Research on Coupling and Coordination of Carbon Emissions-Economic Growth-Urban Physical Environment Three-Dimensional System

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Abstract. Smart cities and low-carbon buildings have gradually entered the public's field of vision. Realizing carbon peaking and carbon neutrality is a significant strategic choice taken by the nation to concentrate on dealing with pressing issues of resource and environmental restrictions, and is a fundamental precondition for creating a society with a shared destiny for humanity. This paper takes 36 key provincial capital cities in China as the research object, uses the emission coefficient method to measure carbon emissions, and then measures the degree to which the three-dimensional (3D) system is interrelated and coordinated of carbon emissions-economic growth-urban physical environment from the perspective of coupling and spatial evolution, and analyzes the spatial correlation of the coupling coordination degree of each province is shown. The study's findings revealed that all of our nation's provinces' 3D systems are essentially only minimally balanced and coordinated, and the spatial heterogeneity of their geographic distribution is visible. The study of spatial correlation shows that the 3D systems have a positive correlation that decreases year by year. According to the characteristics of spatial agglomeration, most provinces do not have the effect of spatial agglomeration. Then, based on the results of empirical analysis, relevant suggestions are put forward from the aspects of adjusting energy structure, promoting regional low-carbon emission reduction cooperation, and promoting structural reform of local urban industries.

Keywords: carbon emissions; economic growth; urban physical environment; coupling coordination degree; temporal and spatial differences.

1 Introduction

Urban economic growth is now progressing gradually over the world. The process of urban construction affects the physical environment of cities as well as the outward expansion of cities and towns, in addition to energy consumption and emissions. There are differences among provinces and cities in metropolitan physical surroundings, uneven economic development, and carbon emission levels, and the relationship be-

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tween them is also complicated. Studying the connection between carbon emissions, economic expansion, and the physical environment of cities is therefore crucial for realizing our country's carbon emission goals, high-quality economic development, and the construction of a green China.

Feng discovered that the degree of economic development in China's border cities is badly out of harmony with the development of the urban physical environment [1] despite research on the link between the economy and carbon emissions from both domestic and international scholars. Urban infrastructure only meets the requirements of safety, efficiency, and use, and it is difficult to meet people's growing material and cultural needs. Yuan Xiaoling found that the regional economic environment determines the shape, magnitude and location of the critical point of urban environmental output [2]. Song thinks that the establishment and enhancement of the urban physical environment are positively impacted by economic expansion in conjunction with ongoing, high-level technical investment [3]. Domestic scholar Fan found that optimizing the urban physical environment in the short term requires a certain economic price, and a good environment is a necessary factor for long-term, steady and healthy economic development [4]. Zhou found that the technological elements in economic development have an important impact on the structural changes of the urban physical environment [5]. Research scholar analyzed the interaction among technological innovation, financial development and real economy based on the dynamic space Durbin model [6]. It is challenging to fulfill both the aim of quick and sustained economic expansion and the decrease of overall carbon emissions, according to Zheng [7] and others. Mardani [8] emphasized that research on the connection between carbon emissions and economic expansion aids in the development of sensible urban energy usage strategies. According to Shahbaz [9] and others, the rise in carbon emissions brought on by economic expansion ought to be given primary attention. Domestic academics have also studied the connection between economic growth and carbon emissions in great detail. Yuan and Sun found that China is still in the stage of simultaneous growth of carbon emissions and economic development [10,11]. The problem cannot be ignored. Many researchers believe that the economic agglomeration effect of the Yangtze River Delta urban agglomeration has a direct impact on carbon emission intensity, which is promoted first and then suppressed. According to the research situation, it is very important to establish an effective three-dimensional model to explore the impact of various physical factors on urban development prospects.

2 Methodology

2.1 Three-dimensional system coupling system

In a three-dimensional system, when any subsystem cannot coordinate with other subsystems, the overall coupling coordination level will be reduced. When the three subsystems are coupled, the development level of two subsystems decreases, while the other rises, and the overall coupling coordination level decreases. Even though the levels of development are both rising or falling, if one of the subsystems grows or declines at a rate that cannot match the other two, the overall coupling coordination will decline. Also, a decoupling effect occurs when the interrelationship between two or more subsystems no longer exists. Therefore, the development level and change speed of the three subsystems of carbon emissions, economic growth and urban physical environment will affect the overall coupling coordination degree. When two subsystems are decoupled, the coupling coordination degree of the 3D system will also decrease.

2.2 Index selection

First off, fossil fuels are the resources that are used up the fastest during urban building. Fossil fuel burning will result in significant carbon dioxide production. The consumption of gasoline, kerosene, diesel, and natural gas is calculated for carbon emissions and is estimated in accordance with the accounting method proposed by the Intergovernmental Panel on Climate Change (IPCC), taking into account the types of energy consumption and the data that are available, referring to previous research, and selecting coal, coke, and crude oil.

$$CO_2 = \sum_{i=1}^{n}(E_i \times NCV_i \times CEF_i \times COF_i) \quad (1)$$

Where CO_2 is carbon emissions, n is the number of energy types, E_i is i the consumption of the first energy, NCV_i is the average heat production of energy type i, CEF_i is the carbon content of energy type i, and COF_i is the carbon oxidation factor of energy type i.

China's economy is transitioning from a high-speed expansion phase to a new normal economy phase between 2005 and 2021, and the GDP growth rate has shifted from rapid speeds to medium-high-speed. The features and patterns of the economic growth of China's major cities at different stages may be more precisely reflected when the GDP growth rate is used to gauge the country's economic growth, and reflect the time and geographical differences between the cities in a more effective way. Therefore, the GDP growth rate of China's provincial capital cities from 2005 to 2021 is adopted as the indicator for economic growth.

Therefore, the urban environmental indicator apparatus incorporates 14 secondary indicators (temperature, precipitation, industrial smoke, sewage treatment rate, urban construction level, etc.) in addition to five core indicators (climate, ambient air, air quality, sewage, built environment)., and its specific indicators are shown in Table 1.

Table 1. Physical environment index system of key cities in China

First level indicators	Secondary indicators	Indicator properties
Climate	Air temperature	just
	humidity	burden
	precipitation	burden
	sunshine	just
Ambient Air and Air Quality	sulfur dioxide	burden
	industrial dust	burden

Sewage	Sewage treatment rate	just
Energy supply	Gas penetration rate (%)	just
	Residential gas consumption per ca-pita	burden
	Comprehensive electricity consumption per ca-pita	burden
	Residential water consumption per ca-pita	burden
Built environment	Public transit	just
	green level	just
	Urban construction level	just

2.3 Comprehensive index calculation

The entropy method is used to calculate the weight, and the time variable is added to obtain the following calculation model of the comprehensive index. The first step is data standardization of positive indicators and negative indicators.

$$x'_{\theta ij} = x_{\theta ij}/x_{max} \tag{2}$$

$$x'_{\theta ij} = x\theta ij_{min} \tag{3}$$

Where $x'_{\theta ij}$ is the jth index value of province i in year. $x_{\max}$is the maximum value of a certain index, and $x_{\min}$ is the minimum value of a certain index.

Then, determining the weight of a certain province's data in a certain year in a certain indicator $y_{\theta \mathrm{ij}}$:

$$y_{\theta ij} = x_{\theta ij}/\sum_{\theta}\sum_{i} x'_{\theta ij} \tag{4}$$

Thirdly, determining j the entropy value of the item index e_j:

$$e_j = -\ln(rn)\sum_{\theta}\sum_{i} y_{ij} \ln\left(y_{\theta ij}\right) \tag{5}$$

r is the amount of time in years, n is a count of provinces.

Fifthly, determining j the initial indicator's value for information usefulness h_j:

$$h_j = 1 - e_j \tag{6}$$

Fifthly, determining the weight of each indicator w_j:

$$w_j = h_j/\sum_j h_j \tag{7}$$

Finally, determining the composite index $S_{\theta i}$:

$$S_{\theta i} = \sum_j\left(w_j x'_{\theta ij}\right) \tag{8}$$

The investigation, which excludes the Tibetan plateau, Hong Kong, Macao, and Taiwan, analyzes information obtained from 36 important Chinese cities from 2005 to 2021 primarily because of its scientific validity and data availability. The primary data sources are the *China Environmental Statistical Yearbook*, *China Energy Statistical Yearbook* and *China Statistical Yearbook* from 2006 to 2020 since the most recent statistics yearbook is 2022.

3 Model building

Firstly, the coupling coordination degree model is constructed to calculate the coupling coordination degree of each province from 2005 to 2021. Secondly, a spatial econometric model is constructed to analyze whether the coupling coordination degree of each province has spatial correlation and spatial aggregation effects.

3.1 Construction of coupling coordination degree model

The magnitude of linkage coherence may simultaneously assess the amount of coordination and determine if the system achieves coordination via the process of mutual influence. The particular stages for building the three-dimensional coupling degrees of coordination model of carbon emission, economic growth, and urban physical environment are as follows:

Establish a carbon emission-economic growth-ecological environment coupling model, and calculate the coupling degree C:

$$C = \left\{ \frac{U_1 U_2 U_3}{\frac{(U_1+U_2+U_3)}{3}} \right\}^{\frac{1}{3}} \tag{9}$$

In the formula (9), C represents how tightly the two are linked. U_1、U_2、U_3 represents the encompassing indices of economic growth, the exhaustive index of urban physical environment, and the comprehensive gauge of carbon emissions in each province, in that order.

(1)Generate a blueprint for ensuring the coordination of the relationships between carbon emissions, economic growth, and the environment, and determine the coupling degree D:

$$T = \alpha U_1 + \beta U_2 + \lambda U_3 \tag{10}$$

$$D = \sqrt{CT} \tag{11}$$

In the formula: T is the indicator of cooperation, α、β、λ and is the importance of greenhouse gas emissions, economic development, and environmental sustainability, order $\alpha = \beta = \lambda = 1/3$ [12]. The coupling coordination degree of the 3D system is divided into 8 stages, and 8 different coordination levels are given, the specific classification is listed in Table 2.

Table 2. Coupling coordination degree and classification of carbon emission-economic growth-urban physical environment

Grade	Coupling coordination degree D	coordination level
1	$0.8 < D \leq 1$	High quality coordination
2	$0.7 < D \leq 0.8$	well coordinated
3	$0.6 < D \leq 0.7$	medium coordination
4	$0.5 < D \leq 0.6$	mild coordination
5	$0.4 < D \leq 0.5$	Barely coordinated
6	$0.3 < D \leq 0.4$	mild disorder
7	$0.2 < D \leq 0.3$	moderate disorder
8	$0 \leq D \leq 0.2$	severe disorder

3.2 Geographical economics and statistics algorithm construction

The geographic auto-correlation model may quantify a variable's spatial aggregation properties. This paper is mainly used to analyze the spatial dependence or relationship between the coupling coordination degree of the three-dimensional system of carbon emissions, economic growth, and urban physical environment among provinces and the geographic location of each province's degree of spatial association. In this paper, the global Moran's I index is used to judge whether there is the spatial correlation in each province. The specific formula is:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(X_I-\bar{X})(X_j-\bar{X})}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(X_i-\bar{X})^2} \tag{12}$$

Where n represents the number of provinces, x_i, x_j is the coupled province i to j province coordination, w_{ij} is the average value, $\overline{x}$ is the spatial weight matrix, and the range of Moran's I is [-1, 1].

The Moran indices may be utilized to determine if a model has spatial association, since it can measure how comparable attribute metrics for physically neighboring or nearby area units are.

3.3 Lagrangian multiplier test and Hausman test

The robust LM-Lag and robust LM-Error tests, as well as the maximum likelihood LM-Lag and LM-Error tests, have been incorporated in the unified LM trial. The four types of statistical analyses mentioned above are subject to the Chi-square distribution with one degree of freedom.

The likelihood ratio (LM) test is then run based on the acquired residue from the ols regression, which is used to determine the regression algorithm's residual. The primary objective of the LM examination is to determine if the spatial economic framework can be broken down into a spatial error model and a spatial auto-regressive model. Results of computation are displayed in Table 3 below.

Table 3. Joint LM test and Hausman test

test	test result	P value
LM-Lag test	276.8548	0.00445
Robust LM-lag test	48.54354	0.00125
LM-Error test	284.7435	0.00000
Robust LM-Error test	0.154	0.69500
Hausman test	1597.75356	0.00010

The experimental findings show that the resilient LM-Lag test, robust LM-Lag test, and robust LM-Error test do not show any meaningful outcomes, but the LM-Error test is significant. This result shows that the spatial econometric model established above cannot be reduced to a spatial lag model, so the spatial autocorrelation model was finally chosen as the main model of this study. The purpose of the Hausman test is mainly to determine whether the spatial model chooses fixed effects or random effects. The experiment's score eliminates the spatially distributed random variation since the Hausman statistic's result is less than 0.05. Therefore, the analysis will establish a fixed effect and explain it in detail from different situations such as fixed space, fixed time, and double fixed effects of space and time.

4 Research results analysis

From 2005 to 2012, my country's GDP growth rate exceeded 10%, and economic accumulation increased rapidly. From 2013 to 2019, the development speed gradually slowed down, but the economic volume continued to increase. From 2020 to 2021, affected by the epidemic and the global economic depression. The impact has entered a new normal period of economic development.

This study employs both the regional and global Moran indices to assess the geographic association of the three-dimensional system of carbon dioxide emissions, economic expansion, and urban physical surroundings, and ultimately comes to the following conclusions.

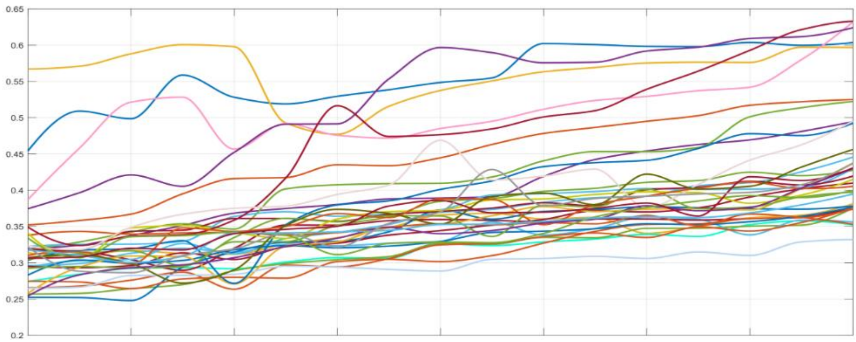

Fig. 1. Change curve of physical environment score of 36 cities in China from 2005 to 2021

As shown in Figure 1, the comprehensive index of economic growth shows a downward trend, while the thorough catalogue of cities and the thorough catalogue of carbon emissions rise. The former has a large increase while the latter has a small increase. This is consistent with the slowdown of China's economic growth, the continuous optimization of the urban environment, and the promotion of the implementation of energy conservation and emission reduction policies.

Figure 2 shows that the general coupling synchronization level is rather low. The regional disparity in the degree of coupling coordination has shrunk from the time of great-speed expansion in the economy to that of the socioeconomic new normal, and the level of coupling coordination has demonstrated the characteristics of growing first and then declining, high in the eastern region and low in the western part of the country. The quantity of coupling and coordination has decreased in some provinces, which may be attributed to modifications in the structure of industry, the decoupling of emissions of carbon dioxide, as well as shifts in regional economic growth patterns. (Calculations are made at intervals of four years)

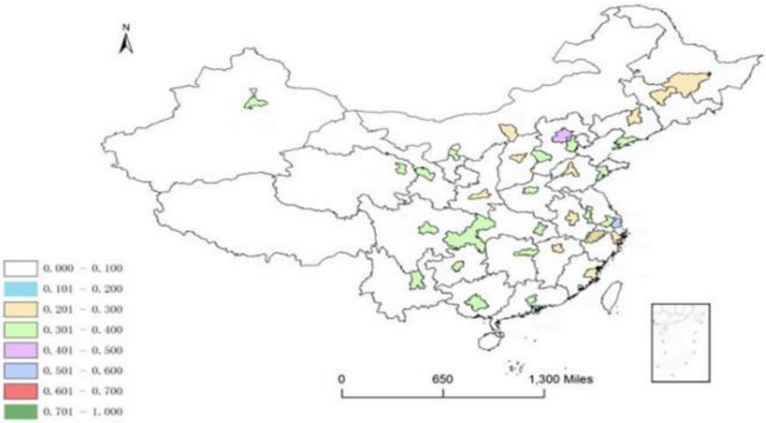

Fig. 2. Legend of the distribution of coupling coordination degrees in 36 cities in China in 2021

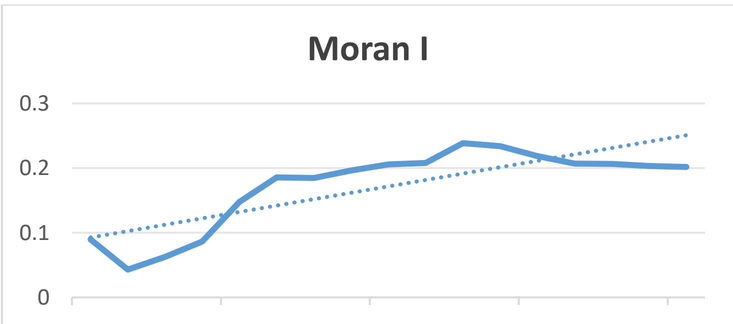

Fig. 3. Global Moran index trend chart

From the analysis of the Moran index in Figure 3, it can be concluded that the coupling coordination degree of the three-dimensional system is positively correlated, but the spatial correlation shows a downward trend with the continuous advancement of social and economic structural reforms. In terms of spatial dimension, the score distribution in the whole region generally presents a nebula-like distribution pattern, and there is no extreme differentiation. Major provincial capital cities are symbolized by the urban agglomerations in the middle ranges of the Yangtze River, the valley of the Pearl River, Beijing-Tianjin-Hebei, and the rest of the Yangtze River Delta. They are located in the middle of a highly valuable nebula-shaped region, which progressively extends to the edges. At the same time, it changes from the east and southeast to the inland overall balanced distribution. This may be mainly due to strong government support, rapid economic development, and rapid expansion of the built environment. The coupling and coordination degree of cities in old industrial production centers has been increasing in recent years, which shows to a certain extent that the development of these areas no longer pursues GDP growth one-sidedly. There is no agglomeration effect in most provinces. The possible reason is that the economic and social factors affecting carbon emissions are complex, and it is one-sided to only consider the impact of economic growth and the urban physical environment on them. The decoupling effect of carbon emissions on some provinces' revenue growth and the low coordination and cohabitation intensity of the three-dimensional in form system, which has minimal bearing on adjacent provinces, could have been the causes. As a result, there is no aggregation effect.

5 Conclusion

The three-dimensional in nature linkage coordination level of important Chinese cities is typically rising, according to the preceding studies and investigations, and the overall distribution pattern is favorable in the east compared with low in the west. The coupling coordination degree is out of equilibrium in some places, and its coordination degree characteristics decrease from the south towards the north. The fundamental asymmetry of the local manufacturing sector may be a factor.

At present, the three-dimensional coupling system of carbon emissions-economic growth-urban physical environment is still in its infancy. In order to figure out the overall coherence of the model in this paper, simply the global Moran's equation I index is evaluated on the multidimensional linking data. The regional Moran index analysis is not carried out on the local special details in order to obtain the specifics of the interaction coordination degree. Further studies might reinforce this aspect of the theoretical framework. Secondly, this paper focuses on the establishment of the overall three-dimensional model, which can be demonstrated with diagrams or processes in the actual detailed description process to make the data more intuitive. Last but not least, the overview of economic indicators in this article is relatively general. In future research, the economic indicator system needs to be discussed in detail to clarify the positive and negative impact of indicators at all levels on the coupling degree.

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