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Temporal and Spatial Divergence of Embodied Carbon Emissions Transfer and the Drivers—Evidence from China's Domestic Trade

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Abstract: To understand the embodied carbon transfer in China's domestic trade from 2007 to 2017 and its driving forces, we quantitatively measured the embodied carbon transfer among 30 provinces by using the Multi-regional input-output (MRIO) model, explored the temporal and spatial evolutionary features of the interprovincial embodied carbon emission transfer by using spatial autocorrelation, and further revealed its drivers using the Geographical Detector Model for the first time. We find that: (1) Based on the producer and consumer accounting principles, the amount of embodied carbon emissions of each province has increased, and there are huge differences. (2) The number of provinces with net embodied carbon emissions transfer is increasing, to 18 in 2017 and the target provinces are mostly energy-rich regions, such as Shanxi, Xinjiang, and Inner Mongolia, which have a severe "carbon leakage" phenomenon with developed coastal provinces. (3) The scale and spatial distribution of net carbon transfer out shows a characteristic of "high in the north and low in the south", and the tendency of net transfer from the less developed provinces to the developed regions is becoming more and more obvious. (4) The global differences in the promoting factors of the net embodied carbon transfer are not prominent, but the differences at the local scale are significant, with energy intensity and environmental regulation playing an increasingly significant role. Therefore, it is recommended to strengthen low-carbon technology innovation and environmental regulation, increase the percentage of renewable energy consumption, accelerate the mobility of various resource factors, and improve energy utilization efficiency.

Keywords: multi-regional input-output; carbon emission transfer; geographical detector model

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1. Introduction

At the 75th session of the United Nations General in 2020, our Chief Secretary Xi Jinping solemnly proclaimed that "we should increase our national contribution, adopt more vigorous policies and measures, and strive to achieve carbon peaking by 2030 and carbon neutrality by 2060" [1,2]. In addition, China's 14th Five-Year Plan for National Economic Development (2021–2025) already includes "carbon peaking" and "carbon neutrality". Up to now, the Chinese government has highly valued the development of the low-carbon economy, and a collection of 198 documents have been issued, which have built up a "1 + N" policy system of "Dual-Carbon Target" in China, thus it can be seen that promoting provinces to achieve the target in an orderly manner has gradually risen to a national strategy [3–5]. Shanghai, Jiangsu, and Guangdong have taken the lead in announcing the timeline and pathway to reach the carbon peak; however, these plans are only based on the production and consumption calculations of their provinces, and the transfer of carbon emissions caused by interprovincial trade (referred to as "carbon transfer") is not included in the calculation [6]. The increase in interprovincial carbon transfer, not only lowers the overall efficiency of carbon reduction, but also has a disadvantageous influence

on the interprovincial collaboration in emission reduction, and carbon reduction policy formulation [7].

By promoting the flow and redistribution of capital, energy, and other factors among trade subjects, interprovincial trade promotes economic development while also making the production and consumption of commodities geographically separated, which leads to the occurrence of interregional carbon transfer, which further leads to the transfer of part of the emission reduction responsibility of the region to other regions, or the region assuming the emission reduction responsibility of other regions, thus affecting the area division of emission reduction liability in China and the game of various stakeholders on this issue [8,9].

The central key to promoting regional carbon reduction lies in the equitable accounting of carbon emissions. Producer-based and consumer-based accounting methods are usually used to measure GHG emissions [10,11]. In a "producer responsibility" based accounting system, a country or province is responsible for all emissions generated during its production process, no matter the final demand for the product. On the contrary, in a "consumer responsibility" based accounting approach, emissions are assigned to the final consumer [12]. Peters (2008) argues that accounting based on "consumer responsibility" can help avoid "carbon leakage". According to Peters (2008), accounting based on "consumer responsibility" can contribute to avoiding the phenomenon of "carbon leakage" [13]. Therefore, quantifying the effect of carbon emissions within the domestic trade, revealing the transfer of carbon emission responsibility across provinces was, is, and remains to be the only pathway to solve the challenging issues of carbon emission rights assignment and achieve the goal of "double carbon" [14–16]. Chen et al. (2019) proposed that the scale and intensity of carbon transfer from each province within interprovincial trade should be scientifically and reasonably accounted for, and the drivers of carbon transfer and the responsibility of each province and region for carbon emission reduction should be determined to ensure that each economic entity enjoys the welfare effects brought about by trade while assuming responsibility for environmental protection [17].

Interprovincial trade economic agents have closer ties and stronger interaction of interests, by accounting for the carbon emissions and transfer of each region, and in the context of the launch of carbon emissions rights trading in China's power industry, it provides a reference for other industries [18,19]. Meanwhile, studying the drivers of carbon transfer is helpful for different provinces and municipalities to find the direction of action for emission reduction targets; formulating a reasonable carbon emission reduction sharing mechanism under the principle of "common but differentiated responsibilities", and establishing a regional cooperation and monitoring mechanism to help escort the achievement of "Dual-Carbon Targets" [20,21].

Due to differences in resource endowments and uneven development, the phenomenon of carbon transfer exists between regions, provinces, industries, and even enterprises [22,23]. In 2017, carbon transfer due to interprovincial trade exceeded 35% of China's total carbon emissions [24]. Therefore, provinces must take carbon transfer caused by inter-provincial trade into consideration when formulating and adjusting emission reduction policies [25]. In recent years, with the attention of domestic and foreign scholars, the issue of embodied interregional carbon spatial transfer in China has become an important direction and hot spot for research in this field. In terms of research objects, there are mainly eight regions in China, the Yellow River basin, the Yangtze River basin, and energy-rich regions [26–29], and it is found that carbon emissions are mainly transferred from the central and western regions to the southeast coast, from undeveloped regions to developed regions [30]; there are also some specific province and city-level studies [31–36], which target specific provinces and carbon transfer studies are gradually increasing, mainly in heavy industrial developed or energy-rich provinces, such as Hebei and Shanxi [37,38]; while those for city level are less and mainly focus on Beijing, Tianjin, and Shanghai [39]. In terms of research perspectives, the amount of embodied carbon emissions and transfers are quantified from the perspectives of production, consumption, and value added [40–44]. In addition, there

are more studies on specific industries, mainly the construction industry, service industry, and electric power industry [45–47], and the studies found that the industries with large carbon transfer scales are mainly distributed in the secondary industry, especially the pollution-intensive industries [48]. Previous studies do not provide a clear perspective of the flow of carbon transfer in each province; therefore, studying interprovincial carbon transfer can further point out the direction and path for interprovincial cooperation, and then as soon as possible cut down carbon emissions and interprovincial transfers by shrinking the differences in emission reduction technologies among provinces [49].

To explore the drivers of carbon transfer, research methods usually include Structural Decomposition Analysis (SDA) [50–52], Index Decomposition Analysis (IDA) [53,54], and Geographically Weighted Regression (GWR) models [55,56], etc. The former two methods are more mainstream for analyzing energy consumption and air pollution emission drivers; the latter, as an extension of traditional regression, is widely applied to the fields of environmental, social, economic, and earth science, etc. Although the method can quantify the change in the rate of change, the regression coefficients are location-specific rather than global estimates [57]. In contrast, the Geographical Detector Model (GDM) can avoid the problem of multicollinearity and is better able to avoid the endogeneity problem of mutual causality, enabling the identification and analysis of multiple types of qualitative drivers [58]; Ding et al. (2019) adopted it to discover the influence of social factors during the study period on PM2.5 influence trends [59]. Therefore, this paper uses the Geographical Detector Model to discuss the traits influencing carbon transfer from interprovincial trade for the first time.

Previous studies have used different approaches to explore carbon transfer in different regions and the key drivers, but there are still some shortcomings. Therefore, the possible contributions of this paper are: (1) from the production and consumption sides, quantifying the carbon transfers caused by domestic trade, the scale and orientation of carbon transfers within provinces in the last decade from 2007 to 2017, and identifying and testing whether the phenomenon of "carbon leakage" exists in interprovincial trade; (2) making use of the Geographical Detector Model firstly in this paper to further enrich the research methodologies in the analysis of the influence forces on the carbon transfer within interprovincial trade.

The rest of the paper is organized as follows: the second part demonstrates the model and data, the third part analyzes the scale and evolutionary characteristics of the embodied carbon transfer in interprovincial trade from 2007 to 2017 and explores the influencing factors of the carbon transfer within regional trade through the Geographical Detector Model, the fourth part is the discussion and conclusion, and the last part concludes with policy recommendations and limitations.

2. Materials and Methods

2.1. Multi-Regional Input-Output Model

In recent years, the Multi-regional input-output model (MRIO) model has gradually become a mainstream analytical instrument to study carbon transfer [60–62]. In this paper, this model is used to quantify the amount and transfer of interregional sectoral carbon emissions among 30 provinces in China. The basic structure is shown in Table 1. The model has m provinces, and each province has n sectors, where $x_{i,j}^{r,s}$ represents the intermediate inputs from sector r region i to sector s region j (i, j = 1...n; s, r = 1...m), Y_i^{rs} is the final product that sector i in region r ends up using in region s, X_i^r is the total output of sector i in region r, Y_j^r is the total input of sector j in region r, and E_i^r is the export of sector i in region r. V_j^s is the value added of sector j in region s, and I_j^s is the import of sector j in region s.

Table 1. China MRIO.

			Intermediate Use in Various Industries in the Region						**Area Final Use**			**Export**	**Total Output**
			Province 1			…	**Province m**		**Province 1**	…	**Province m**		
			Sector 1	…	**Sector n**		**Sector 1**	**Sector n**					
Regional input	Province 1	Sector 1	x_{11}^{11}	…	x_{1n}^{11}	…	x_{11}^{1m}	x_{1n}^{1m}	Y_1^{11}	…	Y_1^{1m}	E_1^1	X_1^1
		…	…	…	…	…	…	…	…	…		…	…
		Sector n	x_{n1}^{11}	…	x_{nn}^{11}	…	x_{n1}^{1m}	x_{nn}^{1m}	Y_n^{11}	…	Y_n^{1m}	E_n^1	X_n^1
	…	…	…	…	…	…	…	…	…	…	…	…	…
	Province m	Sector 1	x_{11}^{m1}	…	x_{1n}^{m1}	…	x_{11}^{mm}	x_{1n}^{mm}	Y_1^{m1}	…	Y_1^{mm}	E_1^m	X_1^m
		…	…	…	…	…		…		…		…	…
		Sector n	x_{n1}^{m1}	…	x_{nn}^{m1}	…	x_{n1}^{mm}	x_{nn}^{mm}	Y_n^{m1}	…	Y_n^{mm}	E_n^m	X_n^m
	Import		I_{11}^1	…	I_{1n}^1	…	I_1^1	I_n^1	I^1	…	I^m		
	Added-value		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					

From the row direction we can derive:

$$X_i^r = \sum_{s=1}^{m} \sum_{j=1}^{n} X_{ij}^{rs} + \sum_{s=1}^{m} Y_i^{rs} + EX_i^r \quad (1)$$

Written as a matrix form as:

$$\begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_m \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1m} \\ A_{21} & A_{22} & \cdots & A_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ A_{m1} & A_{m2} & \cdots & A_{mm} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_m \end{bmatrix} + \begin{bmatrix} Y_{11}+Y_{12}+\ldots+Y_{1m}+EX_1 \\ Y_{21}+Y_{22}+\ldots+Y_{2m}+EX_2 \\ \vdots \\ Y_{m1}+Y_{m2}+\ldots+Y_{mm}+EX_m \end{bmatrix} \quad (2)$$

where X_i^r is the column vector of the total output of sector i in region r, the chunking matrix A_{ij} denotes the matrix of direct consumption coefficients of intermediate product inputs from sector i to sector j in a region, and Y_i^r denotes the final demand of sector i in region r.

The column vector of CO_2 emissions for each industrial sector in region i is:

$$TF_i = \hat{E}_i X_i = \hat{E}_i (I - A_{ii})^{-1} \left(\sum_{\substack{j=1 \\ j \neq i}}^{m} A_{ij} X_j + \sum_{\substack{j=1 \\ j \neq i}}^{m} Y_{ij} + Y_{ii} + EX_i \right) \quad (3)$$

where F_p^i denotes the embodied carbon emissions from domestic consumption of m regions (including region i) to region i, referred to as the production-side embodied carbon emissions of region i in this study and F_c^i denotes the consumption-side embodied carbon emissions of m regions (including region i) consumed by region i.

$$F_p^i = \sum_{j=1}^{m} \hat{E^i} (I - A)^{-1} \left(A_{ij} X^i + Y^i \right) \quad (4)$$

$$F_c^i = \sum_{i=1}^{m} \hat{E^j} (I - A)^{-1} \left(A_{ij} X^j + Y^j \right) \quad (5)$$

The net carbon transfer from region i is expressed as the amount of CO_2 transferred from region i to all other regions minus the amount of CO_2 transferred from all other regions to region i.

$$OF_i = \sum_{\substack{j=1 \\ j \neq i}}^{30} \hat{E}_j (I - A_{jj})^{-1} (A_{ji} X_i + Y_{ji}) \quad (6)$$

$$IF_i = \sum_{\substack{j=1 \\ j \neq i}}^{30} \hat{E}_i (I - A_{ii})^{-1} (A_{ij} X_j + Y_{ij}) \quad (7)$$

$$NF_i = OF_i - IF_i = \sum_{\substack{j=1 \\ j \neq i}}^{30} \hat{E}_j (I - A_{jj})^{-1} (A_{ji} X_i + Y_{ji}) - \sum_{\substack{j=1 \\ j \neq i}}^{30} \hat{E}_j (I - A_{ii})^{-1} (A_{ij} X_j + Y_{ij}) \quad (8)$$

2.2. Spatial Autocorrelation

Global autocorrelation is used to analyze the spatial correlation of the net transfer of embodied carbon emissions between provinces at the global scale, which is often reflected by the global Moran's I index:

$$\text{Moran's I} = \frac{\sum_{i=1}^{n} \sum_{i \neq j}^{n} W_{ij} (x_i - \bar{x}) (x_j - \bar{x})}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \quad (9)$$

In Equation (9): n = 30, x_i is the observed data, and W_{ij} is the neighborhood weight matrix. Moran's I > 0 is positive spatial autocorrelation, which implies that the regions with high or low net embodied carbon emission transfer between provinces are spatially aggregated; Moran's I < 0 is negative spatial autocorrelation, which means that there are obvious spatial differences in net embodied carbon emission transfer between adjacent regions; Moran's I = 0 means no correlation and a random distribution.

2.3. Geographical Detector Model

The Geographical Detector Model can probe the temporal and spatial gradual forward progress of the interprovincial net carbon transfer more validly and reasonably. The model is as follows:

$$P_{D.G} = 1 - \frac{1}{\sigma_G^2} \sum_{i=1}^{m} n_{D,i} \sigma_{D,i}^2 \quad (10)$$

In Equation (10): i = 1, . . . , m is the hierarchy of the driver, $n_{D,i}$ is the number on layer i, σ_G^2 , and $\sigma_{D,i}^2$, i is the variance of the carbon transfer shift in the observation area, and layer i, respectively. $P_{D.G}$ takes values in the range [0, 1], the larger the value of $P_{D.G}$, the greater the driving effect of the D factor on carbon transfer. The larger the value of $P_{D.G}$, the greater the urging effect of the D factor on the carbon transfer, and vice versa, the smaller the value.

2.4. Selection of Indicators and Data Sources

Due to data availability, this study analyzed data from 30 provinces in China, excluding Tibet, Hong Kong, Macao, and Taiwan, using MRIO tables for 2007, 2010, 2012, 2015, and 2017. The MRIO tables for 2007 and 2010 were obtained from the Key Laboratory of Regional Sustainable Development Analysis and Modelling, Chinese Academy of Sciences; the MRIO tables for 2012, 2015, and 2017 were obtained from the China Emission Accounts CEADS (China Emission Accounts and Data Set) https://www.ceads.net.cn/ (accessed on 30 September 2022). The industry sections of the above MRIO tables were combined into 26 according to the China National Classification of Economic Activities (GB/T4754-2017) respectively (see Table 2 for details).

Table 2. Department merger.

Serial Number	Sector	Serial Number	Sector
1	Agriculture, Forestry, Animal Husbandry and Fishery	14	Smelting and processing of metals
2	Mining and washing of coal	15	Manufacture of metal products
3	Extraction of petroleum and natural gas	16	Manufacture of general and special-purpose machinery
4	Mining and processing of metal ores	17	Manufacture of transport equipment
5	Mining and processing of nonmetal and other ores	18	Manufacture of electrical machinery and equipment
6	Food and tobacco processing	19	Manufacture of communication equipment, computers and other electronic equipment
7	Textile industry	20	Manufacture of measuring instruments
8	Manufacture of leather, fur, feather and related products	21	Other manufacturing
9	Processing of timber and furniture	22	Production and distribution of electric power and heat power
10	Manufacture of paper, printing and articles for culture, education and sport activity	23	Production and distribution of gas and tap water
11	Processing of petroleum, coking, processing nuclear fuel	24	Construction
12	Manufacture of chemical products	25	Transport, storage, and postal services
13	Manuf. of non-metallic mineral products	26	Other services

In order to avoid the impact of price fluctuations, the double deflation method (Xu., 2011) is used to convert the MRIO table from the current price to the constant price [63]. Deflators are based on price index data provided by the China Statistical Yearbook and the China Price Statistics Yearbook. Using 2012 as the base period, prices for 2007, 2010, 2015, and 2017 are deflated to be comparable to 2012.

3. Temporal and Spatial Evolutionary Trend of Carbon Transfer among Provinces

3.1. Analysis of the Temporal Evolution

Production-side carbon emissions are based on the production of goods, while consumption-side carbon emissions are based on the products and services consumed by consumers, reflecting the principle of "common but differentiated responsibilities". Carbon emissions with two types of accounting principles of China's provinces in 2017 are calculated according to Equations (4) and (5) and are shown in the Figure 1.

In terms of accounting for different emission responsibilities, in 2017, for the production side, Shandong (1143.23 Mt), Hebei (1005.67 Mt), Jiangsu (973.60 Mt), Inner Mongolia (834.77 Mt), and Guangdong (769.78 Mt) were the provinces with the highest carbon emissions, together sharing of 34.83% of the total for the whole country; while the bottom five provinces and regions (Shanghai, Tianjin, Qinghai, Beijing, and Hainan), accounted for only about 4.25% of the national carbon emissions. From the consumption side, Guangdong (1126.83 Mt), Shandong (993.29 Mt), Jiangsu (906.48 Mt), Hebei (834.88 Mt), and Henan (808.68 Mt) were the provinces with the highest carbon emissions, sharing of 34.40% of the national total; the bottom five provinces and regions (Ningxia, Beijing, Shanghai, Qinghai, and Hainan) account for about 4.51% of the national carbon emissions. The provinces of Shandong, Jiangsu, Hebei, and Guangdong are ranked relatively high under both responsibilities, but the rankings are less consistent. Conversely, Beijing and Shanghai are ranked relatively low, and Hainan is always ranked 30, mainly because of its remote location, making it a "marginal player" in the carbon transfer network. Overall, all provinces' total amount of carbon emissions, both on the production and consumption sides, show a rigid increase compared to 2007.

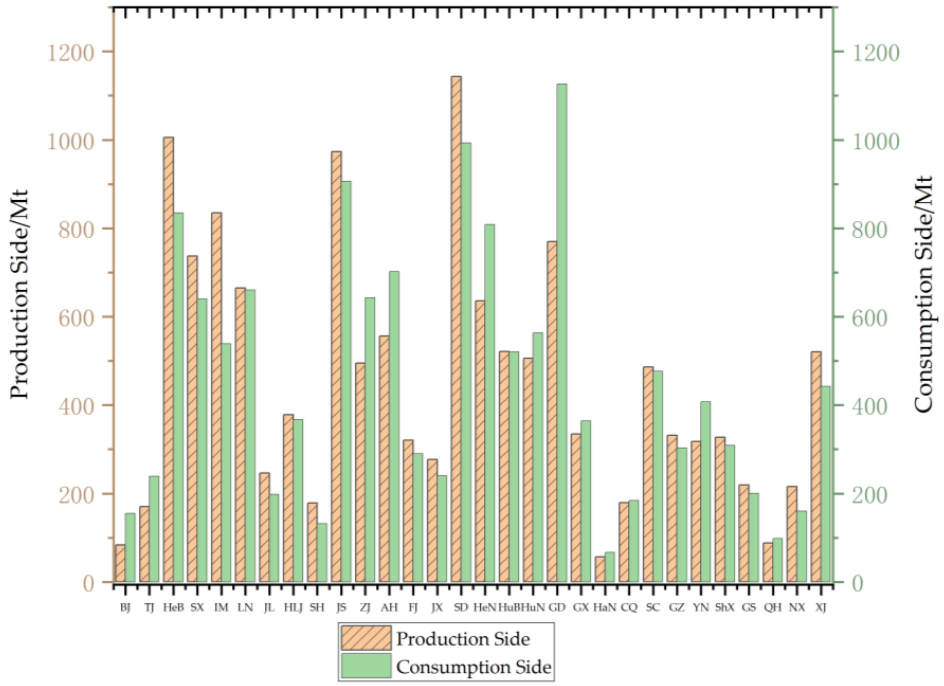


Figure 1. Carbon emissions on the production and consumption sides of 30 provinces in 2017. Provinces: BJ (Beijing), TJ (Tianjin), HB (Hebei), (SX) Shanxi, (IM) Inner Mongolia, (LN) Liaoning, (HLJ) Heilongjiang, (JL) Jilin, SH (Shanghai), JS (Jiangsu), ZJ (Zhejiang), (AH) Anhui, FJ (Fujian), (JX) Jiangxi, SD (Shandong), (HeN) Henan, (HuB) Hubei, (HuN) Hunan; (GD) Guangdong, (GX) Guangxi, (HaN) Hainan; (CQ) Chongqing, (SC) Sichuan, (GZ) Guizhou, (YN) Yunnan, (ShX) Shaanxi, (GS) Gansu, (QH) Qinghai, (NX) Ningxia, (XJ) Xinjiang.

In 18 provinces, including Hebei, Shaanxi, Inner Mongolia, Liaoning, Jilin, Xinjiang, Ningxia, Shaanxi and Gansu, CO_2 emissions from producer responsibility are greater than CO_2 emissions from consumer responsibility. The remaining 12 provinces are the ones where the amount of CO_2 emitted from consumer responsibility is greater than the amount of CO_2 emitted from producer responsibility, with Guangdong and Zhejiang emitting much more CO_2 from consumer responsibility than from producer responsibility, with the former being 375.05 and 148.23 Mt higher than the latter, respectively, and both of these provinces are also provinces with rapid economic development. The inter-provincial trade has increased sharply, which has led to some regions supplying a large quantity of intermediate and final products to other regions. When accounting for the amount of CO_2 under producer responsibility, the CO_2 emitted from these products is counted within the region, but when calculating the amount of CO_2 emitted from the region under consumer responsibility, the CO_2 emitted from these products is counted where the products are consumed.

According to Figure 2: In 2007, there were 15 provinces with net carbon transfer-out, including Hebei, Shaanxi, Inner Mongolia, Jiangsu, Henan, and Guizhou, and the remaining provinces with net carbon transfer-in, including Beijing, Tianjin, Shanghai, Guangdong, Anhui, and Chongqing. In 2017, the amount of target provinces increased to 18, where provinces such as Hebei, Shanxi, Inner Mongolia, Liaoning, and Hebei are the main energy-rich regions in China, with their high emissions and high-polluting industries having a large share, and as energy bases providing stable energy security for sister provinces and cities. This further suggests that there is a phenomenon called "carbon leakage" between the economically developed coastal provinces and the undeveloped provinces in China's economic development process. Eight provinces(Hebei, Shanxi, Inner Mongolia, Liaoning, Shandong, Guizhou, Gansu, and Ningxia) have always been target provinces, while the status of the remaining 18 provinces has changed; among them, Xinjiang (2010–2012), Shaanxi (2012–2015) and Sichuan (2010–2012) have gradually shifted

from net carbon transferring-in provinces to net carbon transferring-out provinces, while Henan (2015–2017), Zhejiang (2007–2010) and Shanghai (2012–2015) are changing from net carbon transferring-out provinces to net carbon transferring-in provinces. The shift in the role of the above provinces in the carbon transfer network may have been influenced by the *Guidance on the Transfer of Industries to the Central and Western Regions* published by the State Council in 2010, as well as various environmentally binding policies. This is due to several factors, the drivers of which are analyzed subsequently.

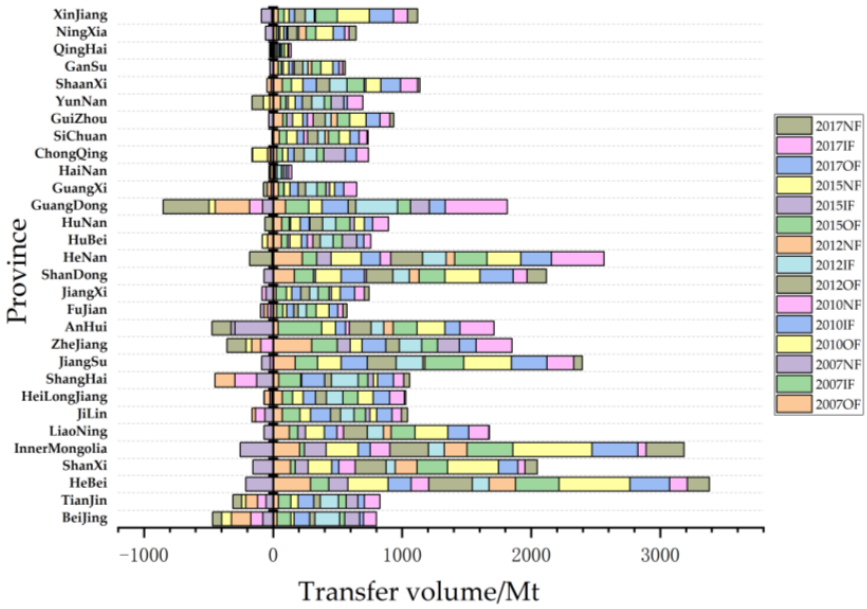


Figure 2. The transfer of embodied carbon emissions in 30 provinces from 2007 to 2017.

3.2. Spatial Evolution Analysis

3.2.1. Spatial Analysis Features

To further clarify the spatial heterogeneity of the embodied carbon emission transfer in each province, the carbon transfer was graded and visualized with the help of ArcGIS10.7.

Figure 3 shows that from 2007 to 2017, the number and amount of target provinces where carbon transfers have occurred have increased. As time goes by, the distribution of target provinces showed a significant "westward" and "northward" trend. In 2007, net carbon transfer in provinces was scattered and concentrated in central and western, and southeastern coastal provinces, while target provinces were mainly in the northwest; by 2017, non-target provinces were mainly located in the southwest, and southern coastal regions, while target provinces were mainly located in the northwest. In 2017, net carbon transfers were primarily focused on the southwest and southern coastal provinces, while net carbon transfers were mainly from the northwest and central provinces. It can be seen that the northwest and central regions are the main receiving regions for carbon transfer. As far as the direction of net carbon transfer-out, from the less developed provinces to the developed provinces it is more obvious. Overall, the phenomenon of net carbon transfer-out from domestic trade in China is characterized by a "high in the north and low in the south".

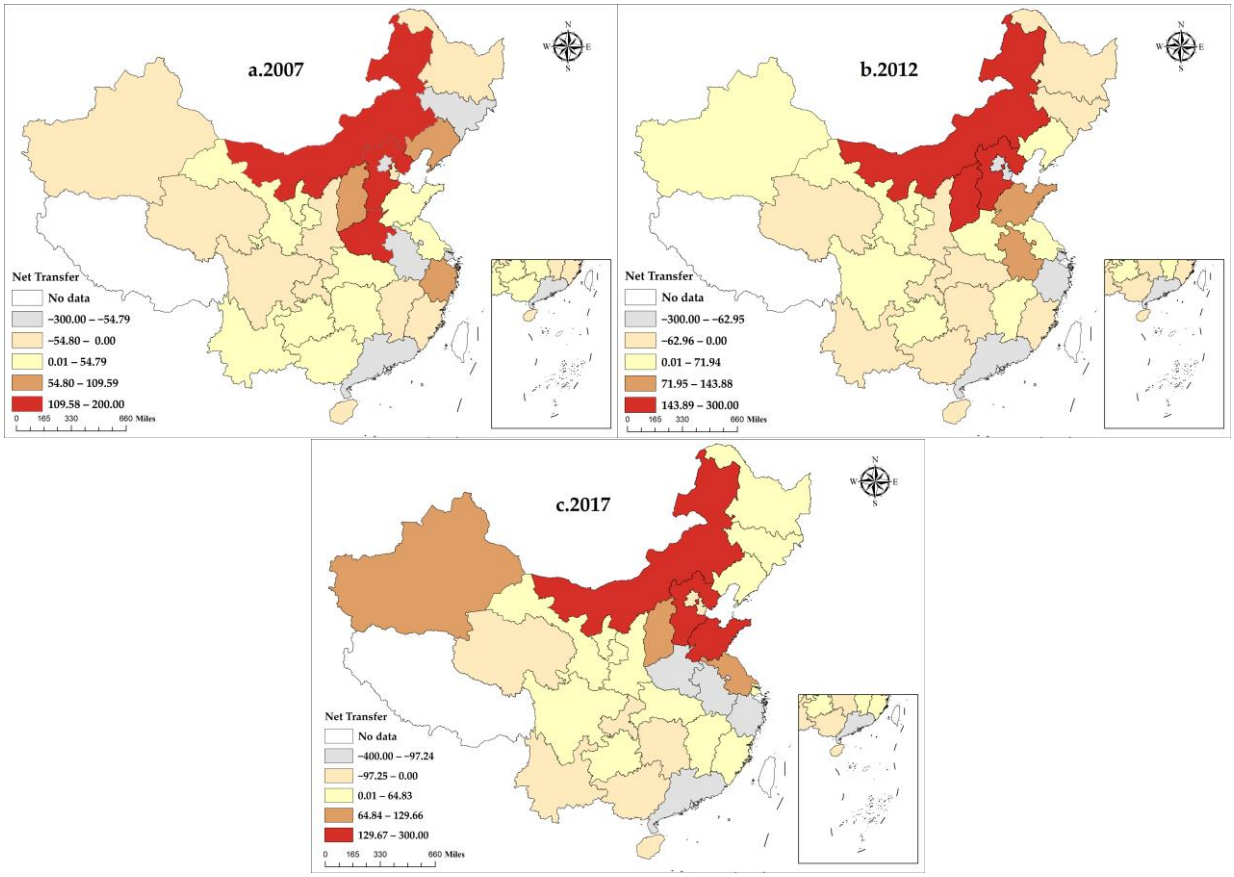


Figure 3. Net transfer (NF) of embodied carbon emissions in 30 provinces of China from 2007 to 2017. Note: Based on the standard base map based on the standard map service system of the Ministry of Natural Resources, with the review number of GS (2016) 1569, and the base map is not modified.

3.2.2. Spatial Correlation Characteristics

To further understand the spatial correlation of the net carbon transfer-out, a global spatial autocorrelation analysis was conducted on each province in China from 2007 to 2017 (see Table 3). The results show that Moran's I index of the net carbon transfer-out of each province in China is greater than 0, and overall, they all pass the 1% significance level test, which means that there is significant spatial autocorrelation of the net carbon transfer-out of each province.

Table 3. Moran's I index of embodied carbon emission transfer in China's intra-provincial trade from 2007 to 2017.

Variable	Year	2007	2010	2012	2015	2017
Net carbon transfer out	Global value	0.176	0.411	0.456	0.349	0.280
	p value	0.051	0.000	0.000	0.000	0.004

3.3. Exploration of the Drivers of Net Carbon Transfer by Province

To further comprehend the underlying mechanism of the temporal and spatial divergence of the net carbon transfer within China's domestic trade, it is required to pay attention to exploring key drivers of the evolution of the net carbon transfer-out in China's interprovincial trade, and the similarities and differences of the drivers of the carbon transfer in distinct periods and regions.

3.3.1. Selection of Indicators

The evolutionary features of net carbon transfer-out about spatial and temporal are complex and are influenced by a combination of factors, such as natural resource availability, level of economic development and technological development, and transportation accessibility [64]. Through literature generalization, this study mainly examines the level of economic development (X1), industrial structure (X2), urbanization level (X3), energy intensity (X4), energy intensity (X5), consumption structure (X6), investment and consumption structure (X7), environmental regulation (X8), technological innovation level (X9), marketization level (X10), green financial development level (X11) [65], transport development (X12) and other 12 detection factors to quantitatively investigate the drivers of the inter-provincial spatial and temporal divergence of net carbon transfer in China(see Table 4); the above data were obtained from the China Statistical Yearbook and the statistical yearbooks of each province.

Table 4. Driving force index of inter-provincial embodied carbon emission transfer.

Code	Detection Factor	Specific Settings
X1	Economic Development Level	GDP per capita (actual value converted from the 2007 base period)
X2	Industrial Structure	Value added of tertiary industry/value added of secondary industry
X3	Urbanization Level	The proportion of the urban population in the total population at the end of the year
X4	Energy Intensity	The proportion of total energy consumption to GDP at the end of the year
X5	Energy Consumption Structure	Coal consumption as a proportion of total energy consumption
X6	Pattern of Consumption	Household consumption expenditure per unit of GDP
X7	Investment and Consumption Structure	The proportion of total capital formation in GDP
X8	Environmental Regulation	The proportion of investment in environmental pollution control in GDP
X9	Technical Innovation Level	The proportion of total R&D expenditure to GDP
X10	Marketization Level	Fan gang Marketization Index
X11	Green Financial Development Level	Green credit, investment, insurance, and government support
X12	Transportation Development	The mileage of railways, inland rivers, and highways in each province accounts for the proportion of the whole country.

3.3.2. Detection of Embodied Carbon Transfer Drivers from a Whole Area Perspective

Firstly, the detection factors were discretized and categorized using the natural fracture method (see Figure 4), and then the $P_{D.G}$ values of each detection factor on the net carbon transfer driver of China's trade were measured by the Geographic Detector Model, as shown in Table 5.

The results denote that all forces play a significant driving impact on the net carbon transfer from trade in China. In 2007, the core drivers were energy consumption structure (0.288), level of urbanization (0.287), energy intensity (0.271), level of green financial development (0.260), and industrial structure (0.216); in 2017, the core drivers were energy intensity (0.316), and level of green financial development (0.249), and only the drivers of both energy intensity and environmental regulation strengthened, while the drivers of the other 10 factors all decreased.

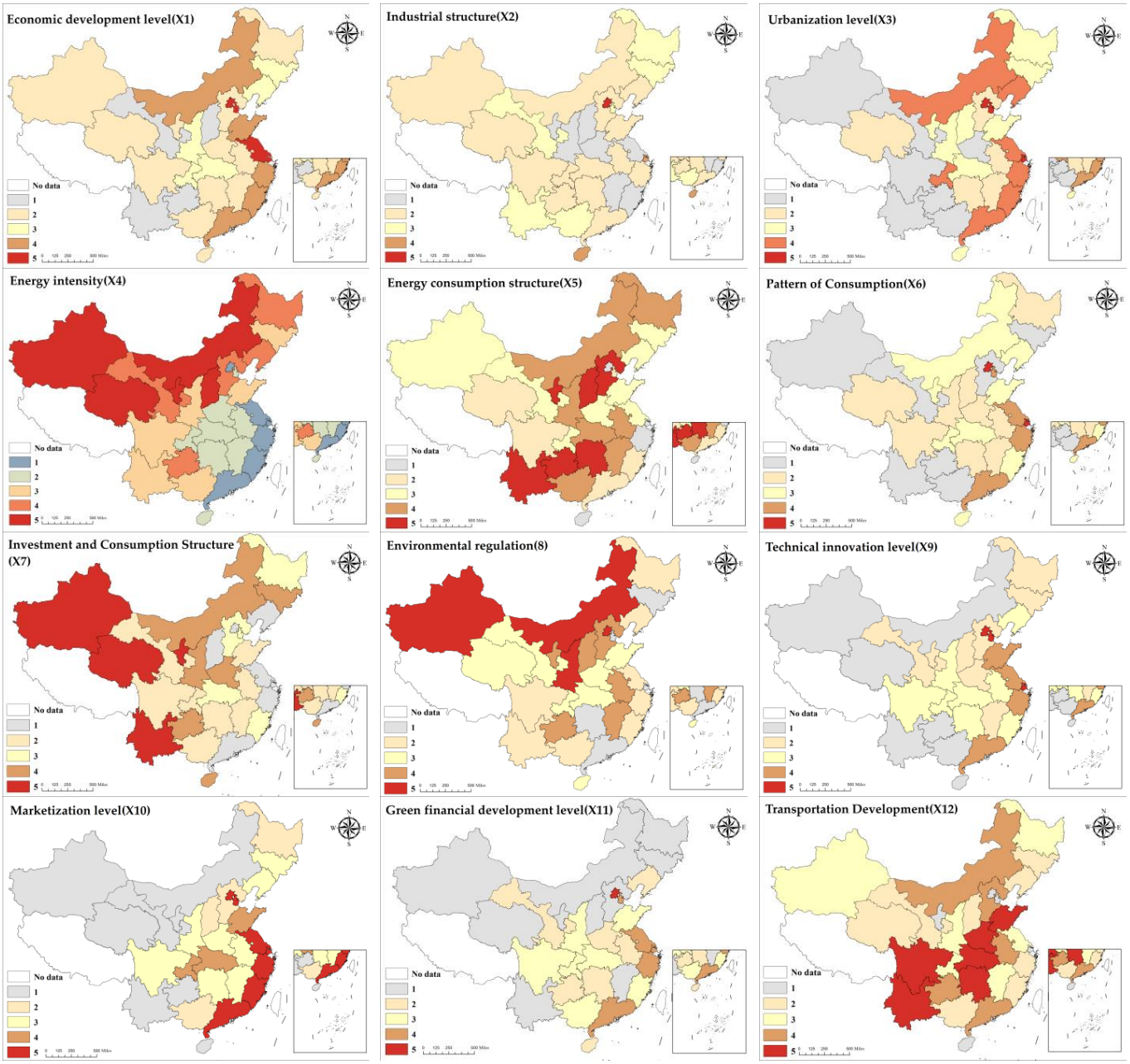


Figure 4. Spatial distribution of geographic detection factor classification. Note: Based on the standard base map based on the standard map service system of the Ministry of Natural Resources, with the review number of GS (2016) 1569, and the base map is not modified.

As for the structure of energy consumption, it has an important role in driving the net transfer of embodied carbon out of inter-provincial trade. "The 14th Five-Year Plan" period is a critical period to lay the foundation for achieving carbon peaking by 2030 and carbon neutrality by 2060, and it is important to accelerate the adjustment of energy systems to accommodate the large-scale development of new energy sources and promote the formation of green development and lifestyles. Therefore, adding the share of non-fossil energy consumption may be useful to achieve carbon emission reduction, but at the same time, it will further boost the final demand for energy-intensive products by residents or enterprises, which in turn, will result in a huge growth in the net transfer of carbon transfer by interprovincial trade.

Table 5. National detection factor $P_{D.G}$ results.

Code	Detection Factor	$P_{D.G}$		Driving Effect
		2007	2017	
X1	Economic development level	0.224 ***	0.032 ***	Decrease
X2	Industrial structure	0.216 ***	0.127 ***	Decrease
X3	Urbanization level	0.288 ***	0.123 ***	Decrease
X4	Energy intensity	0.271 ***	0.316 ***	Increase
X5	Energy consumption structure	0.287 ***	0.139 ***	Decrease
X6	Pattern of consumption	0.180 ***	0.162 ***	Decrease
X7	Investment and consumption structure	0.137 *	0.031 ***	Decrease
X8	Environmental regulation	0.053 ***	0.134 ***	Increase
X9	Technical innovation level	0.169 ***	0.125 ***	Decrease
X10	Marketization level	0.209 ***	0.087 ***	Decrease
X11	Green financial development level	0.260 ***	0.249 ***	Decrease
X12	Transportation development	0.123 ***	0.104 ***	Decrease

Note: *** and * indicate that the variables are significant at the 1% and 10% levels, respectively.

The variable of urbanization has a prominent implication on inter-provincial net carbon transfers. Urbanization is an inevitable result of socio-economic development, and with the shift of labor to non-agricultural industries and towns, China's urbanization process has further accelerated. On the one hand, the supply of urban public infrastructure and regional supporting transport networks must meet the growing demand of urban consumers. Relevant government departments are vigorously promoting the construction of commercial complexes at the urban planning and implementation levels through investment promotion and other means to raise the consumption level, thus increasing the inter-regional demand for high-carbon and energy-consuming products and further increasing the net carbon transfer within inter-regional trade. On the other hand, with the expansion of urban scale, the positive effects of economies of scale and urban factor concentration play their full role in maximizing the effective and rational allocation of public resources, and with the escalating of consumption concepts, the need for high-carbon products by consumers and enterprises decreases, ultimately reducing the net carbon transfer within interprovincial trade. Thus, from 2007 to 2017, the driving role of urbanization level on interprovincial carbon transfer gradually decreases.

The driving influence of energy intensity on interprovincial net carbon transfers is significant and intensifying, which implies that a reduction in energy intensity is conducive to reducing the embodied carbon transfer from inter-regional trade. This study uses total energy consumption per unit of GDP to characterize energy intensity, so it can be used as a level of technological progress to further examine its impact on net interprovincial embodied carbon transfer. As economic development varies greatly across provinces and the level of production technology varies, with developed eastern coastal regions having advanced production technology relative to other provinces in central and western China, there may be significant spatial heterogeneity in the driving effect of energy intensity on interprovincial carbon transfer. The introduction of advanced technologies by local governments in each province has led to the full utilization of various production factors and the effective improvement of energy use efficiency, further reducing the amount of energy consumption and carbon transfer originating from trade.

The level of green financial development has a significant impact on the net carbon transfer from interprovincial trade. Green financial development can not only continue to precisely empower the green transformation and upgrading of enterprises and even industries, helping them to reduce financing costs and achieve multi-channel financing; it can

also increase the introduction of technological innovation and energy-saving technologies, and promote the implementation of environmentally friendly regulations. The introduction of a series of carbon emission reduction support tools has eased the financing difficulties of enterprises in the clean energy and energy conservation and environmental protection sectors, promoting the ability of enterprises to invest more capital in the production of their products and, therefore, driving the net carbon transfer in the interprovincial trade process.

Industrial structure exerts an essential driving guide on interprovincial net carbon transfers. The industrial structure is an inevitable result of economic development and an important indicator of economic development, so switching to an industrial structure will be favorable to own the changes in the carbon emissions of interprovincial trade. The development of a rationalized and advanced industrial structure cannot be achieved without the division of labor. Developed regions have well-developed infrastructure, a good business environment, and a sound market division of labor system, so the tertiary sector is the dominant industry, while the backward regions take over high-carbon and high-energy-consuming manufacturing industries through industrial transfer, thus driving the growth in the scale of carbon transfers sourced from interprovincial trade [66].

Environmental regulation is also an important factor driving the net carbon emissions transfer. The greater the variations in the standards and intensity of environmental regulation between local governments, the larger and more diversified the scale and direction of the net carbon transfer. With lower transport costs for economic activities, carbon transfers are likely to take place in geographically adjacent regions. Moreover, to diminish the higher environmental governance costs, most of all pollution-intensive industries move from eastern provinces with higher environmental regulation intensity to weaker central and western provinces. The final result is that the eastern provinces have to import products from the western provinces to satisfy their consumers, resulting in a shift in trade-implicit emissions.

3.3.3. Discussions of the Spatial and Temporal Variation of the Drivers from a Local Perspective

Although the above detection factors demonstrate a vital influence on net carbon transfer at the national scale, the driving effect of these drivers on carbon transfer may be different across regions. Therefore, geographic detectors were used to detect each of the four major regions (The northeast region includes: Heilongjiang, Jilin, Liaoning; the east includes Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan; the central include Shanxi, Anhui, Jiangxi, Henan, Hubei, Hunan; the west includes Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang) in China in 2017 to derive the $P_{D.G}$ values of each factor on different regions (see Table 6), further revealing the heterogeneity of the driving effects of each factor on net carbon transfer.

In 2017, energy intensity (0.220) and environmental regulations (0.131) were the main drivers of the net carbon transfer from Northeast China's participation in domestic interprovincial trade. During 2007–2017, Liaoning acted as a net carbon transfer area, while Jilin and Heilongjiang had net carbon transfers into net carbon transfers out during 2012–2015. In 2017, the total amount of Northeast China 2017 was 63.23 Mt, accounting for 5.42% of the total net carbon transfer out of the country. The serious problem of population loss in the Northeast has a serious impact on the attraction of investment by enterprises, resulting in a serious talent shortage in the Northeast, which is harmful to sustainable economic development. Thus, the three provinces should highlight the importance of efficiency and technology for emission reduction and support the policy of talent recruitment to promote high-quality economic development in the province.

Table 6. 2017 regional detection factor $P_{D.G}$ results.

Code	Detection Factor	$P_{D.G}$			
		Northeast	**Eastern**	**Center**	**Western**
X1	Economic development level	0.239	0.271 ***	0.024	0.164
X2	Industrial structure	0.225	0.302 ***	0.030	0.025
X3	Urbanization level	0.010 ***	0.395 ***	0.008	0.099
X4	Energy intensity	0.220 ***	0.441 ***	0.110 ***	0.358 ***
X5	Energy consumption structure	0.536	0.523 ***	0.008	0.067
X6	Pattern of consumption	0.320	0.346 ***	0.053	0.048
X7	Investment and consumption structure	0.817	0.177 ***	0.152	0.008
X8	Environmental regulation	0.131 ***	0.189 ***	0.088 ***	0.118 ***
X9	Technical innovation level	0.127	0.278 ***	0.011	0.128
X10	Marketization level	0.151	0.266 ***	0.007	0.151
X11	Green financial development level	0.852	0.476 ***	0.091	0.099
X12	Transportation development	0.083	0.314 ***	0.077 ***	0.065

Note: *** indicate that the variables are significant at the 1% levels.

From the eastern region, the core drivers are energy consumption structure (0.523), green financial development (0.476), energy intensity (0.441), urbanization level (0.395), consumption structure (0.346), and accessibility (0.314). From 2007 to 2017, Hebei, Shanxi, Shandong, and Jiangsu (except 2010) were targeted areas, while Beijing, Tianjin, Guangdong, Zhejiang (except 2007), and Hainan (except 2010) were net carbon transfer in areas, Shanghai, and Fujian shifted from net carbon transfer in areas to target areas during 2012–2015. In 2017, the total amount of target regions was 562.52 Mt, sharing 48.20% of the total net carbon transfer out nationwide. Provinces such as Beijing, Guangdong, and Zhejiang have large economies, high economic activity, high urbanization levels, and high population concentration levels; provinces such as Hebei and Jiangsu have developed heavy industries and booming manufacturing industries; therefore, they are the regions that should be focused on under the "double carbon" goals. These provinces should accelerate industrial transformation and upgrading, increase R&D and financing support for key environmental industries to promote inclusive low-carbon economic development, and cut down the scale of net carbon transfer.

Energy intensity (0.110), environmental regulation (0.088), and accessibility (0.077) have significant effects on net carbon transfer from trade in the central areas. Henan transformed from a net transfer-out province to a net transfer-in province during 2015–2017, Jiangxi shifted from a net transfer-in province to a net transfer-out province during 2010–2012, while the change in status of the other provinces is more volatile. The central region has the advantage of being geographically located to the east and the west, connecting the south and the north, attracting and radiating from all directions and is, therefore, often used as a hub for industrial transfer and transportation. As a result, the central region plays a greater role in the net carbon transfer of interprovincial trade due to its energy use efficiency, environmental protection policies, and geographical and transportation advantages. Therefore, in the process of vigorously expanding the low-carbon economy in the future, resource allocation efficiency should be optimized, transport layout should be reasonably planned, and industry transfer-in and transfer-out restriction policies should be appropriately adjusted.

For the western region, the key factors affecting the net carbon transfer are energy intensity (0.358) and environmental regulations (0.118). During 2007–2017, Inner Mongo-

lia, Gansu, Ningxia, Guizhou, and Sichuan (except 2007–2010) were net carbon transfer provinces, while Chongqing, Yunnan (except 2007–2010), and Qinghai (except 2012–2015). In 2017, the total net carbon transfer from the western region was 504.60 Mt, accounting for 43.24% of the national total. The execution of the Western Development Strategy has given a major boost to the industrialization process of Western provinces. However, due to their special geographical location and unique natural resources, these provinces are more inclined to develop traditional manufacturing industries than high technology industries. The resulting irrational industrial structure is the main reason for the high level of net carbon transfer from these regions. These provinces prefer to evolve the high energy-consuming and high-polluting industries due to their resourcefulness, which results in an increasing fossil energy consumption and net carbon transfer. The structure of energy inputs in the production of raw material industries and energy industry products is unreasonable, and energy use efficiency is low. Therefore, the development and investment in energy technology should be increased to reduce the transfer of carbon emissions resulting from the source and end of products and services.

4. Discussion and Conclusions

In this paper, we used the MRIO model to quantify carbon shift within 30 provinces. In addition, spatial autocorrelation is used to explore the evolutionary characteristics of carbon transfer among provinces on spatial and temporal. Then we reveal the spatial heterogeneity of its drivers by using Geographical Detector Model.

1. From 2007 to 2017, the embodied carbon emissions of all provinces demonstrated a significant upward tendency on both the producer-based and consumer-based and the amount of CO_2 emissions measured by the two responsibilities differed significantly. Therefore, a "flexible mechanism" that takes into account regional differences between trading entities should be explored, and inter-provincial synergies should be explored to promote fairness and effectiveness of carbon emissions reduction. For example, the principle of "who benefits, who compensates, and who protects, who benefits" should be implemented, and a mechanism for sharing responsibility for pollution control among multiple parties should be established. It will also clarify how to coordinate between regions, who should bear more responsibility and who should enjoy more ecological compensation and establish and improve regional embodied carbon emission accounts to lay a scientific basis for regional carbon emission reduction responsibility quotas.
2. The number and size of provinces where carbon transfer is occurring are increasing. In 2017, the number of provinces with net carbon transfer out increased to 18, and the scale of net carbon transfer increased from 821.78 Mt in 2007 to 1166.90 Mt. The expansion of provincial carbon transfers created large variations in carbon emissions from consumption among provinces, with the scale and spatial distribution of carbon transfers showing a "high in the north and low in the south". For provinces with a large net carbon transfer out, such as Inner Mongolia, Hebei, and Shandong, the entry threshold for high-emission and high-energy-consuming enterprises should be raised, the mobility of various factor resources should be fully mobilized, and the industrial transformation and upgrading of high-carbon industries should be accelerated to cut down the net carbon transfer during the trade process.
3. These provinces and regions, such as Shanxi, Xinjiang, and Inner Mongolia, while providing strong support for the economic growth of other provinces and regions, have also become the provinces and regions where the division of responsibility for emissions reduction under the producer responsibility principle has been most severely compromised and the tendency of carbon transfer from the less developed provinces located in central and western areas to the developed provinces on the eastern coast has become more obvious. In particular, the less developed regions should, through technological innovation and industrial structure optimization, improve the efficiency of energy use, gradually change their product trade patterns in domestic

circular trade, and promote the optimization of the regional trade division pattern. In this way, through technological progress and the updating of the industrial division of labor system in the region, it will be possible to improve its status and "bargaining power" in the domestic cycle and change the current pattern of the domestic trade division of labor.

4. The global differences in the drivers of the net carbon shift are not prominent, but the differences at the local scale are significant, and the influence of energy intensity and environmental regulation is increasingly significant. For provinces located in the north and south regions, differential environmental regulations and carbon reduction policies should be formulated. Support provinces in finding a natural resource price accounting method that is in line with their own ecological and environmental system characteristics, so that ecological compensation can be based on a more accurate basis and achieve the multi-dimensional goals of ecological "co-construction", resource "sharing", complementary advantages and economic win-win. The aim is to achieve the multi-dimensional objectives of ecological "co-build", resource "sharing", complementary advantages, and economic win-win.

5. Implications and Limitations

5.1. Implications

As there is a spatial mismatch between the distribution of energy resources and economic development and carbon emissions in China, our findings have prominent significance for the establishment of provincial segmentation of responsibility with more fairness and effectiveness for emission reduction. The main policy recommendations are as follows:

Firstly, great progress has been made since the activation of China's carbon emissions trading market; however, as the current carbon quotas are allocated according to industry benchmarks, and the market targets relative emission reductions, historical emissions have not been taken into account. Therefore, the disposition of carbon emission allowances should not only be on the basis of a single indicator but should be considered from the perspective of shared responsibility, so that enterprises and consumers can take on responsibilities that they should have taken on in the past but did not.

Secondly, innovative development and technological progress are the keys to promoting high-end and highly intelligent industries. Under the multi-dimensional environmental regulation system of the central and local governments, the "innovation compensation" effect of enterprises is greater than the "compliance cost" effect, providing a technical basis for regional green and low-carbon high-quality development; especially in less developed regions it is more important to improve energy use efficiency through technological improvement and industrial structure.

Finally, a scientifically oriented ecological compensation mechanism should be built up to facilitate regional "shared management" of carbon emissions to "shared benefits" of ecological and environmental public goods, and to promote balanced regional development and positive interaction. At the same time, the market-based allocation system for resources and environmental factors should be improved.

5.2. Limitations

There are some limitations in this study and potential future research directions. Firstly, due to limitations in data availability and time, this study analyzed the scale, direction, and influencing factors of implied carbon emissions transfer in trade between provinces in China from 2007 to 2017, with some lag. In the future, further in-depth research will continue after the release of China's 2020 multi-regional input-output extension table and 2022 input-output table. Secondly, we did not calculate the carbon emissions transfer generated by trade between 30 provinces in China and other countries around the world. In the future, we can connect China's multi-regional input-output table with the world's multi-regional input-output table, which can help the Chinese government comprehensively

clarify the direction and basis for responsibility allocation of carbon reduction policies for each province in participating in the dual cycle process.

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