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Polycentric spatial structure and carbon dioxide emissions: An empirical analysis based on nighttime light data

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ABSTRACT

While urbanization is driving economic development, it has caused more than 70% of global carbon emissions. Reducing urban carbon emissions is an inevitable requirement for low-carbon city construction. At the same time, in order to alleviate the urban diseases caused by urbanization, polycentric agglomeration has become a new form of urban spatial expansion. Does the polycentric spatial structure help reduce regional carbon emissions? This paper uses nighttime light data to measure the polycentricity of provincial and municipal spatial structure in China and empirically analyzes the impact of polycentric spatial structure on carbon dioxide emissions at different geographic scales. The results show that the eastern region of China presents a significant stronger trend of polycentric spatial development, while its polycentricity has significantly increases emission due to excessing optimal level. As for western areas, polycentricity on provincial distribution strengthens specialization and increases productivity to reduce carbon emissions. At the city level, polycentric spatial structure is suitable emission reduction, especially for western area. Therefore, current common polycentric spatial structure is not beneficial to emission reduction. Urban planning needs to comprehensively consider internal and external conditions. Inter-provincial cities should strengthen collaboration and specialization and avoid vicious competition. The internal development of cities can properly develop multi center and form vertical division and efficiency improvement.

Keywords: polycentric development, carbon dioxide emissions, nighttime light data, urbanization

1. Introduction

As the center of human socioeconomic activities, urban areas account for less than 3% of the earth's land surface, but produce more than 70% of the global carbon dioxide emissions (Cai and Zhang) [1]. In general, urbanization is not only a major driving force for economic development, but also a major source of carbon dioxide emissions [2]. Therefore, while maintaining economic development, curbing the use of fossil energy and carbon dioxide emissions in urban areas is a key challenge faced by governments around the world. Especially China, the world's largest emitter of carbon dioxide [3], is under pressure from international community to balance rapid urbanization and carbon dioxide emission. Identifying factors affecting carbon dioxide emission in urban areas is necessary to achieve the goal of emission reduction. Can we control emission from the perspective of adjusting city spatial structure? This is an urgent problem to be solved.

Meanwhile, under the background of rapid urbanization, traffic congestion and environmental degradation has occurred in central cities by excessive agglomeration. To reduce negative externalities, on the one hand, some people and industries moved out from the center spontaneously; on the other hand, urban planners started putting forward the transformation from single-center to polycentric spatial structure in order to reduce the burden of large central cities. Alonso (1973) first proposed the concept of borrowed size which means that the small and medium-sized cities in the polycentric urban network can share the agglomeration economic effect from the nearby large cities, while avoiding the congestion cost caused by agglomeration. Polycentric development not only conforms to the principle of agglomeration economy, but also avoid the disadvantage of single-center being too large. Therefore, policy makers have tended to adopt polycentric spatial development strategy to deal with the problems of urban and regional development. In 1999, the European Spatial Development Perspective appealed multi-center

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structure at the European level to realize the balanced development of regions. Sun et al. (2017) found that the spatial structure of most urban agglomerations in China has presented a trend of multi-center since 1980. In November 2018, the government of China emphasized the strategic policy of "strengthening the close cooperation among the cities within the region, and the central city leads the urban agglomeration and then drives the regional development", suggesting that polycentric spatial structure will become an important part of China's new urbanization.

Although there are many studies discussing about the economic performance of polycentric development pattern such as on economic performance, economic efficiency, regional income gap, but the impact of polycentric spatial structure on CO_2 emissions is not clear. Many explored the effect of urbanization and urban expansion. Bereitschaft and Debbage [4] found that under the control of land area, population and climate, urban sprawl usually showed high carbon dioxide emissions in metropolitan areas. Therefore, this study conducted an empirical analysis on the relationship between the polycentric spatial structure and carbon dioxide emission on provincial and municipal scale. Thus, we can adjust city corporation and specialization to form reasonable spatial structure to reduce emission. First of all, this study used the night light data to measure polycentric spatial structure at the level of province and city. Provincial panel data from 1997 to 2013 and city data from 2000-2012 are used to explore the polycentric spatial structure's impact on emission of carbon dioxide. We attempt to answer the following questions: What is the spatial structure of Chinese provinces and cities? Does polycentric spatial development pattern will become a new measure to reduce the emissions of carbon dioxide? We desire to explore a cleaner and low-carbon urban spatial layout to settle carbon dioxide emission issue and promote the new type of urbanization.

2. Model, variables and data specification

2.1 Models

IPAT model (Ehrlich and Holdren, 1971[5]) has been widely used in analyzing the impact of economic activity on the environment. Here, environment impact *I* is driven by population size *(P*), affluence (*A*) and technology (*T*). Based on IPAT, Dietz and Rosa (1994, 1997) [6] modified it into a random form, STIRPAT model:

$$I_i = aP_i^b A_i^c T_i^d e_i \quad (1)$$

where *I*, *P*, *A*, *T* have the same meaning as in the IPAT model; *a* is the constant term; *b*, *c* and *d* are undetermined parameters; and *e* represents the random error. After taking the logarithm form, the equation (1) turns into the model as below:

$$lnI_i = lna + blnP_i + clnA_i + dlnT_i + lne_i \quad (2)$$

Thus, *b*, *c* and *d* can be obtained by regression and referred as the percentage change in environment impact caused by a 1% change in a driver when other factors remained unchanged, which is also called elasticity in economics. STIRPAT also allow us to expand the model by adding impact factors according to specific situation and quantify their impact.

Here, we want to explore the impact of polycentric spatial structure on carbon dioxide emission. The core explanatory variable polycentric index is added, and several other important variables that can affect carbon dioxide such as industrial structure, foreign direct investment and education are also considered. The expanded model is shown as equation (3):

$$ln(emission_{it}) = \alpha + \beta poly_{it} + \gamma \ln(x_{it}) + \lambda_i + \mu_t + \varepsilon_{it} \quad (3)$$

where $emission_{it}$ denotes carbon dioxide emission per GDP of province i or city i in time t, we also used carbon dioxide emission per capita for robustness check. $Poly_{it}$ is the core explanatory variable which measure the spatial structure of provinces and cities. x_{it} is the other control variables that may affect emissions, including real GDP per capita (pgdp) and population (pop). The above two factors are likely to have a significant positive impact on energy demand through scale effect. Foreign direct investment may have an impact on carbon dioxide emissions, and foreign investment is usually concentrated in energy-intensive industries, such as the chemical industry, in which case it may have an adverse impact on the environment. In addition, foreign investment may also bring technology spillover to improve resource utilization efficiency and reduce emissions. In this paper, the share of foreign direct investment in real GDP (pfdi) represents foreign direct investment. Levels of human capital (edu) and financial development (finance) may have an impact on CO2 emissions from levels of education, environmental awareness and technology. Fixed asset investment reflects the government's investment in infrastructure construction, which is measured by the ratio of fixed asset investment to the real GDP (pinvest). λ_i is used to control provincial fixed effect. μ_t control the fixed effect of time. ε_{it} is the error term. Most importantly, coefficient β reflects the effect of polycentric spatial structure on carbon dioxide emission.

2.2 Measurement of polycentric spatial structure

Here, polycentric spatial structure shows much even distribution of people in top cities rather than only top one city. In this paper, we use rank-size rule by Meijers and Burger [7] to calculate spatial structure in terms of morphology. This method is based on the regression line slope reflecting the relationship between urban size and urban rank. The flatter slope, the more polycentric characteristics. It has been widely applied to the study of polycentric spatial structure. The specific measurement method is as follows:

$$lnP_{it} = C - qlnR_i t \quad (4)$$

From the perspective of provincial structure, in equation (4), P denotes the population of city i. C is constant and R represents the rank of population of city i in the province in year t, ranking from large to small. By regression, we are able to get coefficient q, the greater q indicates that the core city is very outstanding and the province is monocentric structure. The smaller q shows more dispersed population distribution and more polycentric structure. Considering different provinces have different numbers of cities, in order to make the polycentric indexes between provinces are more comparable, regression estimation was carried out for the top 2 to the top 4 cities, and then take the average of q as the polycentric index of each province.

To calculate spatial structure, we need each cities' population data. But registered population data in regional statistical yearbooks can not accurately reflect the size of resident population and migrant population, reducing the accuracy of using population size to calculate the polycentric index. Besides, there's problem from the adjustment of administrative divisions in the process of rapid urbanization. Administrative changes such as removal of the city and zone are frequent in the process of urbanization in China, reducing the comparability of the economic data of the same city in the years before and after. Therefore, DMSP/OLS nighttime light brightness is adopted in this paper to measure the polycentric spatial structure substituted for population data. In recent years, the application of satellite remote sensing data on the investigation to the economic problems, get the attention of more and more economists. Objective night light data not only eliminates the human the possibility of fraud, also get rid of the interference. A large number of studies have shown that night light data can be used as a regional economic development (Xu, 2015), population distribution (Liu, etc., 2017 b). Figure 1 shows nighttime light of China, 2013.

Fig1 DMSP/OLS nighttime light data of China's region in 2013

2.3 Data sources

Based on 1997-2013 provincial panel data and 2000-2012 municipal panel data, we analyze the effect of polycentric spatial structure on carbon dioxide emission. Provincial emission data is from China's carbon emissions database (CEADS). City emission data is extracted from Fossil Fuel Data Assimilation System (FFDAS) global 0.1° ×0.1° grid data. DMSP/OLS nighttime light data can be obtained from China Research Data Service Platform (CNRDS). Other economic information is obtained from China Statistical Yearbook, China City Statistical Yearbook, China Yearbook for Regional Economy, and CSMAR database. In this paper, Beijing, Shanghai, Tianjin and Chongqing were excluded, as well as prefecture-level cities in Tibet, Qinghai, Xinjiang, Hainan, Zhejiang due to missing data. And Hong Kong, Macao and Taiwan were also excluded.

3. Results and discussion

3.1 Polycentricity distribution in China

Before the empirical analysis, Figure 2 and Figure 3 respectively shows the spatial patterns of CO_2 emission and polycentric spatial structure across different provinces. The more orange color of the provinces' background indicates that there is a small gap in economic development between the top cities in this region, that is also polycentric development. Overall, the eastern costal developed areas are more polycentric. From 1997 to 2013, polycentric development mode seems to spread to inland areas. In addition, the larger green circle represents more CO_2 emission in this area. We can find that provinces with a higher level of polycentricity tend to induce greater emission. After exploring the correlation between polycentric and CO_2 emission on the provincial scale (Figure 4), we predict that provincial polycentric structure drives emission and exert negative impacts on environment.

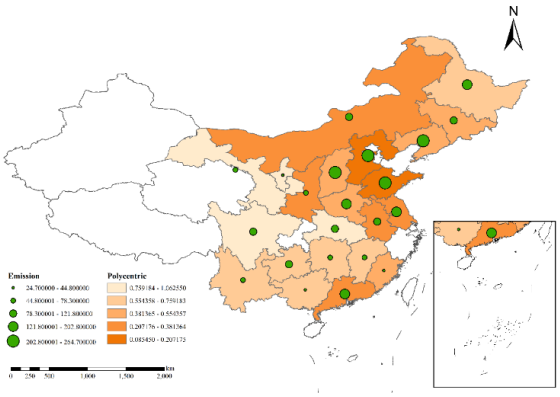

Fig2 Distribution of CO_2 emission (mt) and polycentric spatial structure in China, 1997.

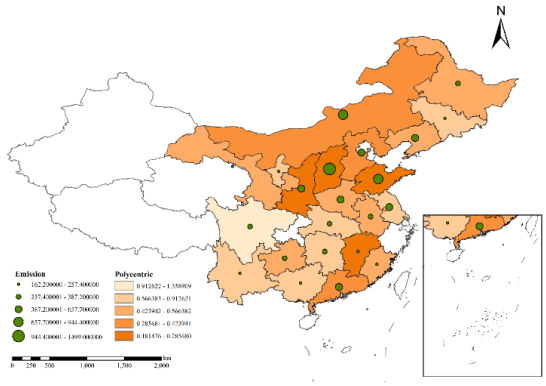

Fig3 Distribution of CO_2 emission (mt) and polycentric spatial structure in China, 2013.

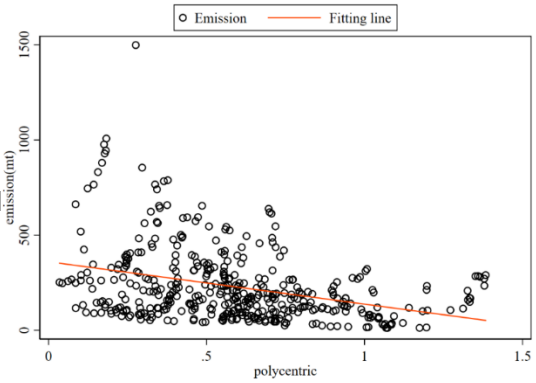

Fig4 Correlation between polycentric and CO_2 emission

3.2 Preliminary analysis

After controlling province effect and time effect, the estimation results of the fixed effects model presented in Table 1 show that index *poly* is significantly negative with emission. Higher index *poly* means the region is more monocentric. Thus, higher *poly* reduced emission and polycentric spatial structure induced more CO_2 emission which might relate to fierce competition between cities and large scale of repetitive construction. Where, columns (1) and (2) present the results of using emissions per GDP as the explained variable, and columns (3) and (4) show the results of using emissions per capita as the explained variable. After adding control variables, columns (3) and (4) show that a unit decrease in poly (more polycentric) lead to 16.1% and 16.4% increase in emission per GDP and emission per capita. Besides, economic expansion (*lnpgdp*) increases emission and high level human capital (*edu*) helps reduce emission.

Table1 Provincial baseline estimates of polycentric structure with dependent variable: Log (Emission per GDP) and Log (Emission per capita).

	(1)	(2)	(3)	(4)
VARIABLES	Emission per GDP		Emission per capita	
poly	-0.155**	-0.161**	-0.247***	-0.164**
	(0.0737)	(0.0746)	(0.0873)	(0.0759)
lnpgdp		0.196*		1.141***
		(0.106)		(0.108)
lnpop		0.133		-0.158
		(0.243)		(0.247)
second		0.0913		0.237
		(0.298)		(0.303)
pfdi		-0.483		-0.348
		(0.698)		(0.710)
edu		-10.68**		-11.60**
		(5.135)		(5.223)
finance		0.468***		0.504***
		(0.0923)		(0.0939)
pinvest		0.0711		0.0405
		(0.118)		(0.120)
Constant	1.462***	-1.849	1.093***	-8.248***
	(0.0510)	(2.330)	(0.0604)	(2.370)
Province effect	Yes	Yes	Yes	Yes
Year effect	Yes	Yes	Yes	Yes
Observations	425	424	425	424
R-squared	0.750	0.773	0.883	0.921

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

Considering heterogeneity in resource endowment, geographic condition and development pattern across different regions, we separate provinces into three groups: east, middle and west to explore the impact of polycentric structure on emission specifically in Table 2. In column (1) and (4), the coefficients of poly are significantly negative, so polycentric development enlarge emission in eastern regions. Polycentric structure also exacerbates emission in middle region but not obvious. As for western areas, positive coefficients indicate polycentric structure conduces to emission reduction. As we know, polycentric structure is more common in eastern area, so polycentric development is intensify the severity of high emission problem.

Table2 Provincial estimation with regional heterogeneity. Dependent variable: Log (Emission per GDP)

	(1)	(2)	(3)
VARIABLES	east	middle	west
poly	-0.326***	-0.144	0.154
	(0.110)	(0.239)	(0.0963)
lnpgdp	-0.547***	0.718	0.419***
	(0.164)	(0.578)	(0.134)
lnpop	-0.826***	1.498	1.103***

	(0.313)	(1.022)	(0.313)
second	0.818*	-2.156*	-0.499
	(0.445)	(1.117)	(0.477)
pfdi	-1.625***	9.357***	-2.589
	(0.581)	(3.218)	(1.572)
edu	14.67	-32.58*	-6.840
	(13.54)	(19.19)	(6.964)
finance	0.967***	-0.464	0.495***
	(0.160)	(0.375)	(0.150)
pinvest	-0.184	-0.0436	0.234
	(0.148)	(0.329)	(0.183)
Constant	12.17***	-16.12	-10.99***
	(3.058)	(10.07)	(2.887)
Year effects	Yes	Yes	Yes
Province effects	Yes	Yes	Yes
Observations	119	135	170
R-squared	0.930	0.682	0.869

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

3.3 Heterogeneity and mechanism analysis

Above, we analyze the impact of provincial structure on provincial emission. Then the relationship between provincial structure and municipal emission within provincial border is explored to understand influencing mechanism. Table 3 shows baseline estimation and regional heterogeneity. Columns (1) and (2) are results of fixed effects model for full sample. The coefficients of *poly* and $poly^2$ are respectively positive and negative at 1% level, implying there is a significant inverted U-shape relationship between index *poly* and *emission*. It also indicates that polycentric structure has a significant U-shape relationship with CO_2 emission. As the degree of polycentricity increases, emissions first decrease and then increase. This phenomenon can be explained as follows. On the one hand, in the process of China's rapid urbanization, market congestion and efficiency decline are emerging due to the excess of carrying capacity of cities. In this case, with the increase of polycentricity, the formation of a vertical division system and the promotion of industrial cooperation are conducive to achieving the improvement of energy efficiency. Thus, energy conservation and carbon dioxide emissions reduction are achieved. On the other hand, high level of polycentric spatial structure means that the development level of the major cities are too close with each other in the region, leading to more competition than cooperation between cities and impede the flow of factors and more efficient energy use. Meanwhile, blind expansion without reasonable planning lead to repetitive construction. Therefore, excessive polycentric levels in region will exacerbate carbon dioxide emissions.

According to column (3), polycentric structure also shows U-shape influence to emission in eastern area. Thus, we can speculate that negative influence of provincial polycentric to eastern emission is related to excessive polycentric levels. However, middle and western region don't show U-shape impact. Provincial polycentricity respectively increase and reduce emission in middle and west area.

Table3 Estimation of provincial polycentric structure with municipal emission and regional heterogeneity. Dependent variable: Log (Emission per capita).

VARIABLES	(1) fe	(2) fe	(3) east	(4) middle	(5) west
poly	0.423***	0.552***	-0.380***	-0.138***	0.594**
	(0.0803)	(0.0849)	(0.115)	(0.0436)	(0.289)
$poly^2$	-0.273***	-0.353***	0.582***		-0.331
	(0.0575)	(0.0635)	(0.125)		(0.207)
lnpgdp		0.228***	0.221***	0.0932***	0.320***
		(0.0220)	(0.0261)	(0.0296)	(0.0566)
lnpop		-0.657***	-0.286***	-0.648***	-0.651***
		(0.0593)	(0.109)	(0.0627)	(0.145)
second		-0.159**	-0.558***	0.269***	0.00865
		(0.0732)	(0.0917)	(0.0843)	(0.220)
pfdi2		0.0477	0.413***	0.361	-0.246
		(0.147)	(0.126)	(0.288)	(0.572)
inno2		-5.80e-05	-0.00125***	0.000757	0.00327
		(0.000343)	(0.000285)	(0.00108)	(0.00296)
edu3		3.728***	2.739***	4.145***	4.063**
		(0.450)	(0.478)	(0.523)	(1.626)
pinvest		0.0743***	0.0836***	0.0906***	0.0814*
		(0.0199)	(0.0274)	(0.0259)	(0.0488)
Constant	13.03***	14.90***	13.31***	16.07***	13.77***
	(0.0273)	(0.424)	(0.745)	(0.491)	(1.059)
Province effects	Yes	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes	Yes
Observations	3,508	3,054	1,142	1,161	751
R-squared	0.835	0.841	0.939	0.923	0.661

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

Then we explore the relationship between polycentricity and economic variables, such as GDP per capita (*pgdp*), the share of industry (*second*), goods volumn (*goods*) and passenger volumn (*passenger*). We estimated the coefficients of full sample, eastern cities, middle cities and western cities and organized the results in Table 4 which shows the direction of the change of economic factors as polycentricity is strengthening. "——" in table means the result is not significant. For full sample, polycentric development enlarges economic scale, but reduce the share of industry and the amount of goods. The number of passengers is in U-shape relationship with polycentric structure. In general, polycentric development promote the economic growth of cities and strengthen vertical division. Some cities acquire the ability to supply themselves and reduce the delivery of goods. While as polycentricity is strengthening, people will communicate more and induce transportation emission. The emission increase for full sample is majorly from the increase of economic scale and expansion of production. As for east areas, increasing industry proportion in middle and small cities might induce emission increase. In middle areas, the effect of increasing scale, lower industry share and

reducing delivery of goods are counteracted. Polycentric structure and vertical division help decrease industry share of western cities and is beneficial to abate emission.

Table4 Mechanism of polycentric on CO_2 emission on the provincial scale.

	more polycentric			
	Full sample	East	Middle	West
Total emission	↗	↗	——	↘
Scale-pgdp	↗	↘	↗	↗
Industry-second	↘	↗	↘	↘
Flow-goods	↘	U-shape,	↘	——
Flow-passenger	U-shape,	——	U-shape	↗

At last, the preliminary analysis of the impact of municipal polycentricity on emission is shown in Table 5. At the scale of city, polycentric development help reduce emission, especially for western cities, while not suitable for central areas.

Table5 Municipal baseline estimates and regional heterogeneity of polycentric with dependent variable: Log (Emission per GDP)

	(1)	(2)	(3)	(4)	(5)
VARIABLES	fe1	fe2	east	middle	west
poly	0.0683**	0.0553**	-0.00976	-0.0996***	0.173***
	(0.0273)	(0.0272)	(0.0430)	(0.0305)	(0.0669)
pgdp		-2.73e-06***	-3.06e-06***	-6.49e-06***	-5.35e-06***
		(2.69e-07)	(2.89e-07)	(6.50e-07)	(7.25e-07)
lnpop		-0.245***	0.551***	-0.223***	-0.377***
		(0.0620)	(0.116)	(0.0807)	(0.129)
second		-1.472***	-1.911***	-1.167***	-0.762***
		(0.0764)	(0.108)	(0.0913)	(0.221)
pfdi2		-0.564***	0.132	0.165	-0.250
		(0.175)	(0.162)	(0.364)	(0.583)
edu3		1.268***	1.247**	2.224***	3.629**
		(0.482)	(0.560)	(0.627)	(1.500)
pinvest		0.127***	0.135***	0.107***	0.143***
		(0.0233)	(0.0336)	(0.0340)	(0.0499)
Constant	13.53***	15.61***	11.07***	15.47***	15.95***
	(0.0193)	(0.362)	(0.699)	(0.468)	(0.739)
Province effects	Yes	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes	Yes
Observations	3,431	3,210	1,181	1,235	794
R-squared	0.736	0.779	0.843	0.880	0.710

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

4. Conclusion and policy implication

While urbanization is driving more carbon dioxide emission, it is necessary to determine if region spatial structure and city spatial structure can be a new power to reduce emission. Using the provincial panel data during 1997-2013 and municipal panel data during 2000-2012, we explore the impact of polycentric spatial structure on emission. Nighttime light data firstly helps us measure polycentricity showing eastern regions are major in polycentric development and spreading to central areas. Empirical results show that at the scale of province, polycentric development is not beneficial to emission decrease. Especially eastern areas, high polycentric structure will exacerbate emission and environmental destroy. On the contrary, western areas are suitable for polycentric development. Tracking the cause of negative influence, we find provincial polycentricity show U-shape relationship with inner city emission. Most of eastern cities may exceed the optimal polycentricity, which enlarge the competition between cities and result in energy efficiency loss. Polycentricity could lead to emission by broadening economic scale and reduce emission by decreasing the delivery of goods. As for city level, preliminary results show that city polycentricity is good for emission reduction.

The results provide several policy implications. Firstly, although polycentric spatial structure has promoted the development of surrounding cities, due to the blind expansion of the scale and fierce competition between cities, excessive polycentricity may result in an increase in carbon dioxide emissions. Therefore, polycentric development needs to fully consider the functions played by each city and combine information such as population, industrial structure, residential area. Scientific and reasonable planning is the prerequisite for construction. Secondly, Implement different policies for different regions. As for eastern cities, we need to pay attention to the optimal polycentricity and control excessive expansion. For developing areas, we can choose suitable cities and strengthen vertical division to improve energy efficiency. Thirdly, at the city level, we recommend suitable polycentric development in top 2 and 3 cities and determine city function positioning.

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