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Impact of the spatial structure of urban agglomerations on carbon dioxide emissions in China#

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ABSTRACT

With urban agglomerations becoming the core areas of economic development and carbon dioxide (CO_2) emissions in China, the impact of the spatial structure of urban agglomerations, including monocentric and polycentric structure and reflecting the distribution of elements and resources among cities on CO_2 emissions should be investigated. This paper empirically analyzed the impact of spatial structure of urban agglomeration on CO_2 emissions and the inherent mechanism. The nightlight data is utilized to firstly evaluate the long-term evolution of the spatial structure of 19 urban agglomerations in China in terms of morphology. Then, econometric model is constructed, combining panel data of urban agglomerations during 2000-2018 to explore the relationship between spatial structure and CO_2 emissions. What's more, the mediation effect model is applied to trace the internal mechanism of industrial division. The results show that the polycentricity of the spatial structure of 19 urban agglomerations in China has increased since 2000, especially those on the coastal area. What's more, polycentric spatial structure of urban agglomerations can help reduce carbon intensity, which is partly realized by promoting industrial division. Besides, spatial structure poses greater CO_2 emission impact on core cities rather than non-core cities. Therefore, this paper could provide new insight into the realization of low-carbon urban agglomerations from the perspective of urban spatial planning and city positioning.

Keywords: spatial structure of urban agglomerations, polycentric development, nightlight data, carbon dioxide emissions, industrial division

1. INTRODUCTION

Since the reform and opening up, urban agglomerations have gradually become the core areas of Chinese economic development and CO2 emissions. The statistics show that China's 19 national urban agglomerations contribute 80.05% of the total economic output and 71.7% of CO2 emissions, while just accounting for 29.12% of the land area. Under the climate crisis, China, as the world's largest CO2 emitter, should pay attention to scientifically guiding the low-carbon development of urban agglomerations to fulfill carbon neutrality.

Center cities play a leading role in the development of urban agglomerations. Between 2000 and 2020, the total number of megacities and supercities with a permanent urban population of over 5 million and 10 million, increased from 2 to 21. Polycentric spatial structure has been adopted by some policymakers to alleviate the problems of congestion and unbalanced development faced by monocentric structure. The spatial structure of urban agglomerations reflects the interrelationship between cities, and the distribution of factors in the region, which will influence the performance of urban agglomerations. So, how did the spatial structure change during the past 20 years? Does different spatial structure of urban agglomerations have varied impact on CO2 emissions? Is polycentric development, which is proposed by the government, conducive to carbon reduction? What is its inner mechanism? Can we achieve a win-win situation of economic growth and green development by planning a reasonable spatial structure? Answering these questions will help us clarify the specific spatial planning measures of urban agglomerations to achieve sustainable development.

2. Literature review and hypotheses

Scholars have discussed the factors influencing CO2 emissions in China, including economic development, energy consumption, population size, industrial structure, trade openness, technological progress, and government actions. However, on the one hand, due to the limitation of carbon emission accounting, the existing

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discussion is mainly on the national or provincial scale rather than the level of urban agglomerations. On the other hand, literature regarding spatial structure mostly focused on the measurement of regional spatial structure, its evolutionary laws, and economic performance. Although few scholars discuss the relationship between spatial structure and CO2 emissions on the city scale, provincial scale, or use PM2.5 concentration data, construct a green economy index, and account for green development efficiency to achieve environmental performance assessment of the spatial structure of urban agglomerations, no study has been conducted to comprehensively identify the spatial structure of 19 national urban agglomerations in China and assess their impact on CO2 emissions and internal mechanisms.

The spatial structure of an urban agglomeration refers to the degree of agglomeration and agglomeration pattern formed by the distribution of elements among different cities, which can be divided into monocentric and polycentric. From the perspective of population distribution, the monocentric structure means obvious city hierarchy with one distinct center, while the polycentric structure shows a relatively balanced distribution with two or more centers. According to the traditional regional development theory, at the early stage of economic development, the region must form the spatial concentration of factors to achieve rapid economic growth as a growth pole, thus presenting a monocentric spatial structure. In the later stage of economic development, with the transformation of leading industries and the increase of agglomeration costs, factors will be redistributed within the region, forming a polycentric spatial structure. The spatial structure of urban agglomerations transforms from monocentric to polycentric, the essence of which is that enterprises and labor force make location choices among cities, and sub-center cities become more attractive. It implies that monocentric spatial structure is a necessary process for development, and it is ineffective and inefficient for government to force polycentricity.

Agglomeration economic theory helps to understand the difference between two types of spatial structure. It is believed that spatial concentration of factors drives economic growth by achieving cost savings and efficiency gains through three channels: sharing, matching, and learning. However, as the city size continues to increase, the crowding effect of over-agglomeration can have a constraining effect on economic efficiency. At first, the dual effects of economic agglomeration are often discussed under the geographical limit of the single city, without distinguishing the difference between structures. With the improvement of transportation and communication technologies, inter-city connections have become closer, and metropolitan contiguous areas and urban agglomerations have emerged. Scholars began to discuss the concept of borrowed size, and urban network externality. It means agglomeration economies will break through the administrative boundaries of cities and interact with their neighboring cities and even non-neighboring cities on a larger scale, for example urban agglomerations.

Similar to economic issues, numerous studies have explored the environmental impact of monocentric agglomerations with geographical boundaries, which usually have a dual effect: the negative externality of output expansion and the positive externality of scale economies and technological progress. Based on provincial panel data in China, Lu and Feng (2014) found that spatial agglomeration of economic activities helps to reduce industrial pollution intensity. Yang (2015) conducted a provincial panel threshold regression and found that industrial agglomeration is beneficial to improving environmental pollution when it is above the threshold. Shao et al. (2019) tested the existence of an "inverted N" curve relationship between economic agglomeration and carbon emission intensity. To sum up, the impact of polycentric spatial structure may be different from that of monocentric. Small and medium-sized cities within urban agglomerations can "borrow" the agglomeration effect of large cities. Therefore, at the level of urban agglomerations, the polycentric spatial structure may help improve the economic efficiency and achieve a rational allocation of factors, thus bringing an improvement in environmental performance. Based on the above analysis, this paper proposes the first hypothesis.

Hypothesis 1: As different spatial patterns of economic agglomeration, the spatial structure of urban agglomerations will have an impact on CO2 emissions. Among them, the polycentric spatial structure presents lower carbon emission intensity.

Then what is the inner mechanism of the polycentric spatial structure of urban agglomerations to reduce CO2 emissions? In fact, agglomeration and division of labor are closely related. The division of labor is an important factor to promote the formation and development of agglomeration, and the formation of agglomeration will promote the further industrial. Based on the theory of new economic geography, the spatial agglomeration of economic activities will initially form a spatial structure of manufacturing "center" and agricultural "periphery". With the upgrading of the industrial structure, the deepening of regional openness, and the further decline of trade costs, the spatial structure will evolve into a "center" of services and a "periphery" of manufacturing.

The industrial division among cities helps to specialize and save costs, thus to achieve economies of scale, and improve overall economic efficiency. Therefore, our second hypothesis is:

Hypothesis 2: Industrial division has a mediating effect in the process of the influence of the spatial structure of urban agglomerations on CO2 emissions.

3. Methodology and data

3.1 Measurement of spatial structure

This study measures the spatial structure of urban agglomerations from the morphological dimension. Using nighttime lighting data to measure the number of economically active urban population, we constructed the index *spatial* to measure the spatial structure of urban agglomerations according to equation (1).

$$\ln(Light_{ijt}) = C - q_{it}\ln(Rank_{ijt}) \quad (1)$$

In equation (1), $Light_{ijt}$ is the total value of nighttime light brightness of city j in the urban agglomeration i in year t, which means the scale of economically active population of city j. C is the constant. $Rank_{ijt}$ represents the ranking of light brightness of city j in the urban agglomeration i in year t after ranking the light brightness of cities in each city group from largest to smallest in each year respectively. The regression coefficient, q_{it} contains the information of spatial structure. Larger q_{it} indicates that the core city is prominent and the urban agglomeration obeys monocentric distribution. Smaller q_{it} shows more polycentric structure. Because the number of cities in 19 urban agglomerations is different, in order to make the spatial structure index comparable, it should be emphasized that we followed Meijers and Burger (2010) to obtain averaged q_{it}, thus to construct the index $spatial_{it}$.

3.2 Models

To test the causal relationship between the spatial structure of urban agglomerations and CO2 emissions, the econometric model shown in Equation (2) is set up to test Hypothesis 1 with the panel data of 19 urban agglomerations in China.

$$ln(EI_{it}) = \alpha + \beta ln(spatial_{it}) + \gamma X_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (2)$$

Considering that China has set the reduction of carbon intensity as a binding indicator in the national economic and social development plan since the 12th Five-Year Plan. Also, the land area, population, and GDP varied greatly among different urban agglomerations. We set carbon emission intensity EI_{it} (tons per million yuan) as our explained variable in the empirical analysis. Core explanatory variable is the spatial structure of urban agglomerations $spatial_{it}$. X is the vector of control variables, specifically including: population size pop_{it}, the proportion of secondary industry $second_{it}$, foreign direct investment fdi_{it}, and the number of patents granted per capita $patent_{it}$. The coefficient β show the influence of spatial structure on CO2 emission. If β is significantly positive, it indicates that monocentric spatial structure is not conducive to carbon emission reduction, and polycentric spatial structure is a low-carbon spatial structure pattern of urban agglomerations. While β is significantly negative, it indicates that monocentric spatial structure reduces carbon intensity of urban agglomerations in China.

Besides, we construct three models (3)-(5) to test the mediating effects of industrial division. Where $division_{it}$ represents the level of industrial division, including three types of measurement, similarity of industrial structure, specialization index of services in center cities, and specialization index of manufacturing in peripheral cities. We test the significance of coefficient β, b_1^1, and b_2^2 stepwise to identify the existence of mediating effect.

$$ln(EI_{it}) = \alpha + \beta\ln(spatial_{it}) + \gamma X_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (3)$$

$$division_{it} = \alpha + b_1^1\ln(spatial_{it}) + \gamma X_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (4)$$

$$ln(EI_{it}) = \alpha + b_1^2\ln(spatial_{it}) + b_2^2 division_{it} + \gamma X_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (5)$$

3.3 Data sources

Based on the panel data of 19 urban agglomerations during 2000-2018, we analyze the impact of the spatial structure on CO2 emission. Emission data of cities and urban agglomerations is extracted from Emission Database for Global Atmospheric Research (EDGAR). A Prolonged Artificial Nighttime-light Dataset of China (1984-2020) is obtained from National Tibetan Plateau Data Center. Other economic information can be found from China Statistical Yearbook, China City Statistical Yearbook, China Yearbook for Regional Economy, China Research Data Service Platform (CNRDS), and CSMAR database.

4. Results and discussion

4.1 Spatial and temporal characteristics of spatial structure of urban agglomerations

Fig. 1 shows spatial and temporal characteristics of the spatial structure of 19 Chinese urban agglomerations in 2000 and 2020. The darker color of the bottom map means a larger $spatial_{it}$ index and monocentric structure. Meanwhile, red asterisks and red circles are used to mark the center cities of each urban agglomeration. It is obvious that most Chinese urban agglomerations showed monocentric spatial structure in 2000 and changed to be more polycentric during the past 20 years. The degree of monocentricity of coastal urban agglomerations was always lower than that of inland urban agglomerations. At present, Shandong Peninsula and Pearl River Delta are the typical polycentric urban agglomerations with over three center cities. Chengdu-Chongqing and Liaoning-South Central urban agglomerations show a dual-nuclei structure. Due to post-development, the central and western regions have fewer center cities and mainly present a monocentric spatial structure. For example, Tianshan Mountain is dominated by Urumqi. City cluster of Lanzhou and Xining is centered on Lanzhou. In addition, the monocentric agglomeration phenomenon of Qianzhong urban agglomeration is rapidly weakening, which is still inconsistent with the planning and needs to clarify the urban industrial pattern and development status.

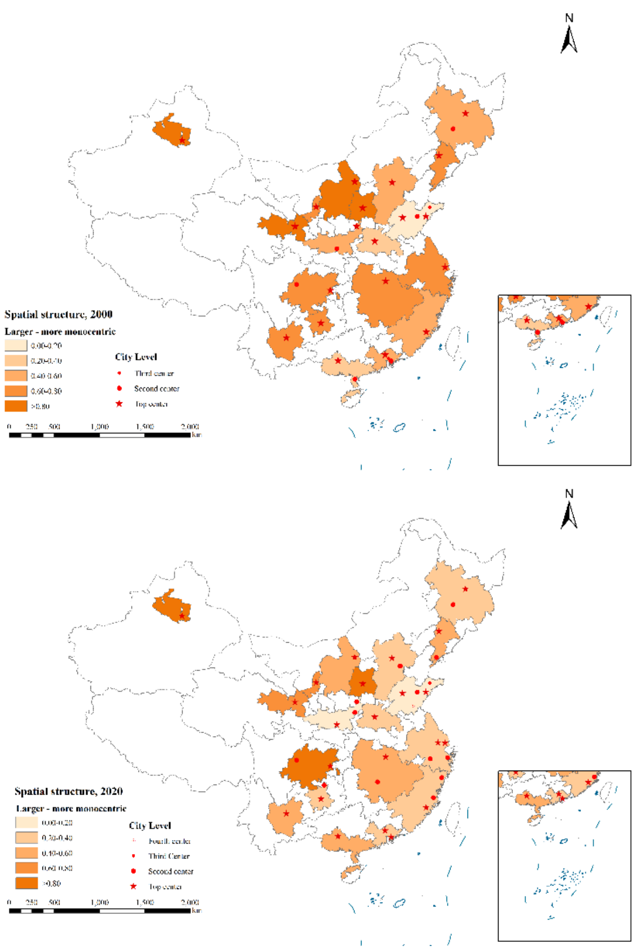

Fig. 1 Spatial structure of 19 urban agglomerations in China, 2000 and 2020.

4.2 Benchmark regression analysis

First, the LLC test and IPS test with BIC criterion were used to test the problem of unit root, which is significantly rejected. Then, OLS method is employed to estimate the impact of spatial structure on carbon dioxide emissions. After the Hausman test, time effect and individual effect are taken into consideration. Table 1 illustrates the basic estimation results for the full sample. The coefficient of Spatial is significantly positive, meaning monocentric spatial structure induced higher emission intensity. Polycentric development seems to be a win-win strategy for economic and low-carbon development.

Table. 1 Impact of the spatial structure on carbon emission (Benchmark regression).

Variables	Emission Intensity		
	FE	FE	FE
	(1)	(2)	(3)
Spatial	0.600***	0.120**	0.165***
	(0.130)	(0.050)	(0.050)
Pop			-0.526***
			(0.200)
Second			-1.876***
			(0.290)
Fdi			-1.560**
			(0.640)
Patent			-0.0663*
			(0.040)
Constant	1.370***	1.593***	6.703***
	(0.090)	(0.050)	(1.570)
Individual Effect	Yes	Yes	Yes
Time Effect		Yes	Yes
Observations	361	361	361
R-squared	0.056	0.881	0.904

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Besides, it should be noted that there may be endogeneity between the carbon dioxide emissions and the spatial structure of a region. This paper further adopts instrumental variable estimation to re-examine the causality relationship. We construct two types of instrumental variables in accordance with the principal which is strongly exogenous, closely related to the polycentric spatial structure and not related to carbon emission. They are river density multiple the reciprocal of exchange rate, and surface roughness multiple exchange rate, respectively. The estimation results are shown in Table 2. It is proved that the IV variables are appropriate to estimate the spatial structure, and the coefficients of 2SLS estimation are significantly positive with emission intensity. We can identify the impact of spatial structure and acknowledge the benefits of carbon reduction of polycentric development.

Table. 2 Impact of spatial structure on carbon emission (IV regression).

Variables	Spatial structure (1)	Emission Intensity (2)	Spatial structure (3)	Emission Intensity (4)
ln(river density/exchange rate)	-0.2982***			
	(0.1176)			
ln(surface roughness*exchange rate)			0.2413***	
			(0.0378)	
Spatial structure		1.4388***		0.4163**
		(0.2795)		(0.1577)
Control variables	Yes	Yes	Yes	Yes
Individual Effect	Yes	Yes	Yes	Yes
Time Effect	Yes	Yes	Yes	Yes
Hausman test		0.0000		0.0000
Weak IV identification		0.0000		0.0000

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

4.3 Robustness check

To strengthen the reliability of the regression results, we take alternative variables and divide samples to conduct the robustness test. All test results are in Table 3. Modified primacy index and four city index substituted for spatial structure are shown in columns (1) and (2). The symbols of regression coefficients are consistent with the correlation coefficients, and significant to prove our hypothesis 1. Also, for fear of the limitation of samples, we take cities' emission intensity as the explained variables, which helps to identify specific effect on different types of cities in columns (3)-(5). The coefficients are significantly positive, showing the carbon reduction effect of polycentric spatial structure. Besides, the spatial structure poses greater impact on center cities than peripheral cities.

4.4 Mechanism analysis

From the perspective of industrial structure, the statistics show that the center cities in the urban agglomeration focus on the development of service industry, while the peripheral cities focus on the development of manufacturing industry, and there may exist a phenomenon of manufacturing enterprises moving from the center cities to the peripheral cities. The evolution of the spatial structure of urban agglomerations to polycentricity may help to form this industrial division, thus bringing energy-saving and emission reduction effects. Table 4 shows the results of mediating effect models. Columns (1), (3) and (5) demonstrate the influence of spatial structure on industrial division. The larger the spatial structure index, the more monocentric the spatial structure appears and the more similar the industrial structure presented within the urban agglomeration. the more unfavorable to the manufacturing specialization of peripheral cities; In contrast, the polycentric spatial structure helps to realize industrial division, especially the formation of manufacturing industrial agglomeration in peripheral cities. Columns (2), (4) and (6) show regression results with mediating variables. The coefficient of industry similarity and manufacture specialization is significant proving the mechanism of industrial division. In summary, in the formation of the polycentric spatial structure of urban agglomerations, the manufacturing industries in the center cities are transferred to the peripheral cities, forming the manufacturing specialization in the peripheral cities and the functional distribution within the urban agglomerations. It exists that polycentric development promotes CO2 emission reduction through the partial intermediary effect of industrial division.

Table. 3 Robustness check.

Variables	Emission intensity				
	Urban agglomerations		All cities	Center cities	Peripheral cities
	(1)	(2)	(3)	(4)	(5)
Spatial			0.0550***	0.0814**	0.0452**
			(0.0200)	(0.0400)	(0.0200)
Mono	-1.694***				
	(0.2930)				
S4		0.539***			
		(0.1060)			
Control Variables	Yes	Yes	Yes	Yes	Yes
Individual Effect	Yes	Yes	Yes	Yes	Yes
Time Effect	Yes	Yes	Yes	Yes	Yes
Observations	361	361	3,734	622	3,112
R-squared	0.91	0.908	0.881	0.911	0.878
Individual Numbers	19	19	206	33	173

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

5. Conclusions

In this paper, we attempt to investigate the impact of the spatial structure of Chinese urban agglomerations on carbon dioxide emissions, which can provide new insights for achieving carbon peaking and carbon neutrality in the context of climate change and rapid urbanization. The study measures the spatial structure of urban agglomerations with the help of nighttime lighting data. Then, combining the global atmospheric research emission database and social-economic information, the panel data of 19 urban agglomerations in China during

2000-2018 are constructed, and the influence of the spatial structure of urban agglomerations on carbon dioxide emissions and the inherent mechanisms are empirically examined.

The results show that the spatial structure of 19 urban agglomerations in China has increased and the spatial structure of coastal urban agglomerations tends to be more polycentric with more developed capital cities and port cities, which is relatively consistent with the planning objectives. This paper finds that the spatial structure of Chinese urban agglomerations does have an impact on CO2 emissions, and the polycentric spatial structure is conducive to carbon reduction. Unravelling the composition of cities within urban agglomerations, the results are still robust, and the reduction effect of polycentric spatial structure on center cities is almost twice that of peripheral cities. Therefore, the polycentric development can promote green development with much agglomeration effect. Finally, the mediating effect of industrial division is identified, which means polycentric development promotes center cities specialized in service and peripheral cities in manufacturing, then reduces carbon intensity.

Based on the results, promoting the evolution of polycentric urban agglomerations to achieve coordinated development and accelerate urbanization can realize CO2 emission reduction effect at the same time. Polycentric spatial structure should become the critical element and future goal of urban planning. However, regarding the situation that the center cities of some monocentric urban agglomerations are not yet developed, polycentricity should not be a one-size-fits-all carbon reduction strategy. We need to clarify the functional positioning of cities to achieve efficiency.

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Table. 4 Mediating effect of industrial division.

Variables	Industry Similarity (1)	Emission Intensity (2)	Manufacturing Specialization (3)	Emission Intensity (4)	Service Specialization (5)	Emission Intensity (6)
Spatial	0.0288*** (0.010)	0.136*** (0.130)	-0.251* (0.140)	0.0978* (0.050)	0.04 (0.060)	0.118** (0.050)
Similarity		4.293*** (0.730)				
Manufacturing				-0.0435** (0.020)		
Service						0.06 (0.050)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Individual Effect	Yes	Yes	Yes	Yes	Yes	Yes
Time Effect	Yes	Yes	Yes	Yes	Yes	Yes
Observations	361	361	361	361	361	361
R-squared	0.177	0.888	0.197	0.886	0.177	0.881

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1