, the transportation and storage industry had a different degree centrality than in previous years. On the one hand, because of the rise of China's e-commerce platforms (and the rapid development of the transportation industry), the e-commerce platforms led by Taobao and Jingdong have initiated a trend of online shopping in China, and a large number of goods are being delivered to all parts of the country by express delivery. On the other hand, international trade has yielded continuous growth in maritime transport, and ports have greatly contributed as an important

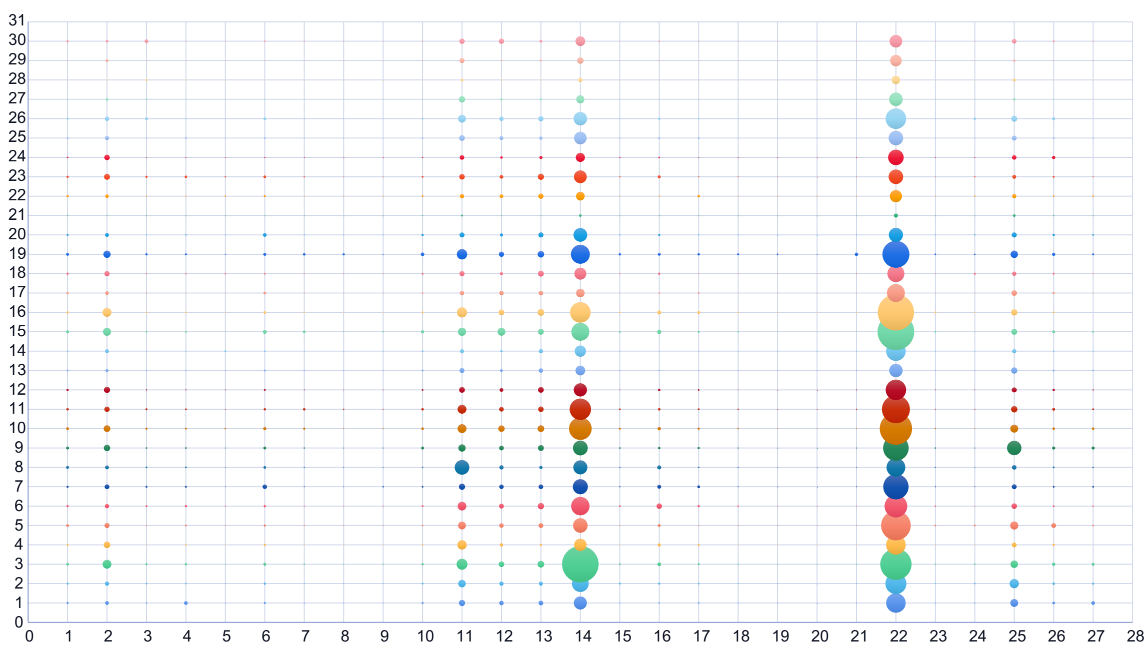



**Fig. 5** Sector degree centrality in 2010

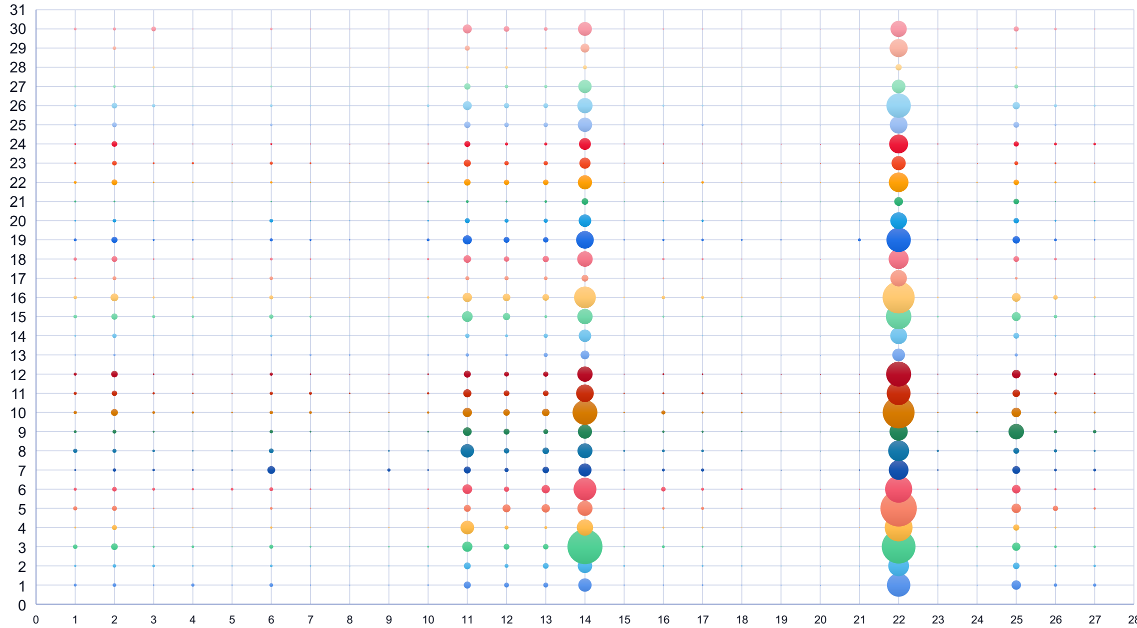


**Fig. 6** Sector degree centrality in 2012. 0–27 on the *x*-axis represents 27 industries, and 0–30 on the *y*-axis represents 30 provinces (see Appendix Table 9 for details).

interface connecting overseas areas with inland China. Shanghai and Jiangsu are coastal cities. They have large ingress and egress ports or docks. Goods that entered via shipping are transported from here to all parts of China. Therefore, Shanghai has the largest degree centrality, which is followed by Jiangsu, Inner Mongolia, and Beijing. The coal resources of Inner Mongolia are constantly being transported to other provinces.

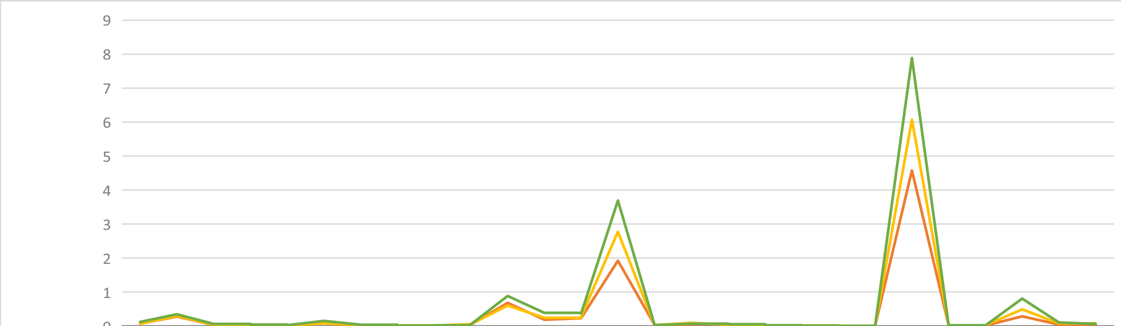
Based on the results of carbon emission transfer calculations of 30 provinces, the path with the largest carbon transfer in 27 sectors during the study years is shown in Fig. 6 (see Appendix Table 9 for specific paths). The input and output of each sector exert clear regional effects, mainly centering on the coastal cities of the Bohai Rim, the Pearl River Delta, and the Yangtze River Delta, while also radiating to neighboring provinces. The prosperity and development of a region can be beneficial for neighboring provinces and share the market's "cake" with the advantages of geographical location and transportation costs. However, China's development is uneven and inadequate, and suffers from clear differences between eastern and western regions.

The carbon emission transfer network density of the metal smelting and rolling processing industry, and the power, heat production, and supply sector have the highest overall network density distribution (Fig. 7), which is followed by the petroleum processing, coking, and nuclear fuel processing sector. These three industries have a dense carbon emission transfer relationship between provinces and are the main source of carbon emissions in China. Hidden behind these three industries is the heavy use of coal, oil, and natural gas in China.

## Block model analysis

The block model analysis demonstrates that the annual average of the carbon transfer network is low, and there is no carbon emission transfer link between Qinghai, Hainan, and other provinces. The CONCOR clustering analysis classified Hainan and Qinghai into one category; however, the relationship between receiving and sending within and outside the plate was 0. Therefore, excluding Qinghai and Hainan, only 28 provinces were clustered to obtain more accurate convergence class results (Table 7).

Figure 8 shows that the role of the plate has not changed in 2007 and 2010. Both plate I and plate II exert a role of bidirectional spillover. Except for Anhui, which changed from a bidirectional spillover role in 2007 to a main inflow role in 2010, other provinces exert a bidirectional spillover role. These provinces are concentrated in the Bohai Rim region and the Yangtze River Delta region. In 2012, as soon as the sector changed to net spillover, Ningxia, Xinjiang, Shanxi, Tianjin, Beijing, Shanghai, and Anhui also changed to net spillover. Ningxia, Xinjiang, and Shanxi provinces are affected by energy resource extraction policies and the western development strategy, and export more resources to other provinces.



| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2007 | 0.06 | 0.27 | 0.02 | 0.01 | 0.00 | 0.07 | 0.01 | 0.00 | 0.00 | 0.03 | 0.67 | 0.18 | 0.22 | 1.91 | 0.02 | 0.05 | 0.03 | 0.01 | 0.00 | 0.00 | 0.00 | 4.57 | 0.01 | 0.00 | 0.27 | 0.03 | 0.02 |
| 2010 | 0.06 | 0.29 | 0.03 | 0.03 | 0.01 | 0.07 | 0.02 | 0.00 | 0.00 | 0.04 | 0.59 | 0.23 | 0.27 | 2.76 | 0.02 | 0.08 | 0.03 | 0.01 | 0.00 | 0.00 | 0.01 | 6.07 | 0.01 | 0.01 | 0.48 | 0.07 | 0.04 |
| 2012 | 0.11 | 0.34 | 0.05 | 0.03 | 0.01 | 0.14 | 0.03 | 0.00 | 0.01 | 0.04 | 0.88 | 0.38 | 0.36 | 3.68 | 0.02 | 0.06 | 0.04 | 0.01 | 0.00 | 0.00 | 0.01 | 7.88 | 0.01 | 0.01 | 0.80 | 0.09 | 0.05 |

**Fig. 7** Density of the overall network from 2007 to 2012 in 27 sectors. The number 1–27 on the *x*-axis indicates 27 sectors (see Appendix Table 9).

From 2007 to 2012, plate III exerted the main inflow role. In 2007, only Guangdong and Zhejiang provided the main inflow. In 2010, Gansu, Sichuan, and Jiangxi changed from the role of agent to the role of main inflow. In 2012, Guangdong, Zhejiang, Jiangxi, Chongqing, Hubei, and Shaanxi became the main inflow. The plate contains more provinces, and the connections between provinces are close.

In 2007, 2010, and 2012, plate IV was always an agent, and plate IV is mainly concentrated in the western region of China. There are fewer connections within this plate. The numbers of provinces that are agents have gradually decreased, and several of these provinces have changed to main inflow roles, such as Shaanxi, Guizhou, Chongqing, Hubei, and Hunan. Other provinces have shifted to net spillover roles, such as Xinjiang. The exploitation of Xinjiang's petroleum resources has promoted a vigorous development of Xinjiang's petroleum refining and chemical industries, the products of which will inevitably be transported to meet the needs of other provinces (Table 8).

The average values in 2007, 2010, and 2012 were 0.596, 0.394, and 0.388, respectively. Based on the average values of the density matrices in each year, the image matrix of the density matrix was obtained. 0 and 1 indicate below and above

**Table 7** Clustering of carbon transfer networks for 2007, 2010, and 2012

| Year | Plate | Number of contacts received | | Number of contacts sent | | Numbers of plates | Expected internal relationship's proportion | Actual internal relationship's proportion | Role of plates |
|---|---|---|---|---|---|---|---|---|---|
| | | Inside | Outside | Inside | Outside | | | | |
| 2007 | I | 48 | 35 | 48 | 52 | 11 | 37% | 48% | Bidirectional spillover |
| | II | 6 | 39 | 6 | 63 | 3 | 7% | 9% | Bidirectional spillover |
| | III | 2 | 41 | 2 | 23 | 2 | 4% | 8% | Main inflow |
| | IV | 10 | 50 | 10 | 27 | 12 | 41% | 27% | Agent |
| 2010 | I | 25 | 34 | 25 | 39 | 8 | 26% | 39% | Bidirectional spillover |
| | II | 19 | 52 | 19 | 85 | 5 | 15% | 18% | Bidirectional spillover |
| | III | 14 | 42 | 14 | 30 | 6 | 19% | 32% | Main inflow |
| | IV | 6 | 50 | 6 | 24 | 9 | 30% | 20% | Agent |
| 2012 | I | 18 | 48 | 18 | 70 | 9 | 30% | 20% | Net spillover |
| | II | 30 | 62 | 30 | 98 | 6 | 19% | 23% | Bidirectional spillover |
| | III | 14 | 66 | 14 | 19 | 6 | 19% | 42% | Main inflow |
| | IV | 2 | 30 | 2 | 19 | 7 | 22% | 10% | Agent |

The number of received (sent out) relationships in the plate represents the total number of relationships on the main diagonal in the received relationship matrix. The total number of relationships received (sent out) from the plate is the sum of the number of relationships for each column (row) in the reception relationships matrix, with the exception of its own plate. The expected internal relationship ratio = (the number of provinces in the plate I)/(the number of all provinces in the network 1); the actual internal ratio = the number of relationships in the plate/the total number of plate overflow relationships

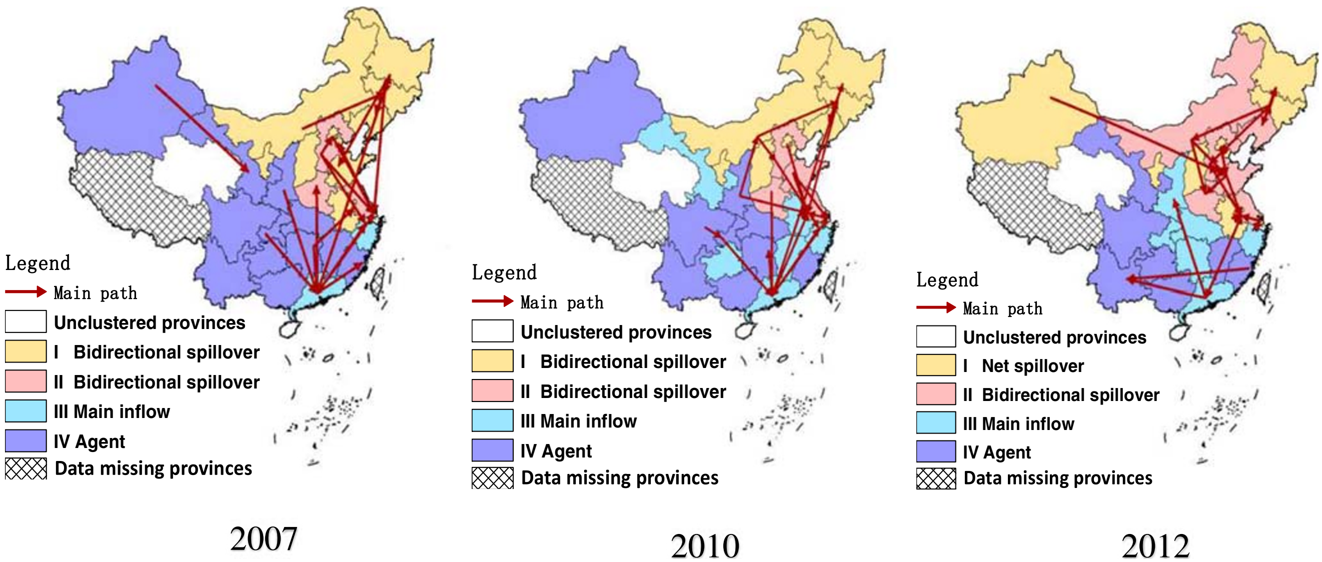



**Fig. 8** Composition of the four plates and main paths of sectors in China

average density, respectively. The conduction relationship between plates can be seen more clearly.

## Conclusions and policy implications

China is blessed with a vast territory, but its provinces have a substantial gap in terms of various socioeconomic factors such as economic status, energy and industrial structures, resource utilization patterns, and life standards of the inhabitants. In recent years, with the increased domestic trade within China, embodied carbon transfer among provinces has become a serious issue for human health and the ecosystem. Therefore, to clarify the carbon emission transfer volume and carbon transfer relationship, this study employed the MRIO model incorporated with SNA to estimate the embodied carbon transfer. Furthermore, carbon emission transfer network structure and its characteristics among were analyzed for 30 provinces and 27 sectors of China using interprovincial input-output tables for 2007, 2010, and 2012. The above analysis provides a more meaningful reference for the formulation and implementation of China's carbon emission reduction policies and the assignment of carbon emission reduction responsibilities. First, according to the results of carbon emission transfer import, carbon transfer export, and net carbon transfer flow of various provinces in 2007, 2010, and 2012, the economic development is bound to increase the amount of carbon emission transfer. The provinces that mainly export energy and resources have caused more carbon emissions, while the developed coastal provinces have shifted a large amount of their carbon emissions mainly by import trade. Second, the carbon emission transfer network indicates that the carbon emission transfer between provinces is closely linked, but only few provinces showed significant carbon emission transfer. In particular, the provinces that radiate outward, with the Bohai Rim, the Yangtze River Delta, and the Pearl River Delta at the center, are most obvious in this regard. Third, the provinces in the Bohai Rim region mainly exert the role of "bidirectional spillover." The provinces in the Yangtze River Delta and the Pearl River Delta regions exert the role of "main inflow," and the provinces in the central and western regions mainly exert the role of "agent." Finally, the four industries of (1) metal smelting

**Table 8** Density matrix and image matrix for 2007, 2010, and 2012

| Year | Plate | Density matrix | | | | Image matrix | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | I | II | III | IV | I | II | III | IV |
| 2007 | I | 0.436 | 0.879 | 0.727 | 0.053 | 0 | 1 | 1 | 0 |
| | II | 0.848 | 1 | 1 | 0.861 | 1 | 1 | 1 | 1 |
| | III | 0.227 | 1 | 1 | 0.5 | 0 | 1 | 1 | 0 |
| | IV | 0.03 | 0.111 | 0.792 | 0.076 | 0 | 0 | 1 | 0 |
| 2010 | I | 0.446 | 0.675 | 0.208 | 0.028 | 1 | 1 | 0 | 0 |
| | II | 0.8 | 0.95 | 0.6 | 0.778 | 1 | 1 | 1 | 1 |
| | III | 0 | 0.567 | 0.467 | 0.241 | 0 | 1 | 1 | 0 |
| | IV | 0.028 | 0.178 | 0.259 | 0.083 | 0 | 0 | 0 | 0 |
| 2012 | I | 0.25 | 0.852 | 0.407 | 0.032 | 0 | 1 | 1 | 0 |
| | II | 0.833 | 1 | 0.806 | 0.571 | 1 | 1 | 1 | 1 |
| | III | 0.056 | 0.333 | 0.467 | 0.095 | 0 | 0 | 1 | 0 |
| | IV | 0 | 0.095 | 0.357 | 0.048 | 0 | 0 | 0 | 0 |

and pressing, (2) production and supply of electricity and heat, (3) petroleum processing, coking, and nuclear fuel processing, and (4) transportation and storage, have caused most of the carbon emission transfer in each province. This represents coal, oil, natural gas-based energy consumption, and uncontrolled carbon emissions in China.

Based on these results, this paper proposes several policy recommendations that will help to decrease China's carbon emission transfer:

**Industrial structural upgrade** The differences in resource endowments and geographical locations of provinces have resulted in a strong flow of goods and services between provinces, and also a large carbon emission transfer. Provinces that focus on heavy industry and processing manufacturing (such as Henan, Hebei, and Jiangsu) should consequently adjust their industrial structures, promote industrial transformation and upgrading, and gradually eliminate both small and medium-sized enterprises that cause high carbon emissions. Instead, the development of high-tech environmental protection technologies and their application for small and medium-sized enterprise should be promoted. Provinces that focus on energy output (such as Inner Mongolia and Liaoning) should optimize industrial allocation, avoid excessive concentration of capital in energy-intensive industries, and promote a diversified industrial development. Provinces with carbon emission transfer export (such as Guangdong, Zhejiang, and Shandong) should implement carbon tax policies in accordance with the specific conditions of each province to decrease the demand for carbon-intensive products. Second, provinces with carbon emission transfer export have developed economies and mature technologies, and should therefore provide technical support and joint talent training for less developed regions to decrease the gap between carbon emission transfer import and export.

**Provincial synergies** Provinces at the center of the carbon emission transfer network (such as Jiangsu and Hebei) should cooperate with neighboring provinces to provide industry outsourcing services. On the one hand, this can promote industrial transfer and decrease carbon emissions. On the other hand, neighboring areas can be utilized to decrease transportation costs. The central provinces of the carbon emission transfer network mainly formed an economic linkage circle, which radiates into the surrounding provinces. While driving the coordinated economic development of surrounding provinces, they should be committed to cooperating toward the management of environmental pollution, and decreasing both carbon emission and carbon emission transfer. At the same time, according to the national economic development strategy deployment (e.g., the Western Development Strategy), the resources of provinces at the network center should be reasonably allocated to avoid a monopoly situation.

**Province role positioning** When assigning carbon emission reduction targets, the main functions of provinces that belong to different plates must be considered. Provinces that belong to the "bidirectional spillover" plate are concentrated in the Bohai Rim region and the Yangtze River Delta region. Because of their large population and dense industry, carbon emission reduction policies should be considered from the aspects of production and living. Low-carbon industries, low-carbon life, low-carbon transportation, and similar concepts should be promoted in these areas. Provinces belonging to the "main inflow" plate (developed coastal provinces) have strong technical and economic strength, which can appropriately increase carbon emission standards. However, provinces in the central region must fully consider to undertake industrial transfer into developed provinces, while considering carbon requirements and set reasonable thresholds. Provinces in the "net spillover" sector, which are dominated by energy transportation, should consider to increase investment in infrastructure construction, the rational development of resources, and the development of specialty industries. Several central and western provinces belong to the "agent" plate, and these regions should exert a strong intermediary role in carbon emission reduction and economic development.

**Industry configuration optimization** Metal smelting and rolling processing industry, power, heat production, and supply industry, petroleum processing, coking, and nuclear fuel processing industry, and transportation and storage industry have the largest carbon emission transfer. Rapid economic development is inseparable from the support of resources such as energy and electricity. Therefore, each province should vigorously promote the use of clean energy, develop new technologies that enable to reduction of carbon emissions, improve the infrastructure for new energy, and establish a complete supporting policy system. In addition, with regard to the carbon emission transfer from the transportation and storage industries, relevant companies should be encouraged to rationally plan storage locations, establish drone distribution, new energy vehicle distribution, and other relevant methods, while simultaneously encourage consumers to avoid excessive consumption of carbon-intensive products .

**Acknowledgments** The authors would like to thank the anonymous referees for their comments and suggestions on an earlier draft of this paper.

**Funding information** This study is supported by the National Natural Science Foundation of China (nos.71874071, 71473107) and the MOE (Ministry of Education in China) Youth Fund Project of Humanities and Social Sciences (no.13YJC630141).

## Appendix

**Table 9** Twenty-seven sectors in the MRIO table and their relevant primary paths for 2007, 2010, and 2012

| | Sector | 2007 | 2010 | 2012 |
|---|---|---|---|---|
| 1 | Agriculture | Heilongjiang-Shandong | Heilongjiang-Liaoning | Hebei-Shandong |
| 2 | Coal mining | Hebei-Shanghai | Shandong-Shanghai | Anhui-Jiangsu |
| 3 | Petroleum and gas | Xinjiang-Gansu | Shaanxi-Jiangsu | Xinjiang-Shandong |
| 4 | Metal mining | Hebei-Zhejiang | Liaoning-Jilin | Beijing-Shandong |
| 5 | Nonmetal mining | Hunan-Jiangsu | Sichuan-Chongqing | Liaoning-Heilongjiang |
| 6 | Food processing and tobaccos | Jilin-Shanghai | Jilin-Jiangsu | Jilin-Heilongjiang |
| 7 | Textile | Zhejiang-Guangdong | Zhejiang-Guangdong | Zhejiang-Shanghai |
| 8 | Clothing, leather, fur, etc. | Zhejiang-Guangdong | Zhejiang-Guangdong | Fujian-Yunnan |
| 9 | Wood processing and furnishing | Jilin-Liaoning | Jilin-Liaoning | Jilin-Hebei |
| 10 | Paper making, printing, stationery, etc. | Guangdong-Shanghai | Guangdong-Shanghai | Guangdong-Shaanxi |
| 11 | Petroleum refining, coking, etc. | Heilongjiang-Jilin | Heilongjiang-Guangdong | Heilongjiang-Liaoning |
| 12 | Chemical industry | Jilin-Heilongjiang | Shandong-Jiangsu | Shandong-Henan |
| 13 | Nonmetal products | Hebei-Beijing | Anhui-Jiangsu | Jilin-Heilongjiang |
| 14 | Metallurgy | Hebei-Zhejiang | Hebei-Zhejiang | Hebei-Jiangsu |
| 15 | Metal products | Guangdong-Zhejiang | Guangdong-Zhejiang | Tianjin-Beijing |
| 16 | General and specialist machinery | Heilongjiang-Liaoning | Liaoning-Jilin | Liaoning-Jilin |
| 17 | Transport equipment | Chongqing-Guangdong | Jilin-Liaoning | Jilin-Inner Mongolia |
| 18 | Electrical equipment | Guangdong-Fujian | Liaoning-Heilongjiang | Liaoning-Heilongjiang |
| 19 | Electronic equipment | Guangdong-Henan | Guangdong-Jiangsu | Guangdong-Yunnan |
| 20 | Instrument and meter | Zhejiang-Guangdong | Chongqing-Guangdong | Jiangsu-Guangdong |
| 21 | Other manufacturing | Hunan-Guangdong | Guangdong-Hunan | Guangdong-Jiangsu |
| 22 | Electricity and hot water production and supply | Inner Mongolia-Jilin | Inner Mongolia-Jilin | Inner Mongolia-Shandong |
| 23 | Gas and water production and supply | Heilongjiang-Guangdong | Henan-Guangdong | Shandong-Jiangsu |
| 24 | Construction | Hunan-Guangdong | Shaanxi-Inner Mongolia | Jiangsu-Hebei |
| 25 | Transport and storage | Shanghai-Tianjin | Shanghai-Jiangsu | Shanghai-Jiangsu |
| 26 | Wholesale and retailing\hotel and restaurant | Shaanxi-Guangdong | Inner Mongolia-Hebei | Inner Mongolia-Henan |
| 27 | Other services | Beijing Shanghai | Beijing-Jiangsu | Beijing-Tianjin |

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