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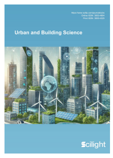

Article

Research on the Associations and Indicative Thresholds of Urban Density on Carbon Performance: A Case Study of Chengdu-Chongqing Urban Agglomeration

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Abstract: Carbon emissions affect sustainable urban development, and cities are the main carbon emission factors. To improve carbon performance from the perspective of urban density, the temporal and spatial evolution characteristics and associations, and indicative thresholds of urban density and carbon performance in the Chengdu-Chongqing urban agglomeration are analyzed by combining Slack Based Measure-Data Envelopment Analysis (SBM-DEA), Standard Deviation Ellipse Analysis, Regression Model, and Spatial Autocorrelation in this paper. The results show that: (1) there is no obvious trend in population density, road density increases faster than building density, and carbon performance shows a decreasing and then increasing trend. (2) The center of gravity of building density and population density migrates towards Chengdu-Chongqing. The road density develops in the southwest-northeast direction, and the spatial pattern of carbon performance shows the characteristic of "high in the southwest and low in the northeast". (3) The building density, population density, road density, and carbon performance show an upward curve, an "N" curve, and an inverted "N" curve, respectively, and the order of influence is building density > road density > population density. (4) There is a positive spatial correlation between urban density and carbon performance in the Chengdu-Chongqing urban agglomeration, but it is not uniformly distributed, and there is a phenomenon of clustering in specific local areas, especially in the core city areas such as Chengdu.

Keywords: urban density; carbon performance; associations and indicative thresholds; Chengdu-Chongqing urban agglomeration; standard deviation ellipse; polynomial regression; bivariate spatial autocorrelation

1. Introduction

With the rapid growth of the global economy, serious damage has been caused to the environment, particularly climate change caused by carbon emissions. Reducing carbon emissions is critical to achieving global sustainable development goals, and countries are taking measures to promote the growth of low-carbon cities in response to global climate change [1]. Cities are a major source of global carbon emissions, contributing about 75% of the world's energy consumption and 85% of greenhouse gas emissions, and play an important role in low-carbon urban development, as they are home to a large number of people and economic activities [2,3]. In 2020, General Secretary Xi Jinping proposed a "dual-carbon" goal at the 75th session of the UN General Assembly, i.e., "strive to peak carbon dioxide emissions by 2030 and strive to achieve carbon neutrality by 2060", providing a clear direction and target for the low-carbon transformation of Chinese cities. The concept of "people's city" has brought urban development to a new level, emphasizing the need to improve the efficiency of resource utilization, guide the green transformation of economic and social structures, and fundamentally realize the harmonious coexistence of human beings and nature [4].

However, the acceleration of the urbanization process leads to the continuous agglomeration and proliferation of population, economy, and industry in cities, which triggers the increase of urban density and the tension of land resources, and the contradiction with the ecological environment and the sustainable development of cities is becoming increasingly prominent. Urban density, as an important indicator of urban construction and development, is also a key factor affecting the low-carbon development of cities [5]. According to data released by China's National Bureau of Statistics, the urbanization rate of China's resident population reached 66.16% at the end of 2023, an increase of 55.52 percentage points from the end of 1949, and an average annual increase of 0.75 percentage points. This increase indicates that China has experienced the largest and fastest urbanization process in world history. Along with the increase in urban population, the built-up urban area has expanded significantly, from 7438 square kilometers in 1981 to 62,038 square kilometers in 2023, an increase of 7.3 times. This rapid urban expansion induced problems such as the strain on land resources, the disorderly spread of urban built-up land, the pollution of resources and the environment, and the trend of urban transformation from low density to high density is inevitable. Therefore, under the dual-carbon goal, analyzing the associations and indicative thresholds of urban density on carbon performance, rationally optimizing the urban spatial structure and land use, and guiding cities to shift from rough development to compact and intensive development are important means of achieving sustainable development between the economy and the environment.

At present, urban density is defined on a relatively solid theoretical basis and is typically measured using a variety of indicators such as population density, economic density, residential density, and so on [6–8]. In the process of exploring the development of low-carbon cities, studies have confirmed that the low-density urban development model is not conducive to energy conservation and emission reduction, and excessive high-density development will also bring a series of heat island effects [5,9]. In recent years, there have been studies discussing urban density from different perspectives around carbon emission intensity, for example, Hong et al. analyzed the relationship between carbon emissions and urban population size and density by using multiple carbon sources, found that there is a left-low-right-high W-shape between urban size and total carbon emissions, and a U-shape with residential carbon emissions [10]. Yang and Takase found that a road network with lower density and abundant branch streets may not necessarily promote the reduction of carbon dioxide emissions [11]. Zheng et al. used residential density as a proxy variable for urban spatial pattern to confirm that an increase in residential density can play a population agglomeration effect and effectively reduce carbon emissions in cities and towns [12].

Performance is a means used by enterprises to evaluate production efficiency employee productivity, and development benefits. With the on-going development, performance is also used to evaluate the spatial development benefits of cities. Most of the research on carbon performance focuses on the fields of urban construction, enterprise management and public energy-saving buildings. For example, Wang et al. found that assembled buildings have a positive impact on carbon performance by improving labor productivity, optimizing resource allocation and improving material utilization using the double-difference method [13]. Yuan et al. found that the level of science and technology, regional economic scale and carbon performance were significantly positively correlated, and government intervention in the economy was negatively correlated with carbon performance [14]. Feng and Zhou explored the main spatial structure and influence weights affecting carbon performance, which were mainly associated with urban density, functional structure, land use, and transportation structure [15].

Previous research has primarily explored the relationship between urban density and carbon emissions from social and economic perspectives, or the relationship between spatial compactness, management policies, and carbon performance from the perspective of spatial layout and management. Additionally, the impact of urban density on carbon performance has primarily been examined from the perspectives of building density, population density, and economic density. Although population density, economic density, and building density are the primary focus of research on the relationship between urban density and carbon performance, there is still an opportunity for improvement in the understanding of how urban density affects carbon performance [16]. Regions, such as the Yangtze River Delta, Yangtze River Economic Belt, and Beijing-Tianjin-Hebei urban agglomeration, have a high level of urban development, and urban density tends to stabilize. The Chengdu-Chongqing urban agglomeration, as one of the most dynamic and development-potential economic regions in western China, shows diversified characteristics of urban density, with obvious differences between different cities, and there is still room for improvement in the selection of typical research areas. In summary, this study takes the Chengdu-Chongqing urban agglomeration in central and western China as a case example. Adopting a dynamic perspective spanning 2012 to 2021, it constructs a joint analysis of urban density indicators and carbon performance based on three dimensions: building density, population density, and road density. This research provides scientific evidence for urban development and carbon reduction policies in the Chengdu-Chongqing economic circle and other similar regions, thereby promoting sustainable urban development and advancing the achievement of carbon neutrality goals.

2. Materials and Methods

2.1. Study Area

The study area is the 16 cities involved in the Chengdu-Chongqing urban agglomeration (Figure 1), including the 15 cities of Chengdu, Deyang, Mianyang, Nanchong, Suining, Ziyang, Neijiang, Zigong, Yibin, Luzhou, Leshan, Ya'an, Meishan, Guang'an and Dazhou in Sichuan Province, as well as Chongqing Municipality, without distinguishing whether or not the cities are fully included in the planning scope of the city cluster.

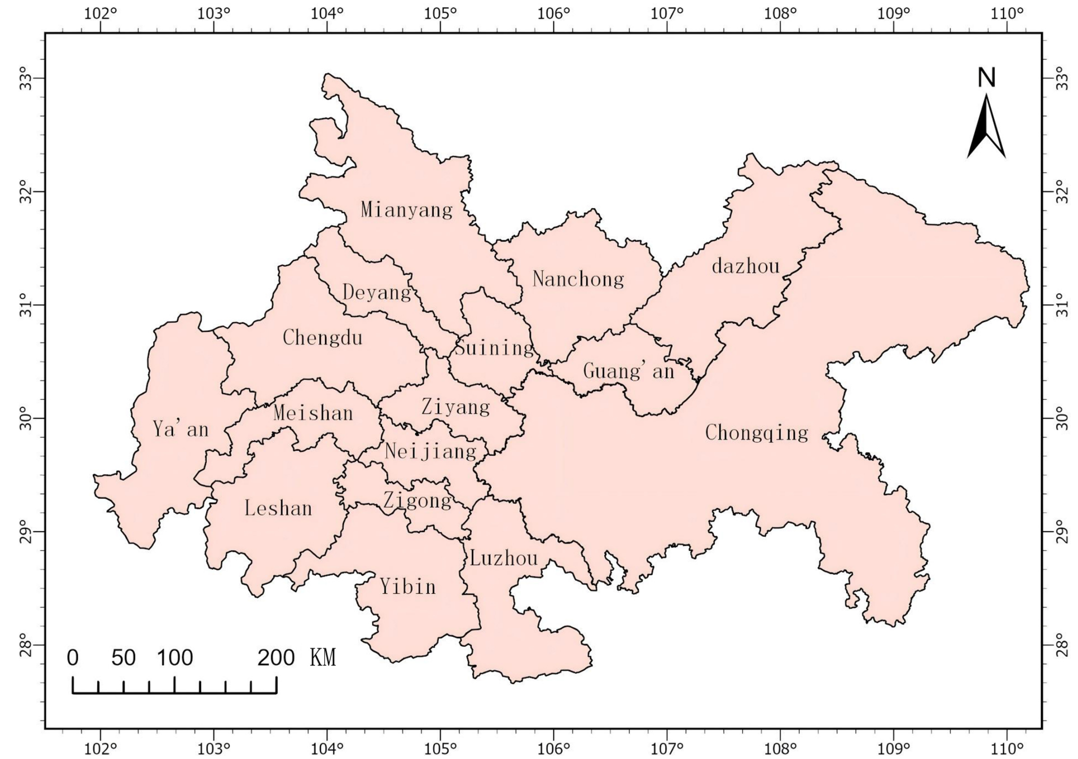


Figure 1. Scope of research (Chengdu-Chongqing urban agglomeration, China). (The map is based on the standard map No. GS (2024) 0650 downloaded from the website of the Standard Map Service of the Ministry of Natural Resources, with no modifications to the base map).

2.2. Research Process

This study aims to analyze the impact of the evolution of urban density and spatial correlation characteristics of the Chengdu-Chongqing urban agglomeration on carbon performance, and puts forward the following research content: (1) Constructing a database of the study area from 2012 to 2021, and analyzing the status quo of the evolution characteristics of urban density and carbon performance in terms of spatio-temporal evolution, respectively. (2) Identifying the correlation between urban density and carbon performance through the change characteristics, and exploring the spatial aggregation or spatial anomalies of the elements of the research object, and identify the spatial correlation between urban density and carbon performance in the whole domain. (3) Based on the analysis results, propose the spatial planning strategy of a low-carbon city based on urban density. The research approach, which can be applied to any city, is illustrated in Figure 2.

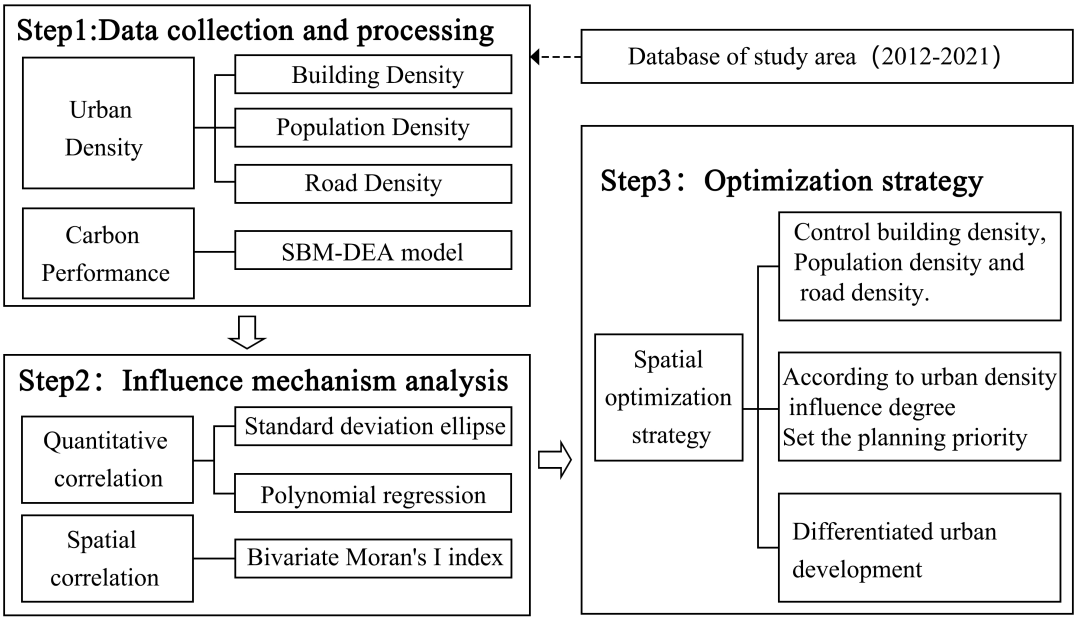


Figure 2. Flow chart of research approach.

2.3. Data Sources

Carbon emissions data and, capital stock data were obtained from China Statistical Yearbook, statistical yearbooks at all levels [17] and the Guidelines for National Greenhouse Gas Emission Inventories published by the IPCC [18], GDP per capita from Sichuan Statistical Yearbook [19], and Chongqing Statistical Yearbook [20]. Data on construction land area, urban population, road length, urban area, greening coverage rate of built-up areas, etc. were derived from the Statistical Yearbook of Urban Construction [21].

2.4. Research Method

2.4.1. Methods for Calculating Carbon Performance

Based on the ecological and economic perspective, carbon performance measures the relationship between resource inputs and outputs from the social, economic, environmental, and spatial levels as a whole, and demonstrates the impact of carbon emission intensity generated by resource factor inputs on the environment. Data Envelopment Analysis (DEA) is a nonparametric assessment method, that is used to evaluate the relative effectiveness of complex decision units with multiple input and output indicators [22]. However, when the decision unit is over-input or under-output, the traditional DEA model overestimates the efficiency value of the decision unit, which makes the calculation results inconsistent with the objective reality. The Slack-Based Measure (SBM) model is a good solution to the above problems. The non-radial SBM model under output orientation focuses on maximizing desired outputs while minimizing undesired outputs (CO_2 emissions) without increasing inputs, aligning more closely with cities' pursuit of low-carbon development goals. To more accurately assess the input-output efficiency of decision-making units, assuming variable returns to scale better aligns with the reality that cities within a city cluster are at different stages of development and exhibit varying economies of scale. The Slack-Based Measure-Data Envelopment Analysis (SBM-DEA) based on the data envelopment analysis method is:

$$\rho^* = min\frac{1-\frac{1}{N}\sum_1^N \frac{s_n^x}{x_{kn}^t}}{1+\frac{1}{M+1}\left(\sum_1^M \frac{s_m^y}{y_{km}^t}+\sum_1^I \frac{s_i^b}{b_{ki}^t}\right)}$$

$$s.t\begin{cases}\sum_{k=1}^{K} z_k^t x_{kn}^t + s_n^x = x_{kn}^t, n = 1,2,3\ldots\ldots N;\\ \sum_{k=1}^{K} z_k^t y_{km}^t - s_m^y = y_{km}^t, m = 1,2,3\ldots\ldots M;\\ \sum_{k=1}^{K} z_k^t b_{ki}^t - s_i^b = b_{ki}^t, i = 1,2,3\ldots\ldots I;\end{cases} \quad (1)$$

$$z_k^t \geq 0, s_n^x \geq 0, s_m^y \geq 0, s_i^b \geq 0, k = 1$$

where x_{kn}^t, y_{km}^t, b_{ki}^t are input and output values in period t, s_n^x, s_m^y, s_i^b are slack variable of input-output. ρ^* denotes carbon performance, The higher the value, the better the carbon performance, and the higher the degree of achievement of the city's low-carbon goal. The 16 cities in the Chengdu-Chongqing urban agglomeration are the decision-making units, and the input indicators are urban construction area, labor population, capital stock and energy consumption, the output indicators are per capita gross domestic product (GDP), green coverage of built-up areas, and carbon emission is the undesirable output [23,24] (Table 1). Carbon emissions calculations employ the internationally recognized "scope" verification methodology, comprehensively covering emissions from transportation and buildings, industrial production processes, agriculture, forestry, and land-use changes, waste management activities, purchased electricity, heating and cooling, as well as other indirect emissions [25].

Table 1. Carbon performance input-output index system.

First Index	Second Index	Variable Declaration
Input	Land	Urban construction land area (km^2)
	Manpower	Urban employment at the end of the year (million people)
	Capital	Urban capital stock (ton)
	Energy Source	Total consumption of electricity, coal, natural gas and Liquefied Petroleum (million tons of standard coal)
Expected Output	Economic Benefit	Per capita GDP (yuan)
	Ecological Benefit	Green coverage rate of built district
Undesirable Output	Carbon Emission	CO_2 emissions (million tons)

2.4.2. Urban Density Index Calculation Method

Building density reflects the degree of intensive urban land use, and increasing building density can optimize living space and shorten commuting distance, which indirectly reduces carbon emissions. Population density is an indicator of the sparseness of urban population distribution, and areas with high population density tend to imply a more compact urban form, which may affect traffic patterns, energy consumption, and the level of carbon emissions. Road density, as a key component of urban infrastructure, is directly influenced by urban traffic flow, traffic patterns, travel efficiency, and urban planning. High-density urban areas with reasonable road density will help to realize the efficient use and sharing of resources and reduce the overall level of carbon emissions. Therefore, we use building density, population density and road density to construct an urban density index, and the specific calculation method is as follows:

(1) Building Density (BD) = (Built-up area/Urban area) × 100% (%)
(2) Population Density (PD) = (Urban population + urban temporary population)/Urban area (Thousands of people/100 km^2)
(3) Road Density (RD) = Road length/built-up area (km/km^2)

2.4.3. Spatio-Temporal Characteristics

The standard deviation ellipse can reflect the spatial distribution pattern and temporal and spatial evolution characteristics of the elements. The gravity center migration, distribution direction and range change of urban density and carbon performance in space are described by gravity center coordinates, long and short axes and other parameters [26].

The calculation formula of ellipse barycenter coordinate is:

$$ZZP(X,Y) = \left(\frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}, \frac{\sum_{i=1}^{n} w_i y_i}{\sum_{i=1}^{n} w_i}\right) \tag{2}$$

where n is the city number of Chengdu-Chongqing urban agglomeration, x_i and y_i are the central coordinates of each city, and w_i is the weight value of each city factor.

$$Tan\alpha = \frac{\left(\sum_{i=1}^{n} w_i^2 \overline{x_i}^2 - \sum_{i=1}^{n} w_i^2 \overline{y_i}^2\right)}{2\sum_{i=1}^{n} w_i^2 x_i y_i} + \frac{\sqrt{\left(\sum_{i=1}^{n} w_i^2 \overline{x_i}^2 - \sum_{i=1}^{n} w_i^2 \overline{y_1}^2\right)^2 + 4\sum_{i=1}^{n} w_i^2 \overline{x_i}^2 \overline{y_i}^2}}{2\sum_{i=1}^{n} w_i^2 x_i y_i} \tag{3}$$

where α refers to the angle formed by the clockwise rotation of the north to the long axis of the ellipse $\overline{x_i}^2$ and is the deviation between the coordinates of the first city and the coordinates of the center of gravity.

The calculation formula of x-axis and y-axis length is:

$$\sigma_x = \sqrt{\frac{\sum_{i=1}^{n}(w_i\overline{x_i}\cos\alpha - w_i\overline{y_i}\sin\alpha)^2}{\sum_{i=1}^{n} w_i^2}}, \sigma_y = \sqrt{\frac{\sum_{i=1}^{n}(w_i\overline{x_i}\sin\alpha - w_i\overline{y_i}\cos\alpha)^2}{\sum_{i=1}^{n} w_i^2}} \tag{4}$$

2.4.4. Quantitative Correlation

There are many linear possibilities in the correlation between urban density and carbon performance. In order to accurately verify the functional relationship characteristics, a polynomial function relationship model is established. The spatial density is included in the regression model as an independent variable, and the curve fitting is performed. Compared to the log-linear model, the general polynomial function model demonstrates superior fitting performance, effectively capturing the relationship between data distribution and class thresholds [27]:

$$Y = a + b_1X + b_2X^2 + b_3X^3 + \cdots + \beta \tag{5}$$

where Y is carbon performance, X is urban density factor index (building density, population density, road density), a is a constant term. b_1, b_2, b_3 represent the coefficients of the first, second and third terms of x, respectively, and β is the random error term.

To avoid the problem of multicollinearity among building density, population density and road density, PLS is used for comprehensive regression analysis. The multivariate linear regression analysis, canonical correlation analysis between variables, and principal component analysis are combined, and the fitting effect is good.

$$\rho^* = aBD + bPD + cRD + \varepsilon \tag{6}$$

where ρ^* represents carbon performance, BD is the building density, PD is the population density, RD is the road density, a, b, c are the regression coefficients, ε is the constant.

2.4.5. Spatial Correlation

The bivariate Moran's I index is used as an indicator of spatial autocorrelation analysis to study the spatial relationship between urban density elements and urban carbon performance. The bivariate global Moran index can directly reflect the overall similarity of the spatial adjacent unit area. The local Moran index explores the specific correlation characteristics of the space from the regional scale and identifies the spatial aggregation or spatial anomalies of the research object elements [28]. In this study, a contiguity-based spatial weight matrix (Queen's case, considering both shared edges and vertices) was employed. The raw binary contiguity matrix was row-standardized so that the weights for each city's neighbors sum to 1. This approach gives equal aggregate weight to all cities regardless of their number of neighbors, facilitating the interpretation of spatial lag coefficients. Its calculation formula is:

$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \overline{x})(x_j - \overline{x})}{S^2 \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \tag{7}$$

$$I_i = \frac{(x_i - \overline{x})\sum_{j=1}^{n} w_{ij}(x_i - \overline{x})}{s^2} \tag{8}$$

where I is the global Moran's I index, I_i is the local Moran's I index. In this study, the urban density factor is used as the independent variable and the carbon performance is the dependent variable. n is the number of samples, $\overline{x}$ is the average value of the attribute value, w_{ij} is the spatial weight matrix, s^2 is variance. The global Moran's I index is in the range of $[-1,1]$. If $I < 0$, it indicates that there is a negative spatial correlation, that is, the change trend of urban density and carbon performance of neighboring cities is opposite. If $I > 0$, it indicates that there is a positive spatial correlation, that is, urban density has the same change trend as its neighboring cities' carbon performance. If $I = 0$, then no spatial correlation exists. The local spatial correlation is represented by the LISA clustering diagram, which is divided into high-high aggregation, high-low aggregation, low-high aggregation and low-low aggregation according to the spatial distribution relationship.

3. Results

3.1. Spatial and Temporal Evolution of Urban Density and Carbon Performance

3.1.1. Spatial Evolution of Urban Density and Carbon Performance

The center of gravity-standard deviation ellipse method is used to analyze the spatial migration trajectory of the center of gravity of urban density and carbon performance in the Chengdu-Chongqing urban agglomeration, with four cross-sectional data points in 2012, 2015, 2018 and 2021 as the research samples (Figure 3). The center of gravity of building density and population density both migrated first towards Chengdu and then gradually towards Chongqing in 2012–2021, indicating that the rapid development of Chengdu's economy attracted more population and industries to gather in the early period, and with the construction of the Chengdu-Chongqing twin-city economic circle, it promoted the development of cities around Chengdu-Chongqing, which in turn affected the migration direction of the center of gravity of urban density. The migration of the center of gravity of road density from the southwest to the northeast in 2012–2021 indicates that the road systems of Chengdu and Chongqing have been relatively perfect, mainly radiating and driving the construction of roads in the surrounding cities. Cities in the southwest direction are located in the Sichuan Basin and the mountainous excesses of southwest China, and are subject to the influence of topography, which makes it difficult to build roads, while emerging industries and technology enterprises gather in the northeast, and the increase of economic activities drives the construction of transport and other infrastructures, which results in the movement of the center of gravity in the northeast direction of road density. The center of gravity moves to the northeast. The center of gravity of carbon performance gradually migrates to the southwest in 2012–2021, mainly because Chongqing municipality invests less in land and labor capital factors, and more non-desired output factors in the jurisdiction, resulting in lower carbon performance in Chongqing municipality, and the northeastern Chengdu-Chongqing urban agglomeration is the eastern Sichuan economic zone, with high energy consuming machinery, energy, natural gas, and petrochemical industry related supporting industries, which have a low level of carbon performance enhancement. Meishan, Leshan, Yibin and other cities in the southwestern region, with tourism and ecological agriculture as their pillars, are rich in ecological resources and have strong carbon sinks, so their carbon performance improves faster, which makes the carbon performance of the Chengdu-Chongqing urban agglomeration show a pattern of "high in the southwest and low in the northeast".

From the perspective of ellipse azimuth, building density and population density have the same trend of evolution, with the long axis becoming shorter and the short axis becoming longer, and there is a trend of balanced development in the region, with the angle of building density varying from 76.587° to 82.005° and the angle of population density varying from 77.098° to 80.956°, which is gradually close to Chongqing municipality and consistent with the direction of the center of gravity migration. The standard deviation of the long axis of the road density ellipse increases from 1.885 km to 2.003 km, the standard deviation of the short axis decreases from 1.267 km to 1.209 km, and the difference between the short and long axes becomes larger, and the angle changes to the northeast, and it tends to strengthen the development of the spatial pattern to the southwest-northeast. The short axis of carbon performance becomes longer, the long axis becomes shorter, the spatial distribution area increases, the difference between the carbon performance level of marginal cities and core cities decreases, and the difference in the regional carbon performance level gradually narrows (Table 2).

Table 2. Standard deviation ellipse parameters.

Time		Areal Coordinates		Standard Deviation along the X-Axis/km	Standard Deviation along the Y-Axis/km	Rotation Angle of the Ellipse Relative to the X-Axis (°)
		°E	°N			
Building Density	2012	105.123	30.436	1.955	1.277	76.587
	2015	105.123	30.359	1.571	1.282	94.185
	2018	105.123	30.261	1.653	1.303	88.398
	2021	105.123	30.256	1.701	1.339	82.005
Population Density	2012	105.123	30.304	1.891	1.25	77.098
	2015	105.123	30.291	1.725	1.264	83.353
	2018	105.123	30.225	1.744	1.27	80.957
	2021	105.123	30.246	1.763	1.298	80.946
Road Density	2012	105.123	30.066	1.885	1.267	75.315
	2015	105.123	30.042	1.867	1.237	76.037
	2018	105.123	30.089	1.946	1.258	73.006
	2021	105.123	30.118	2.003	1.209	73.901

Table 2. *Cont.*

Time		Areal Coordinates		Standard Deviation along the X-Axis/km	Standard Deviation along the Y-Axis/km	Rotation Angle of the Ellipse Relative to the X-Axis (°)
		°E	°N			
Carbon Performance	2012	105.123	30.097	1.884	1.124	75.917
	2015	105.123	30.054	1.889	1.066	75.339
	2018	105.123	30.024	1.812	1.266	73.609
	2021	105.123	30.052	1.806	1.200	71.546

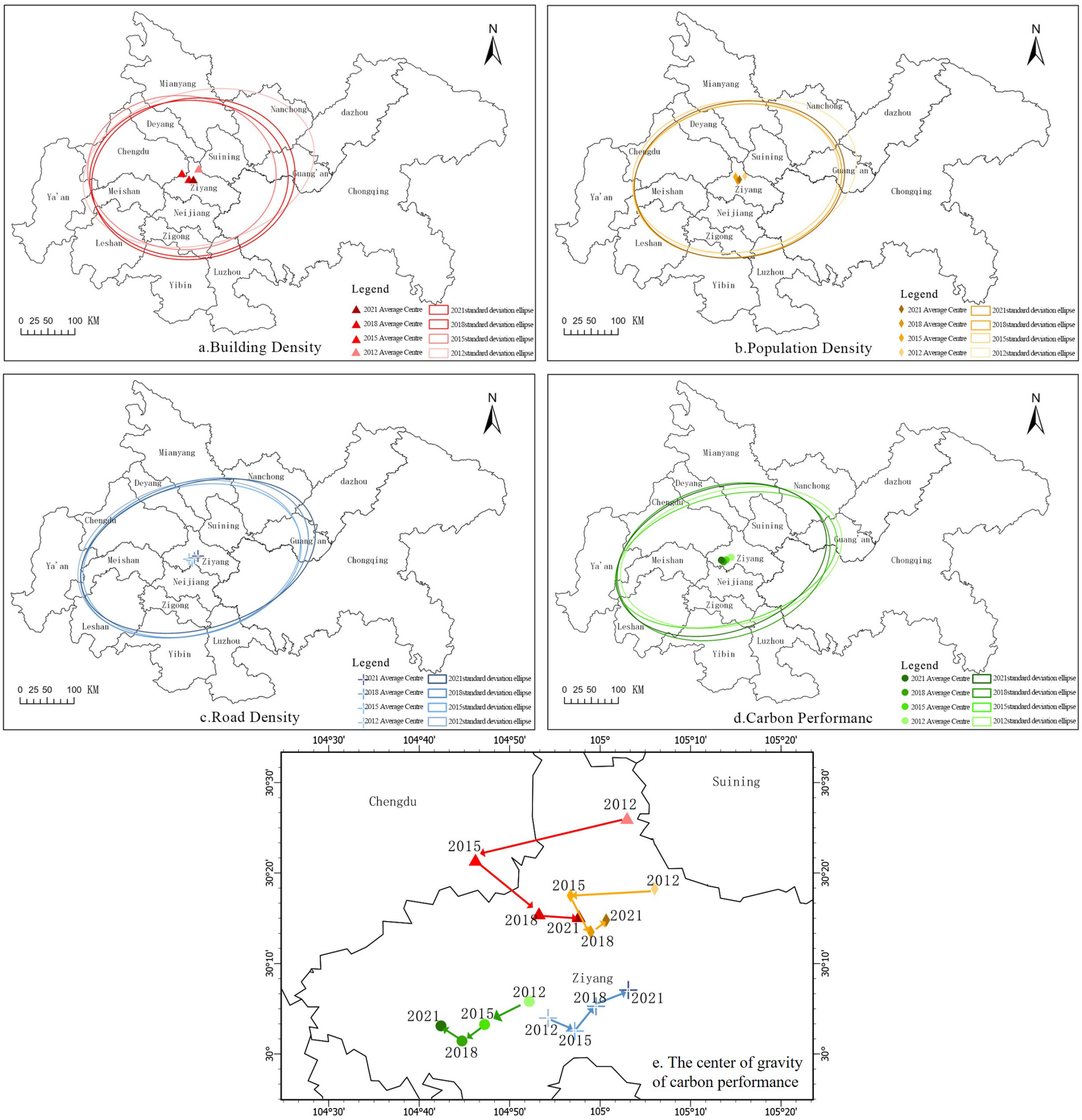


Figure 3. Spatial evolution characteristics of urban density and carbon performance.

3.1.2. Temporal Evolution of Urban Density and Carbon Performance

Although there are distinct patterns, Chengdu-Chongqing urban agglomeration urban density variables and carbon performance evolution characteristics are significantly different (Figure 4). Between 2012 and 2021, as urbanization progressed and the urban area and population grew at a synchronized rate, there was no discernible change in population density. Road density grew at a faster rate after 2016, rising from 6 km/ km^2 in 2016 to 8.23 km/km^2 in 2021. Both building density and road density generally exhibit an upward trend. Carbon performance decreased from 0.598 in 2012 to 0.427 in 2016, indicating that while traditional industries and heavily polluting industries promote the economic growth of Chengdu-Chongqing urban agglomeration, due to the inadequacy of technology and management, land, inputs of production factors such as labor and capital have led to the waste of resources and the decline of production efficiency, and have not reached the optimal state. From 2016, the regional economy gradually shifted to a high-tech and green economy, and this transformation of the economic structure effectively reduced carbon emissions. Carbon performance increased from 0.427 in 2016 to 0.665 in 2020. Fluctuations in carbon performance were observed in 2021, mainly due to the larger decreases in carbon performance in Chengdu City, Meishan City, and Nanchong City. In Chengdu City, the land input increases, the green coverage of output decreases instead, the increase in output GDP per capita is not disproportionate to the increase in capital input, and the marginal benefit decreases, while the CO_2 non-desired output increases by 23.46%, and the energy efficiency decreases. In Meishan City, mainly due to the efforts to build a comprehensive transport system, led to a sudden increase in energy input in 2021, possibly because the city was undergoing industrial restructuring and energy structure optimization, which lowered energy conversion efficiency. Nanchong City has greater capital and energy inputs, yet its greening output rate is declining, and there is idleness of resources, causing a disproportionate relationship where outputs do not increase in line with inputs.

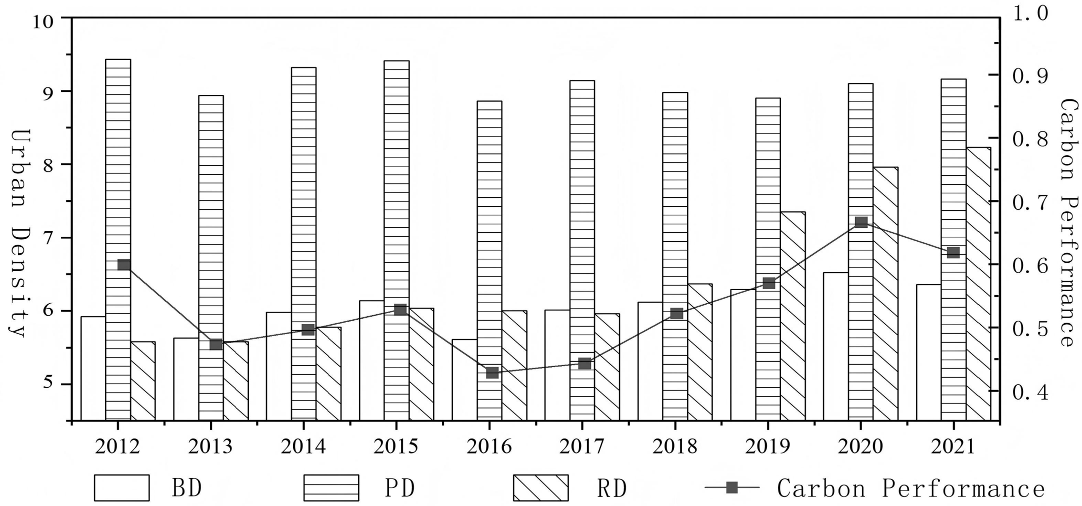


Figure 4. Temporal evolution characteristics of urban density and carbon performance.

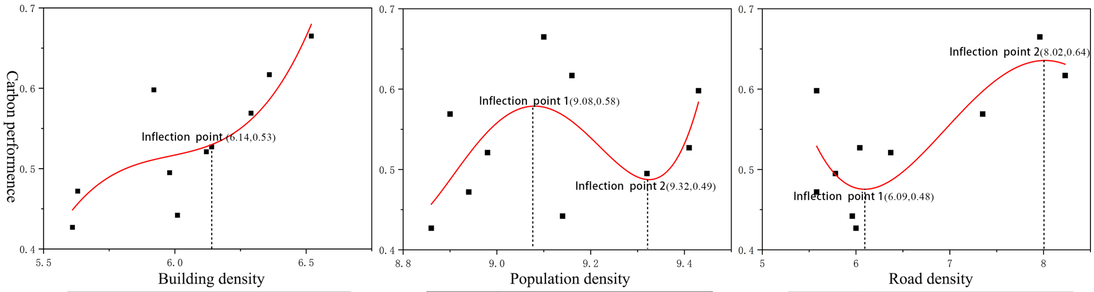
3.2. Correlation Analysis between Urban Density and Carbon Performance

A polynomial function was used to regress the building, population and road densities of the Chengdu-Chongqing urban agglomeration on carbon performance from 2012 to 2021, to explore the trends of urban density and carbon performance over time, and the results showed three different regression curves (Figure 5). The R^2 values for the three regression models of building density, population density, and road density were 0.714, 0.310, and 0.681, respectively, with adjusted R^2 values of 0.702, 0.285, and 0.669. This indicates that urban density and carbon performance exhibit a certain degree of nonlinear trends, but the correlations are not strong. This aligns with the complexity of urban systems, where carbon performance is influenced by numerous socioeconomic, technological, and policy factors.

In the relationship between building density and carbon performance, the R^2 (0.681) of a quadratic equation is lower than that of the cubic equation R^2 (0.714), and the expression of the cubic equation, $p = 0.045 \leq 0.05$, and the model is valid by F-test. The relationship between building density and carbon performance in the cubic curve shows a slow increase followed by a rapid increase (Figure 4a). At the stage of low building density, the rough utilization of land leads to the increase of building density faster than the increase of carbon performance. However, after the building density reaches 6.14%, with the emphasis on the construction of low-carbon cities, the land utilization efficiency is significantly improved, while the technical and management levels also achieve substantial improvements, and these changes effectively contribute to the significant increase in carbon performance from 0.527 to 0.665.

In the relationship between population density and carbon performance, the cubic function did not pass the significance test, and the quadratic function $R^2 = 0.310$ was used for fitting, and the result showed an “N” curve relationship (Figure 5), with inflection point 1 corresponding to a population density of 90,800 people/100 km^2 and inflection point 2 corresponding to a population density of 93,200 people/100 km^2. When the population density is between inflection point 1 and inflection point 2, the crowd activities and urban traffic are increasing, which is negatively correlated with carbon performance.

In the relationship between road density and carbon performance, $R^2 = 0.681$ in the cubic equation, the fit is good, the result shows an inverted “N” curve relationship (Figure 5), and conforms to the time series changes, there are two inflection points, inflection point 1 corresponds to the road density of 6.09 km/km^2 and inflection point 2 corresponds to the road density of 8.02 km/km^2. When the road density does not reach the inflection point 1, the newly built roads lead to the increase of traffic volume and the traffic smoothness is limited, which leads to the increase of carbon emission; when the road density is between the inflection point 1 and the inflection point 2, the road network and the public transportation system are gradually improved, which leads to the reduction of the overall carbon emission; when the road density reaches the inflection point 2, the high road density may lead to the increase of the traffic conflict, which then affects the carbon performance.



Equation	y = Intercept + B1*x + B2*x² + B3*x³
Intercept	−172.81±215.47
B1	86.80±107.03
B2	−14.50±17.70
B3	0.81±0.97
R^2	0.71
Adjusted R^2	0.57

Equation	y=Intercept+B1*x+B2*x²+B3*x³+B4*x^4
Intercept	151473.60±287841.01
B1	−66896.76±126042.14
B2	11078.79±20694.35
B3	−815.205±1509.89459
B4	22.49±41.31
R^2	0.31
Adjusted R^2	−0.24

Equation	y=Intercept+B1*x+B2*x²+B3*x³+B4*x^4
Intercept	35.69±165.05
B1	−18.27±98.47
B2	3.46±21.88
B3	−0.28±2.15
B4	0.01±0.08
R^2	0.68
Adjusted R^2	0.42

Figure 5. The regression curve of urban density and carbon performance.

3.3. The Comprehensive Weight Effect of Urban Density on Carbon Performance

To explore the differences in the influence of urban density elements on carbon performance, a comprehensive regression analysis was conducted using PLS. To estimate the feasibility of direct regression using PLS, the Pearson correlation test was conducted first (Table 3). The results indicate that the correlation coefficient between carbon performance and building density is 0.8, exhibiting statistical significance at the 0.01 level. The correlation coefficient between carbon performance and road density is 0.717, demonstrating statistical significance at the 0.05 level. Conversely, no significant correlation exists between carbon performance and population density. In the PLS regression results (Table 3), the optimal number of principal components is 3, which is valid for cross-section and satisfies the corresponding extraction criterion, and $R^2 = 0.728$, which explains 72.8% of the evolution in the relationship.

Building density, population density, and road density all exhibit positive effects on carbon performance, with road density demonstrating the most significant relative influence. The weights of the influence of the respective variables on the dependent variable explained by the value of the projected importance index is: building density (1.231) > road density (1.108) > population density (0.508) (Table 4). It should be clarified that these coefficients primarily reflect the relative importance of the variables rather than exact elasticity relationships.

Table 3. Pearson correlation analysis.

	Carbon Performance (Correlation Coefficient)	Carbon Performance (*p*-Value)
Building Density	0.800 **	0.006
Population Density	0.287	0.421
Road Density	0.717 *	0.020

* $p < 0.05$ ** $p < 0.01$.

Table 4. Projection importance index summary (VIP).

	One Principal Component	Two Principal Component	Three Principal Component
Building Density	1.246	1.232	1.231
Population Density	0.447	0.511	0.508
Road Density	1.117	1.105	1.108
R^2	0.700	0.717	0.728

3.4. Spatial Autocorrelation Analysis

Based on the global Moran's I index formula, the Rook neighbor space weight matrix was established by the Geoda 1.18.0 spatial analysis tool to calculate the bivariate local autocorrelation LISA was plotted based on a confidence level of 95%, and the results are obtained as shown in Figure 4. According to the analysis of the LISA clustering diagram (Figure 6), the local spatial aggregation status of urban density and carbon performance has changed significantly in the past ten years. (1) The "high-high" agglomeration of urban density and carbon performance is mainly in Chengdu, indicating that the neighboring areas of Chengdu have formed the agglomeration of "high urban density-high carbon performance", while Ya'an has been in the state of "low urban density-high carbon performance". The city of Ya'an has been in the state of "low building density-high carbon performance", and the city of Mianyang will change from a "low building density-low carbon performance" agglomeration to a "high building density-low carbon performance" agglomeration from 2018 to 2021. (2) The "high-high" agglomeration in terms of population density and carbon performance is mainly in Chengdu, and the scope of the "low-low" agglomeration gradually increases from 2012 to 2021, with the northeastern cities dominating, and the western cities in urban space. The urban space in the western part of the city is unstable and changes greatly, from "low-high" to "high-low" and then to "low-high". (3) The high-high agglomeration area of road density and carbon performance is dominated by Ya'an. Chengdu has changed from a low-high agglomeration area to a high-high agglomeration area from 2015 to 2021, and the low-low agglomeration area has been increasing and decreasing year by year, accounting for 40% of the Chengdu-Chongqing urban agglomeration. The southwestern cities don't have significant spatial differences in road density and carbon performance.

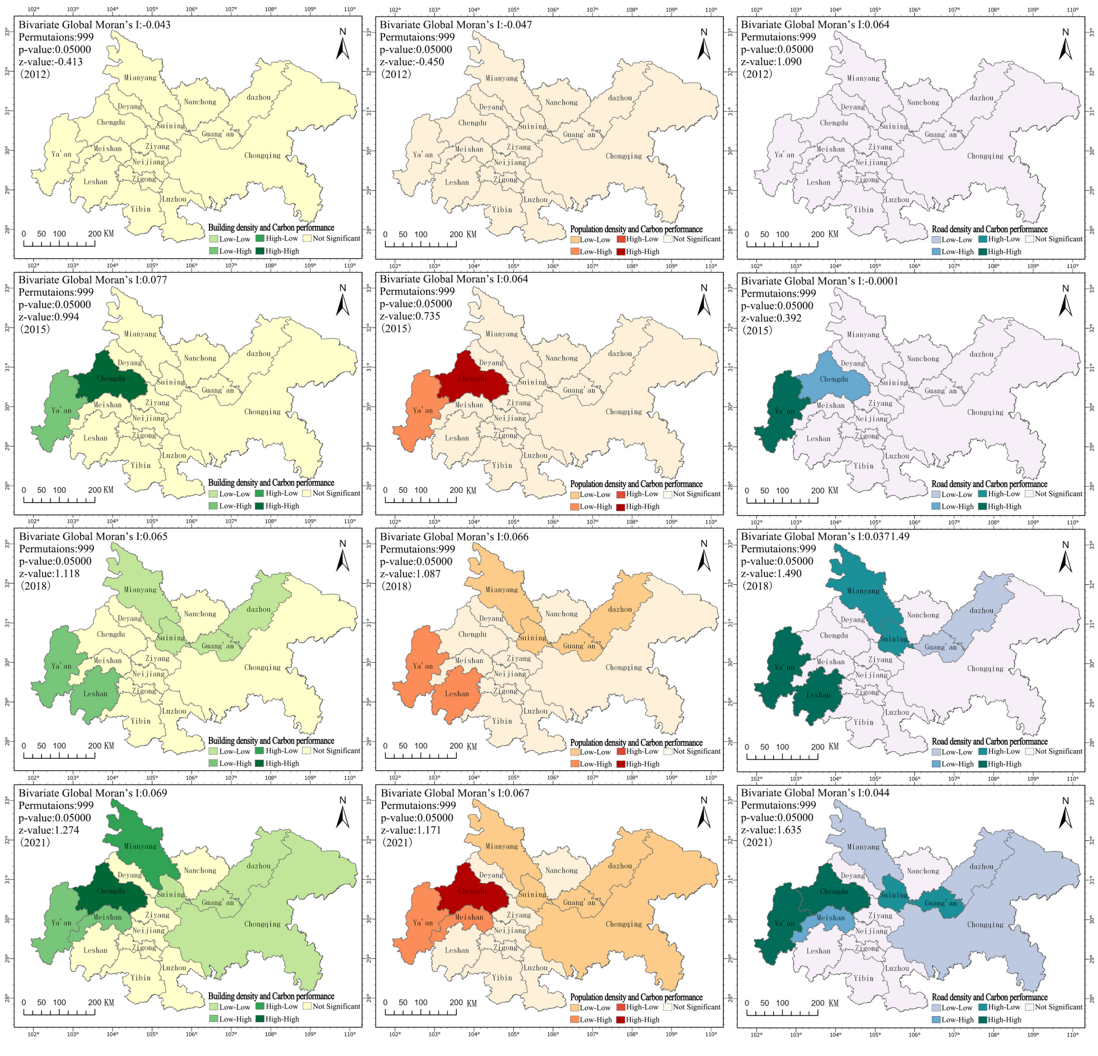


Figure 6. Urban Density and Carbon Performance LISA cluster diagram.

At present, the spatial correlation between urban density and carbon performance is mainly characterized by the following: (1) Chengdu as the core city has gradually entered the stage of high-quality coordination, and the-high-urban density area is surrounded by the high-carbon performance area, and the cities around Chengdu can further improve their carbon performance by strengthening regional cooperation. (2) Cities with Chongqing as their core are characterized by low urban density and low carbon-performance, which indicates that these cities have a weak industrial base and low technological level, and are unable to be radiated by the neighboring cities, and need to strengthen their own development of their own resource advantages, and at the same time, Chongqing, as the core city of the "Double Carbon" project, has the following characteristics. Moreover, Chongqing as a core city should take more responsibility in the task of "double carbon", improve green technology innovation, change the industrial development mode, and drive the neighboring cities to improve carbon performance. (3) The spatial correlation between urban density and carbon performance in the southwest is not significant, and the carbon performance can be improved by its own development factors.

4. Discussion

The study utilizes panel data from 2012 to 2021, employing the SBM model to calculate a carbon performance index as the benchmark for urban low-carbon development. Standard deviation ellipses, polynomial function regression models, and spatial autocorrelation models to analyze the trends, spatial distribution patterns, and associated impact effects of building density, population density, road density, and carbon performance. Based on the findings (statistical relationships within specific policy and economic contexts, not strictly identified causal effects), the study explores feasible planning strategies to promote sustainable urban development in the Chengdu-Chongqing metropolitan area.

(1) Reasonably control building density, population density and road density. Adopt compact and intensive development to improve land use efficiency, and improve building density by optimizing and adjusting building heights and floor area ratios. For specific areas, such as Chengdu and Chongqing, vertical greening and multi-functional buildings can be explored to improve space use efficiency. Conducting reasonable urban planning and housing policies to guide population distribution and avoid over-concentration, controlling the population density in urban areas at 91,000 people/100 km^2 and 93,000 people/100 km^2, giving full play to the population agglomeration effect, which improves the utilization rate of public transportation and infrastructure, and enhances to the allocation of urban resources and the intensive use of land. Encourage the population to move to the urban periphery, while improving the road network and public transportation system, reducing the commuting distance and intensifying the allocation of resources. The road density is controlled at 6 km/km^2 and 8 km/km^2 to reduce reliance on private vehicles, thereby reducing carbon emissions and maximizing resource inputs and outputs.

(2) In the preparation of low-carbon planning for the Chengdu-Chongqing urban agglomeration, the importance of building density > road density > population density should be followed. Firstly, optimize the land use rate and reduce urban sprawl to reduce carbon emissions. Secondly, control the road density to reduce traffic congestion to improve traffic efficiency, thus reducing carbon emissions, and then control the population density to balance the urban development and environmental protection to reduce the commuting distance and energy consumption.

(3) Implementing differentiated urban development strategies to suit their respective geographic, economic and environmental conditions. Gradually transform the high-energy-consuming machinery, energy, natural gas, and petrochemical industries of the northeastern Chengdu-Chongqing cities into high-tech and green economies, develop low-carbon industries, and reduce the proportion of high-carbon-emitting industries. Chengdu, as a center of high building density and high carbon performance, should play its role as a radiation driver, share resources, and collaborate on emission reduction through regional cooperation mechanisms to form a synergy of regional development and promote the neighboring cities to improve carbon performance. Chongqing should take its core responsibility to strengthen green technological innovation, transform the mode of industrial development, and improve the Ya'an, as a region with "low building density and high carbon performance", should further optimize its urban planning to increase building density while maintaining its high carbon performance. Mianyang has changed from "low building density-low carbon performance" to "high building density-low carbon performance", which indicates that its urban planning and industrial development have achieved some success. For areas with high road density and carbon performance, such as Ya'an City, we should continue to optimize the transportation network and increase road density, while paying attention to maintaining and improving carbon performance. Some cities in the southwest do not have significant spatial differences in road density and carbon performance and should improve carbon efficiency from the perspective of their own development factors.

5. Conclusions

In this paper, we use a variety of analytical methods to explore the associations and indicative thresholds of urban density on carbon performance and put forward a feasible development strategy for city clusters to optimize urban density and improve the carbon performance of city clusters to promote sustainable urban development.

(1) Urban density has generally followed an upward trajectory, with carbon performance rising from 0.55 in 2012 to 0.68 in 2021, in which the changes and fluctuations of the growth rate are subject to the macro impact and regulation of policies. In 2016, the Chengdu-Chongqing urban agglomeration was officially given a national positioning, providing strong policy support for the growing demand for housing, transportation and other infrastructure, and the growth of road density and building density increased significantly. At the same time, the "Chengdu-Chongqing Urban Agglomeration Development Plan" clearly puts forward the priority construction of intercity transportation network, resulting in a faster growth rate of road density compared to building density. The 13th Five-Year Plan for Ecological Environmental Protection and the Chengdu-Chongqing Twin Cities Economic Circle Construction Plan guide the transformation of industrial energy structure, so that the center of gravity of carbon performance is shifted to the southwest direction, which has the advantages of ecological resources and strong carbon sinks, and this spatial differentiation highlights the double constraints of topographic resource conditions and industrial structure on low-carbon development.

(2) The polynomial regression model reveals a non-linear relationship between urban density and carbon performance. In the relationship between building density and carbon performance, when the building density exceeds the 6.14%, the carbon performance is significantly increased, which verifies the effectiveness of the compact city theory in low-carbon development. The "N-shaped" relationship between population density and carbon performance reflects the duality of population aggregation effects, which is consistent with the results of Chen et al. [27] study on the carbon performance of population density. The inverted N-shaped relationship between road density and carbon performance indicates that enhancing carbon performance can be effectively achieved by increasing road density to between 6 and 8 km per square kilometre. National and regional policies should priorities low-carbon urban development according to the following order of importance: building density > road density > population density.

(3) Utilizing spatial auto-correlation analysis to identify the spatial correlation and spatial heterogeneity among cities, which to determine the key direction of spatial planning in each city. For example, Mianyang city's "high building density-low carbon performance" status shows that simply increasing building density does not necessarily improve carbon performance, but needs to be combined with industrial structure optimization and green technology application. Chengdu, as the core of the "high-density-high-carbon performance", has effectively driven the low-carbon transformation of neighboring cities through its technological spillovers and regional collaboration mechanisms. In contrast, Chongqing's "low-density-low-carbon performance" is closely related to its heavy-industry-dominated industrial structure, and it needs to break through the path of dependence through green technological innovation.

In the paper, the influence of urban density on carbon performance in the Chengdu-Chongqing urban agglomeration is investigated using a variety of methods, revealing the complex nonlinear characteristics of the density effect. The identified threshold relationships and spatially dependent patterns hold significant reference value for similar metropolitan areas in central and western China. However, the unique "dual-core" structure, mountainous terrain, and industrial foundation of the Chengdu-Chongqing region dictate that its strategies should not be directly applied to coastal metropolitan areas.

The study also has limitations. The sample size is relatively small. Some early data may have quality issues. Additionally, the relatively complex model may affect the stability of threshold estimates and related relationships. The use of administrative divisions in calculations may introduce boundary effects, where actual urban development and carbon emissions activities extend beyond administrative borders. Since these borders may not align with functional urban zones, this discrepancy could compromise the accuracy of findings. Future research could employ grid-based segmentation to create finer spatial units, enhancing precision and resolution to more accurately capture internal spatial heterogeneity within cities.

Author Contributions

Y.L.: conceptualization, investigation, methodology, software, and writing original draft. L.W.: data presentation, software, and methodology. E.Z.: data curation, formal analysis, methodology and software. All authors have read and agreed to the published version of the manuscript.

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All data generated or analyzed during this study are included in this published article.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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