Spatio-temporal heterogeneity of transportation carbon emissions and its driving factors in China's main urban agglomerations

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Abstract: The transportation sector in China has the characteristics of large total carbon emissions, high level, and unbalanced spatial distribution. For carbon emissions reduction, it is of great significance to study the carbon emissions of transportation in China in different regions. Focusing on China's three urban agglomerations: Beijing-Tianjin-Hebei Region, Yangtze River Delta Region and Pearl River Delta Region, this paper explores and compares the spatio-temporal heterogeneity of China's traffic carbon emissions from 2000 to 2019 by using methods such as GWR and ESDA. The results show that: 1) As for carbon emissions, the total carbon emissions and per capita carbon emissions of the three urban agglomerations have shown a significant growth trend. The high-value aggregation in Beijing-Tianjin-Hebei Region has weakened, the high-value and low-value aggregation in the Yangtze River Delta Region has increased, and the change in the Pearl River Delta Region is not obvious. 2) As for influencing factors, motor vehicle ownership has the greatest impact on regional carbon emissions, but the impact intensity of motor vehicle ownership on carbon emissions of the three urban agglomerations is different. 3) As for spatio-temporal heterogeneity, after 2010, the spatial correlation of carbon emissions of the three urban agglomerations was lower than that of the surrounding areas, and all of them were weakened.

Key words: carbon emissions from transportation; urban agglomerations; driving factors; spatio-temporal heterogeneity.

1. Introduction

In recent years, global warming has become one of the most serious environmental problems in the world [1], which undoubtedly becomes a major crisis facing mankind [2]. The greenhouse gases produced by the burning of fossil fuels such as coal, oil and natural gas caused by human activities such as industry and transportation have become the main culprits of global warming. In response to this thorny issue, the United Nations Intergovernmental Negotiating Committee adopted the *United Nations Framework Convention on Climate Change*, the world's first international convention to control greenhouse gas emissions and deal with global warming, in 1992, which clarified the responsibilities among countries [3]. The Pa*ris Agreement* also provides an action guide for climate change, striving to control the global temperature rise within 1.5℃. In 2018, IPCC (Intergovernmental Panel on Climate Change) reached a consensus to achieve the goal of peaking carbon dioxide emissions and carbon neutrality (hereinafter referred to as "double carbon") [4]. China is not an exception. As the world's largest carbon emitter [5], it has also taken corresponding actions in the field of dealing with carbon emissions. In September 2020, at the 75th United Nations General Assembly in China, China formally put forward the goal of achieving "peaking carbon dioxide emissions" in 2030 and "carbon neutrality" in 2060. The goal of "double carbon" is of great strategic significance to the development of China [5].

In recent years, with the rapid development of transportation industry, it has become the second largest carbon emissions industry [6], second only to energy power generation and heating industry. According to the forecast of the International Energy Agency, China's carbon emissions from transportation will account for more than one-third of the world's carbon emissions from transportation by 2035 [7]. Therefore, the research on carbon emissions from transportation is quite instructive for reducing carbon emissions. Many scholars have studied the carbon emissions of different industries and fields from the aspects of energy consumption scale and structure [8], population urbanization [9, 10] and construction land [11]; among which there are many explorations on carbon emissions of transportation industry. In previous studies, LMDI [12-13], STIRPAT model [14-15] and grey relational analysis [16-17] were used to combine carbon emissions from transportation

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with regional economic research, and explore the relationship between urban economic development and carbon emissions from transportation, revealing that regional carbon emissions from transportation are significantly affected by regional transportation industry development and economic development [18]. In addition, the degree of transportation and economic activities among different regions lead to a certain spatial correlation and heterogeneity of regional carbon emissions from transportation [19]. Combined with the spatial econometric model, the interaction between social development and human activities such as population size, passenger and freight turnover, regional GDP and carbon emissions from transportation in space can be explored, and the effects of different factors on carbon emissions from transportation can be revealed and predicted [20].

There are obvious spatial differences in China's economic development, population distribution and industry. The eastern region has the characteristics of relatively developed economy, large population, dense road network, large number of motor vehicles and frequent traffic activities, forming Beijing-Tianjin-Hebei Region, Yangtze River Delta Region and Pearl River Delta Region urban agglomerations. By the end of 2019, the total population of the three urban agglomerations of Beijing-Tianjin-Hebei Region, Yangtze River Delta Region and Pearl River Delta Region accounted for nearly 50% of the total population of the country, contributing more than 40% to the national economy, and the motor vehicle ownership exceeded 35%. Such a huge population base, coupled with frequent economic activities and traffic activities, is bound to cause greater carbon emissions. Therefore, it is still of great significance to focus on the analysis of the characteristics of carbon emissions of the three major urban agglomerations in eastern China and their impact on China. However, few previous studies have directly compared and analyzed the characteristics of carbon emissions from transportation of the three major urban agglomerations. In other words, there is still great research prospect to fully compare the influence of carbon emissions among and within the three major urban agglomerations and analyze the influencing factors and spatial heterogeneity of carbon emissions from transportation from a local perspective.

In this paper, 30 provinces, municipalities and autonomous regions in China (except Tibet Autonomous Region, Hongkong, Macau and Taiwan Province) are taken as the research objects, and the carbon emissions from transportation of the three major urban agglomerations, namely Beijing-Tianjin-Hebei Region, Yangtze River Delta Region and Pearl River Delta Region, are emphatically analyzed. Using ESDA and geographically weighted regression (GWR), the spatio-temporal distribution and heterogeneity of carbon emissions from transportation are explored, and their influencing factors are revealed [20], and corresponding opinions are put forward in terms of carbon emissions reduction from transportation.

2. Methods and Data

2.1 Overview of the research area

The research area of this paper is 30 provincial administrative regions in China, and on this basis, it focuses on the Beijing-Tianjin-Hebei Region, the Yangtze River Delta Region and the Pearl River Delta Region in eastern China (Figure 1). Although the area of the three major urban agglomerations only accounts for about 6% of the country's total area, the population accounts for nearly 50% of the country, the motor vehicle ownership exceeds 35% of the country, and the passenger and freight turnover accounts for about 40% of the country. Such a huge base means that energy consumption from transportation is large and carbon emissions from transportation are large.

Under the background of China's efforts to achieve the goal of "double carbon", it is of great strategic significance [21] and research value to study carbon emissions from transportation for sustainable development and promote the high-quality development of urban agglomerations

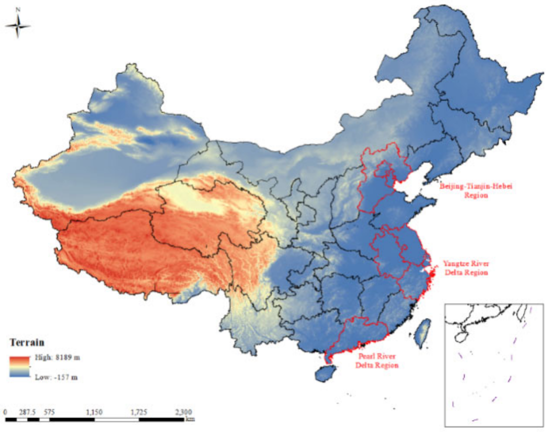

FIG 1 Profile map of Chinese provinces

2.2 Carbon Emissions Measurement Methods and Data Sources

2.2.1 Calculation of total carbon emissions

This study will use the "top-down method" to calculate the total carbon emissions from transportation of three major urban agglomerations in China and the carbon emissions from transportation of prefecture-level cities in each urban agglomeration.

The calculation formula of carbon emissions from fossil fuel consumption and transportation is shown in equation (1):

$$TCE_f = \sum_{i=1}^{9} FC_i \times ALC_i \times C_i \times O_i \times \frac{44}{12} \tag{1}$$

where TCE_f (total carbon emissions from fossil) represents the total carbon emissions from transportation (kg CO2) generated by fossil fuel consumption. i indicates the fuel type (in this study, there are 9 kinds of fossil fuels including crude oil, gasoline, kerosene, diesel oil, fuel oil, raw coal, coke, liquefied gas and natural gas). FCi represents the consumption of the first fossil fuel (kg). $ALCi$ represents the average low calorific value (kJ/kg) of the first energy source. Ci represents the carbon content (T/TJ) of the first fossil fuel. Oi represents the carbon oxidation rate (100%) of the i th fossil fuel.

The calculation formula of carbon emissions of electricity consumption and transportation is shown in equation (2):

$$TCE_e = EC \times EF \tag{2}$$

where TCE_e (total carbon emissions from electric power) represents the total carbon emissions from transportation (kg CO2) generated by power consumption. EC represents the electric power consumption (kWh). EF represents the factor that carbon emissions generated by electric power (kgCO2/ kwh), and the factors that carbon emissions generated by electric power of each province are shown in Table 1.

Table 1 Carbon emissions factors of electricity in different provinces in China

Region	***EF (kgCO2/ kwh)·***
Beijing, Tianjin, Hebei, Shanxi, Shandong, Inner Monggolia	1.246
Heilongjiang, Jilin, Liaoning	1.096
Shanghai, Jiangsu, Zhejiang, Anhui, Fujian	0.928
Henan, Hubei, Hunan, Jiangxi, Sichuan, Chongqing	0.801
Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang	0.977
Guangdong, Guangxi, Yunnan, Guizhou	0.714
Hainan	0.917

Therefore, the total carbon emissions (TE) (kg CO_2) of a certain research area is:

$$TE = TCE_f + TCE_e \tag{3}$$

Because the total amount of carbon emissions is of a large order of magnitude, all TCE involved in the followings are calculated in units of ten thousand tons.

2.2.2 Per capita carbon emissions

Per capita carbon emissions ($PCCE$) refers to the average carbon emissions of each person in a fixed area. Per capita carbon emissions are used to describe how much each person contributes to carbon emissions in this region. Per capita carbon emissions ($PCCE$) can be calculated by the following formula:

$$PCCE = \frac{TCE_x}{P} \tag{4}$$

where TCE_x represents the carbon emissions of the region x and P represents the number of permanent residents in the region.

2.2.3 Carbon emissions intensity

Carbon emissions intensity (CEI) refers to the carbon emissions generated by the growth of unit gross national product, which is mainly used to describe the relationship between the economy and carbon emissions in a certain region, and is of great significance to analyze whether the region can achieve a low-carbon development model. Carbon emissions intensity (CEI) is shown in the following formula:

$$CEI = \frac{TCE_x}{GDP} \tag{5}$$

where TCE_x represents the carbon emissions of the representative region x , GDP represents the gross national product of the corresponding region.

2.2.4 Data sources

In this study, it is necessary to collect the data of the Yangtze River Delta Region, Guangdong, Hong Kong and Macao, Beijing-Tianjin-Hebei Region and the provinces and cities included in the urban agglomerations from 2000 to 2019, involving GDP, car ownership, passenger turnover and freight turnover. These data are obtained from the official website of the National Bureau of Statistics and the *China Statistical Yearbook* [22]. In the carbon emissions calculation method mentioned above, the consumption of fossil fuels, electricity consumption and average low calorific value of energy also come from *China Statistical Yearbook* [22], and the carbon content of fossil fuels, carbon oxidation rate and factors that carbon emissions generated by electric power (Table 2) are obtained from *IPCC 2006 National Greenhouse Gas Inventory Guide* to study the contribution to transportation carbon emissions [23, 24].

2.3 ESDA method

2.3.1 Hot spot analysis

Hot spot analysis, namely Getis-Ord local statistics, compares the local sums of a certain element and its neighboring elements to determine the clustering situation of this element. Getis-Ord local statistics can be expressed as:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \overline{X} \sum_{j=1}^{n} w_{i,j}}{S\sqrt{\frac{[n\sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2]}{n-1}}} \tag{6}$$

$$\overline{X} = \frac{\sum_{j=1}^{n} x_j}{n} \tag{7}$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n}} - \sum_{j=1}^{n} x_j^2 - (\overline{X})^2 \tag{8}$$

Among them, x_j represents the attribute value of element j, $w_{i,j}$ represents the spatial weight of elements i, j and n represents the total number of elements.

2.3.2 Bivariate Moran's *I*

Bivariate Moran's *I* index is in the global scope. The Moran's *I* index is calculated by Geoda spatial analysis tool to evaluate the degree of global aggregation, dispersion or random distribution of data. In this study, considering that there are multiple variables that may affect carbon emissions, in order to describe the spatial correlation characteristics of two variables of geographical elements, bivariate spatial autocorrelation is introduced. Formulas (9)-(11) are given as follows:

$$I_{kl}^{i} = Z_{k}^{i} \sum_{j=1}^{n} W_{i,j}\, Z_{l}^{j} \quad (9)$$

$$Z_{k}^{i} = \frac{(X_{k}^{i} - \overline{X_{k}})}{\sigma_{k}} \quad (10)$$

$$Z_{k}^{i} = \frac{(X_{l}^{j} - \overline{X_{l}})}{\sigma_{l}} \quad (11)$$

In the formula, X_k^i and X_l^j represent the numerical values of two attributes k, l in two spatial units i, j respectively, $\overline{X_k}$ and $\overline{X_l}$ represent the average values of the two attributes k, l respectively, and σ_k and σ_l represent the variance of the two attributes k, l respectively.

2.4 Geographically weighted regression

Geographically weighted regression (GWR) model is usually analyzed by spatial heterogeneity. Generally, a regression equation is established based on the spatial position of data to estimate the spatial distribution characteristics. The expression of GWR model is as follows:

$$y_i = \beta_0(u_i, v_i) + \sum_{k=1}^{n} \beta_k\,(u_i, v_i) x_{ik} + \varepsilon_i \quad (12)$$

where y_i is the dependent variable, x_{ik} is the independent variable (i.e. the influencing factor), (u_i, v_i) is the spatial position of the first observation point, $\beta_k(u_i, v_i)$ is the regression coefficient of the influencing factor k at the regression point k, and ε_i is the independent random error.

3. Results

3.1 Temporal variation trend of provincial carbon emissions from transportation

From 2000 to 2019, the average annual carbon emissions showed a monotonic increasing trend (Table 2). In the past 20 years, the average annual carbon emissions increased from 180,758,300 tons in 2000 to 670,113,100 tons in 2019, with an average annual growth of 25,755,600 tons and a year-on-year growth rate of 7.14%. From 2000 to 2019, the growth of average carbon emissions ranges from 4,131,900 tons to 53,336,800 tons, which shows that the average annual carbon emissions have increased year by year in the past 20 years, and it also means that the total amount of carbon emissions in China has increased year by year. From 2001 to 2019, the year-on-year growth rate of carbon emissions has generally shown a downward trend, and the growth rate of carbon emissions has shown a slowing trend. However, it is worth noting that before 2012, the year-on-year growth rate was high, at about 10%, but after 2012, the growth rate slowed down obviously, and the year-on-year growth rate was less than 4%, and it gradually stabilized.

Table 2 The average carbon emissions, annual average growth rate and annual average growth rate of Chinese provinces from 2000 to 2019

Year	Average carbon emissions (104 ton)	Annual growth (104 ton)	Year-on-year growth rate (%)	Year	Average carbon emissions (104 ton)	Annual growth (104 ton)	Year-on-year growth rate (%)
2000	18075.83	-	-	2010	48342.33	4752.85	10.90
2001	18949.10	873.27	4.83	2011	53676.01	5333.68	11.03
2002	20694.40	1745.30	9.21	2012	55443.52	1767.51	3.29
2003	23831.69	3137.29	15.16	2013	56361.84	918.32	1.66
2004	27647.97	3816.28	16.01	2014	57413.78	1051.94	1.87
2005	31911.64	4263.67	15.42	2015	57826.97	413.19	0.72
2006	35521.76	3610.12	11.31	2016	59172.02	1345.05	2.33
2007	39272.11	3750.35	10.56	2017	61372.06	2200.04	3.72
2008	41186.24	1914.13	4.87	2018	64451.75	3079.69	5.02
2009	43589.48	2403.24	5.84	2019	67011.31	2559.56	3.97

Comparing the inter-annual variation curves of average carbon emissions between the provinces and cities covered by the three major urban agglomerations and China's provinces (Figure 2), it is found that the carbon emissions of Hebei, Jiangsu, Guangdong and Zhejiang provinces are much higher than the national average, while the carbon emissions of Anhui Province are slightly lower than the national average. Because the area and population of Beijing, Shanghai and Tianjin are smaller than those of other provinces, it is too one-sided to compare and analyze their total carbon emissions, and it is necessary to analyze the per capita carbon emissions and carbon emissions intensity of those provinces.

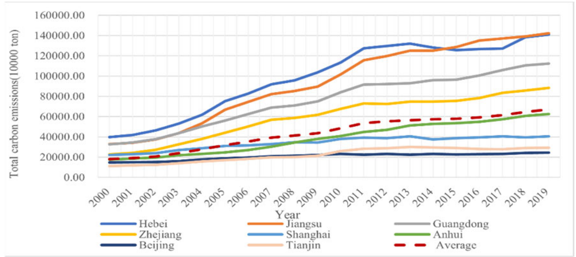

FIG 2 The change trend of carbon emissions of provinces and the national average carbon emissions in the three major urban agglomerations

3.2 Spatio-temporal heterogeneity analysis of carbon emissions from transportation

3.2.1 Spatio-temporal heterogeneity of provincial carbon emissions

In 2019, the provincial TE、$PCCE$、CEI distribution of China mainly showed the spatial distribution characteristics of high in the north and low in the south, high in the east and low in the west (Figure 3). The high total carbon emissions were mainly distributed in Inner Mongolia Autonomous Region, Shanxi Province, Hebei Province, Shandong Province, Jiangsu Province, Zhejiang Province and Guangdong Province, and the carbon emissions in the northern region increased significantly as time goes by. The provinces with higher per capita carbon emissions were roughly consistent with those that have higher total carbon emissions. The carbon emissions intensity shows the most obvious difference between the north and the south. Through the further analysis of temporal variation analysis, it is found that the carbon emissions intensity decreased obviously from 2010 to 2019, and the rate of decrease in the south was faster than that in the north, while the decrease in the southeast coastal areas was much greater than that in the inland areas in the west and north. It is worth mentioning that the total carbon emissions from transportation, per capita carbon emissions and emissions intensity in Beijing are at a low level in the northern cities.

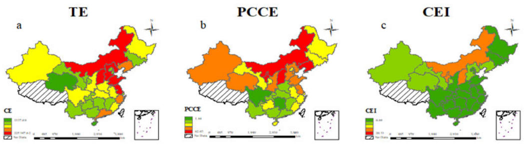

FIG 3 Temporal and spatial variation characteristics of provincial carbon emissions in China in 2019

3.2.2 Spatio-temporal heterogeneity of the three major urban agglomerations

This study focuses on the temporal and spatial evolution of carbon emissions from transportation in Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta urban agglomerations. Because the data of energy consumption in some prefecture-level cities are difficult to collect, and there is a positive correlation between regional economic strength and regional energy consumption. For some cities that are difficult to collect energy consumption, their carbon emissions are estimated according to the proportion of urban GDP in the province (Figures 4 and 5). In the past 20 years, the total carbon emissions and per capita carbon emissions of the three major urban agglomerations have generally shown a sharp upward trend, with the Beijing-Tianjin-Hebei Region and Yangtze River Delta Region regions showing a larger increase, while the Pearl River Delta Region has a relatively small increase. Among them, only Zhaoqing City has shown a decreasing trend in total carbon emissions and per capita carbon emissions in the past 20 years. The high-value centers of carbon emissions in the Yangtze River Delta Region and the Pearl River Delta Region are the cities with the most developed economy and transportation in the region, and radiate from the igh-value centers to the surrounding areas. However, what is unusual is that the high value of carbon emissions per capita in the Beijing-Tianjin-Hebei Region urban agglomeration appears in the peripheral areas of Beijing with the most developed economy and transportation.

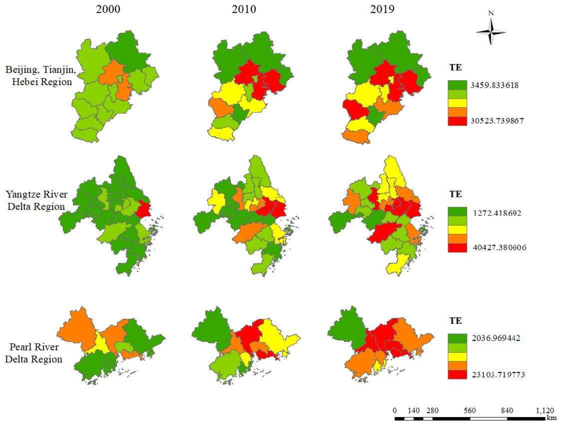

Figure 4 $\boldsymbol{TE}$ of major urban agglomeration in 2000, 2010 and 2019

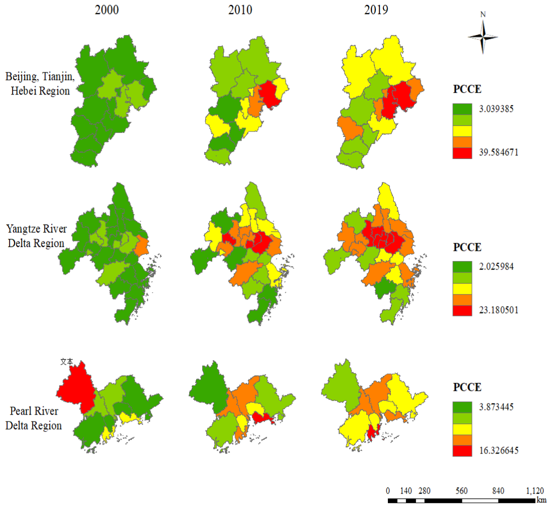

Figure 5 $\boldsymbol{PCCE}$ of major urban agglomeration in 2000, 2010 and 2019

3.3 Hot spot analysis

3.3.1 Analysis of hot spots of provincial carbon emissions

The Z-score of total carbon emissions, per capita carbon emissions and carbon emissions intensity of each province is calculated by cluster analysis, and its spatial distribution characteristics are analyzed (Figure 6). The spatial distribution of total carbon emissions (Figures 6a, d, g) has obvious clustering characteristics. The hot spots of carbon emissions are mainly distributed in the east of Hexi Corridor, while the cold spots are on the contrary, appearing in Xinjiang, Qinghai, Sichuan, Yunnan and so on. Both the per capita carbon emissions and the intensity of carbon emissions show the clustering distribution characteristics of high in the north and low in the south. The high-value concentration areas are mainly in Inner Mongolia Autonomous Region and North China, and the low-value concentration areas are mainly in the Pearl River Basin. From 2000 to 2019, the high-value concentration areas of per capita carbon emissions have not changed much, while the area of low-value concentration areas has shown a shrinking trend, gradually transitioning to lower-value concentration areas, and Xinjiang, Qinghai and other provinces have gradually transformed into higher-value concentration areas, indicating that the population growth rate in the above areas in the past 20 years is higher than its carbon. The concentration of carbon emissions intensity is gradually weakening, and the carbon emissions intensity has dropped significantly in the past decade. Northwest China is a high-value gathering area, which shows that the economic level in northwest China is relatively backward and the energy consumption per unit output value is relatively large. Guangdong Province and Zhejiang Province present the situation of low-value aggregation.

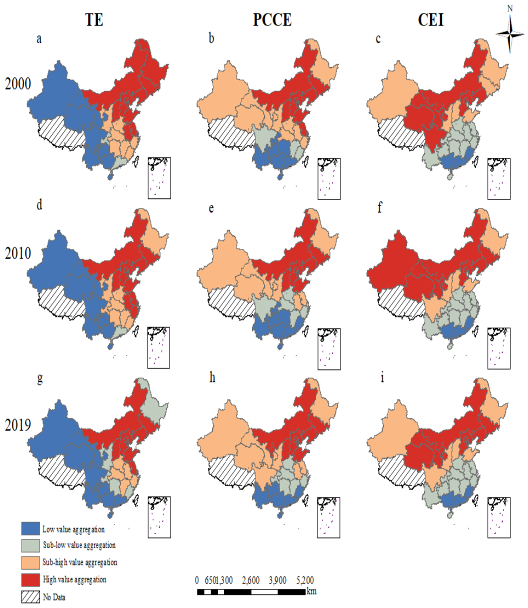

FIG 6 Analysis of hot-spots of carbon emissions in China's provinces in 2000, 2010 and 2019

3.3.2 Hot-spot analysis of three major urban agglomerations

Figure 7-8 reflect the aggregation of total carbon emissions and per capita carbon emissions in Beijing-Tianjin-Hebei Region, Yangtze River Delta Region and Pearl River Delta Region respectively. Generally speaking, there are similarities between Beijing-Tianjin-Hebei and Yangtze River Delta urban agglomerations, and the high-value agglomerations are mainly centered on a few cities and distributed in groups. The high-value agglomerations in Beijing-Tianjin-Hebei urban agglomeration are mainly centered on Beijing-Tianjin-Tangshan, while the high-value agglomerations in Yangtze River Delta Region urban agglomeration are mainly centered on Suzhou and Shanghai, and the clustering state of carbon emissions in coastal areas is generally stronger than that in inland areas. From the perspective of time, from 2000 to 2019, the number of high-value carbon emissions gathering areas in Beijing-Tianjin-Hebei urban agglomeration decreased, mainly changing to the second-highest value gathering areas. The carbon emissions gathering degree in this area in 2010 and 2019 was significantly lower than that in 2000. The difference is that the polarization of the Yangtze River Delta urban agglomeration gradually strengthened, showing more obvious regional differentiation. Some cities in the east of the Yangtze River Delta Region gradually turned into high-value gathering areas, and some cities in the inland areas in the west gradually turned into low-value gathering areas. In the Pearl River Delta Region, Zhongshan, Dongguan and Zhaoqing showed obvious changes, while other cities showed less obvious changes.

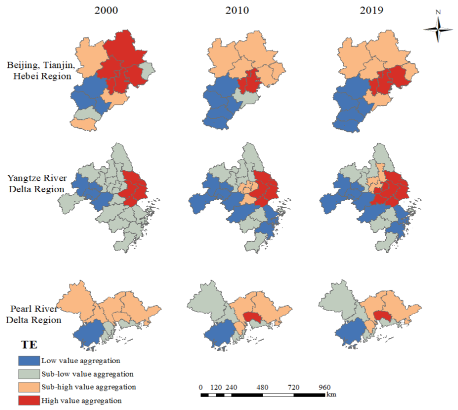

FIG 7 Analysis of hot-spots of $\boldsymbol{TE}$ of major urban agglomeration in 2000, 2010 and 2019

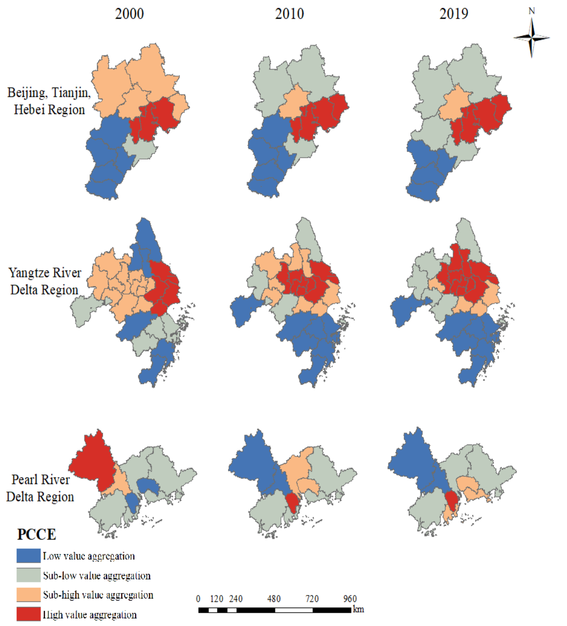

FIG 8 Analysis of hot-spots of $\boldsymbol{PCCE}$ of major urban agglomeration in 2000, 2010 and 2019

3.4 Spatial Correlation of Provincial Carbon Emissions from Transportation

3.4.1 Bivariate spatial autocorrelation of provincial carbon emissions from transportation

In order to explore the spatial correlation between carbon emissions from transportation and its influencing factors, this study uses Geoda for spatial analysis, taking provincial carbon emissions in 2000, 2010 and 2019 as the second variable, and substituting GDP, vehicle ownership, passenger turnover and freight turnover as the first variables. According to the calculation results (Table 3), except passenger turnover in 2000 and 2019, Moran's I under other influencing factors are all greater than 0, and the P value is all less than 0.05, which is statistically significant. According to Table 3, the spatial autocorrelation between provincial carbon emissions and freight turnover is the strongest, and the spatial autocorrelation between provincial carbon emissions and passenger turnover is the weakest. In addition, from 2000 to 2010, the spatial correlation between carbon emissions and these indicators tends to increase, and after 2010, the spatial correlation tends to decrease.

Table 3 Moran's I values of China's provincial carbon emissions under various influencing factors in 2000, 2010 and 2019

	Motor vehicle ownership	GDP	Freight turnover	Passenger turnover
In 2000	0.006	0.085	0.249	-0.013
In 2010	0.098	0.097	0.336	0.026
In 2019	0.063	0.017	0.141	-0.011

Figure 9 shows the local spatial autocorrelation of carbon emissions in China's provinces. In this figure, the high-high concentration areas of each index in each year are mainly concentrated in northern regions of China and the middle and lower reaches of the Yangtze River in eastern China. High-low concentration areas are mainly in Guangdong province and Sichuan province. Low-high concentration areas are mainly concentrated in Anhui and Jiangxi. Low-low concentration areas are mainly concentrated in the sparsely populated and underdeveloped provinces in northwest China, such as Xinjiang province and Gansu province. In addition, from 2000 to 2019, the number of high-high concentration areas tends to decrease, and some provinces with high-high concentration gradually turned into low-high concentration areas.

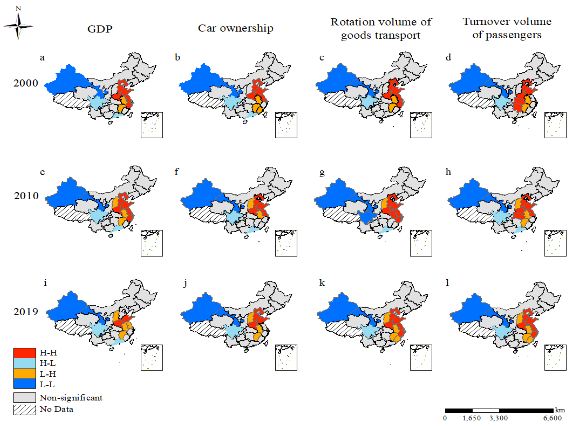

FIG 9 Distribution diagram of $\boldsymbol{TE}$ and bivariate aggregation of 4 driving factors in China in 2000, 2010 and 2019

3.4.2 Spatio-temporal heterogeneity of driving factors of carbon emissions from in transportation in China's provinces

According to the regression result of GWR model (Figure 10), the spatio-temporal heterogeneity of four factors of carbon emissions in China's provinces is analyzed. Generally speaking, the influence of four factors on carbon emissions is strong in the northwest and weak in the southeast. China, Xinjiang, Inner Mongolia and other northwestern provinces have a more significant impact on carbon emissions and these four factors, while southwest provinces such as Sichuan and Yunnan have a less significant impact on these factors. As for the influence of the factors, the regression coefficient of motor vehicle ownership is the largest, which shows that the number of cars has a greater impact on traffic carbon emissions. Therefore, when analyzing the spatio-temporal heterogeneity of carbon emissions in the three major urban agglomerations, we will focus on the analysis of motor vehicle ownership.

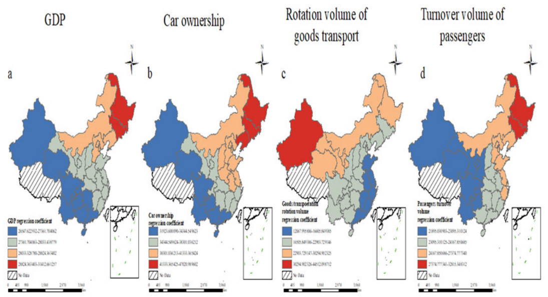

FIG 10 The spatial distribution of regression coefficients of the 4 driving factors in China in 2019

3.5 Spatial Correlation Analysis of Traffic Carbon Emissions in Three Urban Agglomerations

3.5.1 Bivariate spatial autocorrelation of traffic carbon emissions in three major urban agglomerations

According to the results of 3.4.2, the regression coefficient of motor vehicle ownership with carbon emissions in China's provinces is the largest, so this paper will focus on the analysis of motor vehicles. Figure 11 shows the local spatial autocorrelation of carbon emissions and car ownership in three major urban agglomerations in China. For the Beijing-Tianjin-Hebei Region urban agglomeration, the impact of motor vehicle ownership on traffic carbon emissions is not significant. As of 2019, only Langfang and Chengde are L-H clusters. The Pearl River Delta Region urban agglomeration is also not obvious, H-H appears in Dongguan and L-H appears in Huizhou. For the Yangtze River Delta Region urban agglomeration, the spatial differentiation between high-value agglomeration and low-value agglomeration is obvious, with high-value agglomeration in the east and low-value agglomeration in the western cities, and as time goes by, high-value agglomeration has strengthened and low-value agglomeration has weakened.

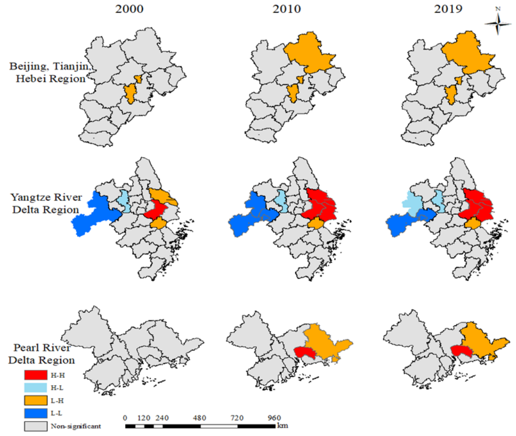

FIG 11 Spatial autocorrelation of carbon emissions and motor vehicle ownership in three major urban agglomerations in China

3.5.2 Spatio-temporal heterogeneity analysis of driving factors of three urban agglomerations

Figure 12 reflects the GWR of motor vehicle ownership in the three major urban agglomerations. The regression coefficients of vehicle ownership in the three major urban agglomerations are all positive, indicating that vehicle ownership has a positive impact on regional carbon emissions. Among them, the regression coefficient of Beijing-Tianjin-Hebei Region and Yangtze River Delta Region regions is small and has little change, while the regression coefficient of Pearl River Delta Region is the fastest in reduction. In 2019, the regression coefficient of Pearl River Delta Region is only one third of that in 2000.

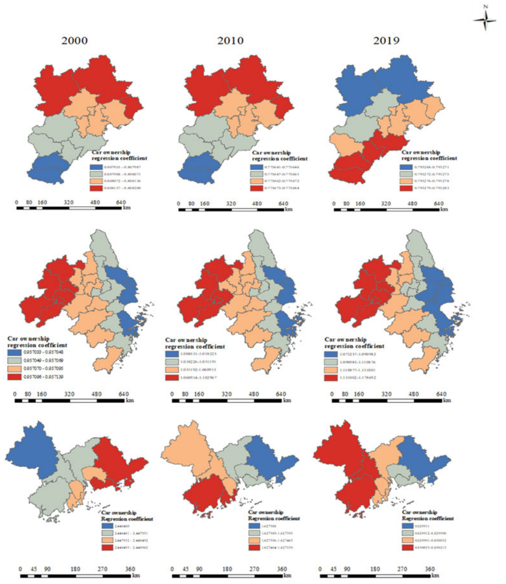

FIG 12 The spatial distribution of regression coefficients of the 4 driving factors of 3 urban agglomerations

4. Discussion

There are obvious spatio-temporal differences in carbon emissions from transportation, per capita carbon emissions and carbon emissions intensity of urban units in China's provinces and three major urban agglomerations. In terms of time, since the 21st century, China has invested heavily in social and economic construction [25], and the economy has maintained the development trend of medium or high speed. At present, the government has set up 19 large and small urban agglomerations [26], which have made great contributions to China's economy. Traffic activities are closely related to economic development [27, 28]. It is precisely because of the establishment of these urban agglomerations that regional traffic activities have been strengthened [29]. Just like the economic scale of China, the traffic industry has also developed vigorously in China [30], and the total carbon emissions from transportation of provinces and urban agglomerations have reached record highs since 2000. As an important part of global economic integration, China was naturally hit by the global economic crisis in 2008. In 2008, the growth rate of road transport freight turnover and port cargo throughput in China decreased [31]. These phenomena are also reflected in China's carbon emissions from transportation, that is, the increase of China's carbon emissions slowed down in 2008 and 2009. From the perspective of growth rate, after 2012, the growth rate of carbon emissions in China has dropped sharply and gradually stabilized. Since the “11th Five-Year Plan”, China has gradually devoted itself to low-carbon pilot projects: in 2010, the National Development and Reform Commission identified Guangdong, Liaoning, Tianjin and Chongqing as the first batch of low-carbon pilot provinces and cities [32], and in 2012, it identified the second batch of low-carbon pilot cities including Beijing and Shanghai [32]. During the "13th Five-Year Plan" and "14th Five-Year Plan" period, the state devoted itself to the study of low-carbon economy, and promoted peaking carbon dioxide emissions and carbon neutrality of cities from the aspects of low-carbon production, low-carbon life and low-carbon transportation [33], for example, formulating new vehicle emissions standards, promoting new energy vehicles, guiding citizens to travel green, and planting trees to increase carbon sinks [34]. These low-carbon measures are of great significance to slow down the growth of carbon emissions and weaken the high-value aggregation of carbon emissions, and they all show results in practical work.

At the level of urban agglomeration, the overall carbon emissions level of Beijing-Tianjin-Hebei Region urban agglomeration is slightly lower than the average level in the northern region, and the per capita carbon emissions in the inner and outer areas of Beijing-Tianjin-Hebei Region urban agglomeration is higher than that in Beijing, showing the phenomenon of high outside and low inside. The carbon emissions level and spatial agglomeration within the Yangtze River Delta Region urban agglomeration are basically consistent with the economic development of its cities. However, the Pearl River Delta Region urban agglomeration, which has the second strongest economic strength, has the lowest level of per capita carbon emissions and carbon emissions intensity among the three major urban agglomerations, and the spatial aggregation and spatial correlation of carbon emissions within the urban agglomeration are not significant compared with the other two urban agglomerations. The reason may be that Beijing has formulated the strictest policy to restrain air pollution, which makes some high-carbon industries in Beijing transfer to the surrounding areas. This industrial layout will strengthen the connection between the surrounding areas and Beijing, and strengthen the traffic between the surrounding areas and Beijing. Commuting, material transfer and other aspects cannot be isolated from traffic activities. However, the industrial structure of the nine cities in the Pearl River Delta Region is relatively perfect, and the relative balance between supply and demand can be achieved within each city or within a short distance, and the material mobilization between cities is relatively infrequent, so the traffic activities among cities are relatively weak compared with Beijing-Tianjin-Hebei Region, resulting in a low level of carbon emissions in the Pearl River Delta Region. In view of the present situation of Beijing-Tianjin-Hebei Region urban agglomeration, we should devote ourselves to adjusting the industrial structure and layout. In planning, we should consider more scientific industrial layout and appropriately narrow the gap between cities, so that we can achieve a relative balance between supply and demand, weaken the traffic activities between cities to a certain extent, and thus reduce the carbon emissions from transportation to a certain extent. In addition, according to the regression results of Moran's I and GWR, it is determined that motor vehicle ownership has the most significant impact on carbon emissions, but the impact of motor vehicle ownership on the three major urban agglomerations is less than its surrounding areas, and within urban agglomerations, megacities such as Beijing, Shanghai, Guangzhou and Shenzhen have smaller impact coefficients, which may be due to the control measures adopted by the state to deal with air pollution in these key cities. It also advocates citizens to develop the concept of green travel. In addition, the urbanization level of these three major urban agglomerations is relatively high, new energy sources are popularized earlier and to a high degree, urban public transport networks are mature, and public transport vehicles are more advanced and environmentally friendly, thus weakening the impact of motor vehicle ownership on carbon emissions to a certain extent. In space, the distribution of carbon emissions from transportation in China is uneven, showing obvious characteristics of high in the north and low in the south, high in the east and low in the west, and has obvious spatial aggregation characteristics. Areas with large economic development scale have greater traffic demand [35]. Therefore, the total carbon emissions from traffic, like economic development in space, shows a trend of high in the east and low in the west. The three major urban agglomerations in China studied in this paper are all concentrated in the eastern region, and their traffic activities are very strong, which drives the traffic carbon emissions of China. However, the difference is that the level of carbon emissions from transportation of the Pearl River Delta Region urban agglomeration, which ranks second in GDP, is not obvious compared with the other two urban agglomerations, and the carbon emissions intensity of the southern region with a relatively high GDP ratio is generally lower than that of the northern region. It is speculated that the GDP of the southern region is growing faster and the energy used is cleaner than that of the northern region. While paying attention to economic development, the carbon emissions from transportation of the southern region is well controlled. Therefore, it is considered that in the future, especially in the northern region, energy structure can be actively adjusted according to local conditions. For example, some areas can make full use of prevailing wind and terrain conditions to develop wind energy, and tidal energy can be developed in coastal areas. Key cities need further follow-up policies and develop new fuel vehicles.

There are also some limitations of this study. First, for some cities that are difficult to collect energy consumption, the proportion of urban GDP in the province is estimated, so there is a certain error in the carbon emissions data at the level of urban agglomeration.

In addition, the calculation formula of total carbon emissions selected in this study is applicable to the calculation of direct carbon emissions. However, with the development and evolution of vehicles, there are more vehicles such as electric vehicles, subways and high-speed railways driven by electricity, so the indirect carbon emissions driven by electricity may not be reflected in this formula, and the completeness of calculation needs to be improved. In the follow-up study, data collection, carbon emissions calculation, influencing factors and other aspects can be further improved, so as to provide a stronger basis for carbon emissions reduction strategies.

5. Conclusion

(1) The carbon emissions from transportation in China provinces show obvious spatial distribution characteristics of high in the north and low in the south. Especially for the northern region, while developing the economy, we should devote ourselves to carbon emissions reduction, actively implement energy structure adjustment, vigorously develop clean energy, and pay attention to the prevention and control of pollutants.

(2) The carbon emissions level of the Pearl River Delta Region urban agglomeration is lower than that of the other two urban agglomerations, and the influence of each driving factor on the Pearl River Delta Region urban agglomeration is relatively smaller than that of the other two urban agglomerations. Therefore, in the carbon emissions reduction work of urban agglomerations, the Yangtze River Delta Region and Beijing-Tianjin-Hebei Region urban agglomerations can learn from the relevant policies of the Pearl River Delta Region urban agglomerations and coordinate the relationship between carbon emissions and their influencing factors.

(3) Among the four driving factors, the motor vehicle ownership has the greatest influence on carbon emissions, but its influence on the Pearl River Delta Region is gradually decreasing, indicating that the carbon emissions reduction work in the Pearl River Delta Region is relatively good in recent years, which can provide theoretical basis for carbon emissions reduction work in other regions.

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