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Scientific Access, 2025, 1(2), 62-81
https://www.hillpublisher.com/journals/sa/
ISSN Online: 3068-7500

Spatial-temporal Evolution and Influencing Factors of Green Development: A Case Study in the Guangzhou Metropolitan Area

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How to cite this paper: Jiaxin Huang, Bo Tang. (2025) Spatial-temporal Evolution and Influencing Factors of Green Development: A Case Study in the Guangzhou Metropolitan Area. *Scientific Access*, 1(2), 62-81.
DOI: 10.26855/sa.2025.09.002

Received: July 15, 2025
Accepted: August 8, 2025
Published: September 3, 2025

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Abstract

Green development is a crucial pathway towards ecological civilisation and economic transformation and development, and is now a core element in sustainable development goals and the well-being of humanity. Based on the concept of green development, this study constructs an evaluation of the index system of green development level in the Guangzhou metropolitan area from three dimensions: green economic growth, green environmental governance, and green policy investment. The entropy method, the coefficient of variation method, and geographic information system (GIS) are used to analyse the levels and spatial pattern of green development in the Guangzhou metropolitan area from 2011 to 2021, and the obstacle degree model is employed to identify the main factors hindering green development. The study reveals that: (1) Over time, the green development level in the Guangzhou metropolitan area shows an overall upward trend, despite some fluctuations during 2011-2021. Cities like Guangzhou and Foshan exhibit higher green economic growth, while peripheral cities, such as Shaoguan, Yunfu, and other cities, demonstrate better performance in green environmental governance and green policy investment; (2) From the spatial level, there are apparent spatial differences in the level of green development in the Guangzhou metropolitan area, which presents a spatial pattern of "low in the middle and high around." In contrast, the gap in green development levels among cities has gradually narrowed, with an overall improvement in synergy for green development. (3) From the perspective of influencing factors, the most critical obstacle to the green development level of the Guangzhou metropolitan area is the investment in green policies, such as the proportion of fixed investment in drainage and landscaping, followed by the proportion of tertiary industry output and per capita GDP. An analysis of the spatial and temporal evolution of the green development level in the Guangzhou metropolitan area and its influencing factors is of great significance for strengthening ecological and environmental synergistic governance systems, promoting regional resilience construction, and achieving sustainable development goals.

Keywords

Green development; Entropy method; Spatiotemporal pattern; Obstacle degree; Guangzhou metropolitan area

1. Introduction

In 2025, the Central Urban Work Conference of China proposed the goal of building modern people's cities that are innovative, livable, beautiful, resilient, civilized, and intelligent, which has pointed out the direction for urban management in the new era. Green development is a second-generation sustainable development concept that emphasises systemic, holistic, and coordinated approaches among economic, social, and natural systems [1, 2]. It promotes efficient resource use, pollution reduction, ecosystem protection and restoration, and social equity and sustainability, with a greater focus on quality of life, resource waste reduction, ecological well-being, and social equality [3, 4]. Cities are undergoing significant transformations with economic and demographic changes and urbanization, but face complex environmental problems such as pollution, biodiversity loss, overpopulation, and land depletion [5, 6]. Natural green factors play a positive role in the physical and mental health of urban populations, directly or indirectly, contributing to human well-being and biodiversity in dense urban spaces [7, 8]. Urban Ecosystem Services (UES) and Ecosystem Services (ES), Green Infrastructure (GI) in green and open spaces contribute to human well-being and biodiversity by regulating water balance, mitigating urban heat island effect, air filtration, increasing biodiversity, shading and cooling, and noise and stress mitigation [4, 9]. The New Urban Agenda agreed upon at the Third United Nations Conference on Housing and Sustainable Urban Development (UNCSD III) aims to create "just, safe, healthy, resilient and sustainable cities"— a core challenge in full realization of the Sustainable Development Goals (SDGs) [10].

Green development research, both domestically and internationally, has primarily focused on several areas: measurement of green development index and green development efficiency (GDE) based on different methods and perspectives, analysis of the spatiotemporal pattern of green development, and exploration of factors influencing green development levels and corresponding countermeasures. In recent years, scholars have constructed the evaluation index system for green development levels [11] and used the entropy value method, combined with the Terrell index, Moran index, and coefficient of variation, to analyse the spatio-temporal evolution of green development [12, 13]. For example, Li et al. developed the "Human Green Development Index (HGDI)" by drawing on the human development index based on the two dimensions of sustainable socio-economic development and ecological resource development. They measured the green development levels of 123 countries, providing the basis for measuring green development [14]. Based on Criteria Importance Through Intercriteria Correlation (CRITIC), Mai measured the green development level and spatial-temporal characteristics of 11 provinces (cities) and 108 cities in the Yangtze River Economic Belt from 2005-2016 [15]. Nguyen et al. analysed the determinants of green development in Central and Eastern European (CEE) countries using OECD green development data, World Bank indicators, and World Payne Scale data from 1996 to 2020, proposing an assessment program for green development [16]. Ma et al., with the mid-Yangtze River city cluster as the research object, used the entropy weight-TOPSIS method to calculate the green development index and the environmental Kuznets curve theory to explore spatial differences [17]. Chen et al. constructed a green development evaluation index system for the Wuhan metropolitan area based on green society, green economic growth, and green ecology, and analyzed spatial and temporal evolution using the entropy value method and exploratory spatial data analysis [18].

Research on factors influencing green development primarily explains these factors from a theoretical perspective, followed by an empirical analysis of their strength using mathematical models [19]. To alleviate the environmental pressure caused by rapid economic growth, many governments have implemented a series of environmental regulation policies to reduce energy consumption and pollutant emissions [20]. Tawiah et al. used pre-regression and econometric modelling to select economic, international, institutional, and energy-related factors influencing green growth in developed and developing countries [21]. Joan et al. selected evaluation indicators from four aspects, namely cost efficiency, rational use of public finance, strong market, and long-term productivity, and constructed an assessment framework to derive the influencing factors of green growth in EU member states [22]. Pawlewicz et al. deeply analysed the relationship between social capital and green economic growth, with an emphasis on the significance of social capital for sustainable development [23]. Guo et al. constructed a county green development efficiency index system based on green total factor productivity from the input and output perspectives and analyzed the green development efficiency of the Harbin-Changsha Urban Agglomeration using Epsilon Based Measure (EBM) and Global

Malmquist-Luenberger (GML), and then explored the spatial spillover effect through cluster analysis [24]. Sun et al. analyzed factors influencing green development in restricted development areas of Jilin Province, using the barrier degree model with 20 indicators, including economic development, social life, resource use, pollution emission, and environmental governance [25].

In summary, both Chinese and international scholars have carried out comprehensive research at different levels and scales on green development, making theoretical and practical contributions to green development and global sustainable development. Firstly, regarding the construction of the green development level indicator system, the common point is to establish first-level criteria based on the economic, social, ecological, and other factors, which are then extended to include government support, market input and output, and environmental carrying capacity for a refined indicator system. Secondly, in terms of measuring green development level, methods like the entropy value method combined with a linear weighted comprehensive evaluation and the Malmquist index model, etc., are often employed. Most of the spatial evolution levels use the Moran index to analyze spatial autocorrelation and apply tools such as cluster analysis, the Terre coefficient, the coefficient of variation, etc., to investigate spatial differences and balance levels. Thirdly, regarding the analysis of factors influencing green development, the barrier degree model is widely used, and some studies also employ models such as the Tobit model, geo-detector model, and spatial Durbin model. Besides, multiple linear regression models or direct integration with policy text analysis are applied.

Since the reform and opening up, China's regional policy precision and regional cooperation mechanisms have improved with the implementation of the regional development strategy. A metropolitan area mainly refers to a region where a metropolis serves as the core, with significant influence on surrounding areas and close connections within the region [26]. The metropolitan area is an essential node in China's urban agglomeration development, amplifying the radiation power of the core cities, breaking administrative boundaries, and achieving regional integration and development. This makes the construction of small-scale, cross-regional, and precise metropolitan areas an essential part of coordinated regional development [27]. Much theoretical and empirical research has focused on the metropolitan areas' spatial structure, growth process, influence effect, gradient pattern, development stage, and governance construction [28-32]. However, many problems persist, such as the administrative barriers in metropolitan areas that inhibit efficient resource distribution. These issues also include the underdeveloped economic synergy among city clusters, and systemic barriers to coordinated cross-regional systems, as well as incomplete consideration of human, social factors, and ecological factors. [33, 34]. In 2023, the People's Government of Guangdong Province issued the "Guangzhou Metropolitan Area Development Plan", which puts forward the general requirements to implement a new urbanization strategy and develop modern metropolitan areas. The aim is to build the Guangzhou Metropolitan Area at a high level, with influence radiating across the whole province, the entire country, and even the world. Green development serves as the basis of high-quality regional development. With the promotion of ecological civilization and green priority development policies, it has become essential to enhance the evaluation of the metropolitan area's resource and environmental carrying capacity and to establish a cohesive ecological and environmental governance system.

On this basis, with the Guangzhou metropolitan area as a case study, this study selects 15 indicators in three dimensions: green economic growth, green environmental governance, and green policy investment, to construct an indicator system for green development level in the Guangzhou metropolitan area. The study employs the entropy method, coefficient of variation, and GIS analyses the measurement and spatial evolution of green development level in the area and applies the obstacle degree model to identify factors influencing green development in Guangzhou. By reviewing the spatial and temporal evolution of green development in the Guangzhou metropolitan area, this study provides a theoretical basis for exploring green development pathways in different regions and offers implications for Guangdong Province to promote the coordinated development of regional green and resilient city construction.

2. Study Area and Data Sources

2.1 Study Area

To facilitate data collection and statistical analysis, this study defines the research scope of the Guangzhou

metropolitan area as the six cities of Guangzhou, Foshan, Zhaoqing, Qingyuan, Yunfu, and Shaoguan. The total economic volume, the number of resident populations, and the quality of economic development of the Guangzhou metropolitan area are among the top domestic metropolitan regions, and the GDP of the metro area will be about 4.46 trillion yuan in 2022. The Guangzhou metropolitan area has a beautiful ecological environment. In the north are Dinghu Mountain, Penjia Mountain, Furong Mountain, Shimen National Forest Park, and other important mountain ecological spaces. However, the Guangzhou metropolitan area faces severe environmental control and stricter environmental governance requirements in economic construction and industrial transfer, especially in cross-regional ecological environment construction; there are inevitable conflicts of interest and contradictions at the institutional level.

2.2 Data sources

The data for this study come from the Statistical Yearbook of Urban Construction in China (2011-2021) published by the Ministry of Housing and Urban-Rural Development of the People's Republic of China, as well as the official websites of the governments of the six prefectural-level cities in the Guangzhou metropolitan area, the Statistical Yearbook of the Guangzhou Metropolitan Area (2012-2022) published by the Bureau of Statistics of the People's Republic of China, and the bulletin of the state of ecological environment published by the Guangdong Provincial Bureau of Ecological Environment.

3. Methodology

3.1 Theoretical framework

The main connotation of metropolitan green development lies in promoting the coordinated and sustainable development of cities and their surrounding regions through ecological prioritization, efficient resource utilization, and low-carbon development. It emphasizes protecting the ecological environment during urbanization, optimizing land use, improving resource efficiency, reducing carbon emissions, promoting clean energy and green transportation, and fostering the application of green industries and innovative technologies [35]. At the same time, metropolitan green development focuses on social inclusiveness, ensuring that the benefits of development reach all groups, and building livable, resilient, and low-carbon urban agglomerations through policy guarantees, regional collaborative governance, and public participation. The ultimate goal is to achieve the harmonious integration of economy, society, and the environment, creating a modern metropolitan area where humans and nature coexist in harmony [36]. In light of the connotation of green development and the unique characteristics of metropolitan development, this study integrates multidisciplinary knowledge from sustainable development theory, ecological economics theory, regional development theory, and systems science to construct a theoretical framework for evaluating the level of green development in metropolitan areas from economic, social, environmental, spatial, and management dimensions. Among these, sustainable development theory emphasizes the coordinated development of economy, society, and the environment, suggesting that metropolitan green development should aim for sustainability [37, 38]. Ecological economics theory focuses on the interaction between economic systems and ecosystems, highlighting resource efficiency and environmental carrying capacity [39, 40]. Regional development theory studies the spatial structure, resource allocation, and coordinated development within and beyond metropolitan areas, providing a spatial perspective for green development [41]. Systems science theory treats metropolitan areas as complex systems, analyzing the interactions and overall functions of their internal elements [42]. The theoretical framework for evaluating the level of green development in metropolitan areas should center on sustainable development, integrating economic, environmental, social, and spatial factors to construct a scientific evaluation index system and methodology. Through systematic analysis and dynamic assessment, key influencing factors can be identified, and targeted policy recommendations can be proposed to promote green, low-carbon, and sustainable development in the Guangzhou Metropolitan Area. Figure 1 shows the theoretical basis for the research method in this study.

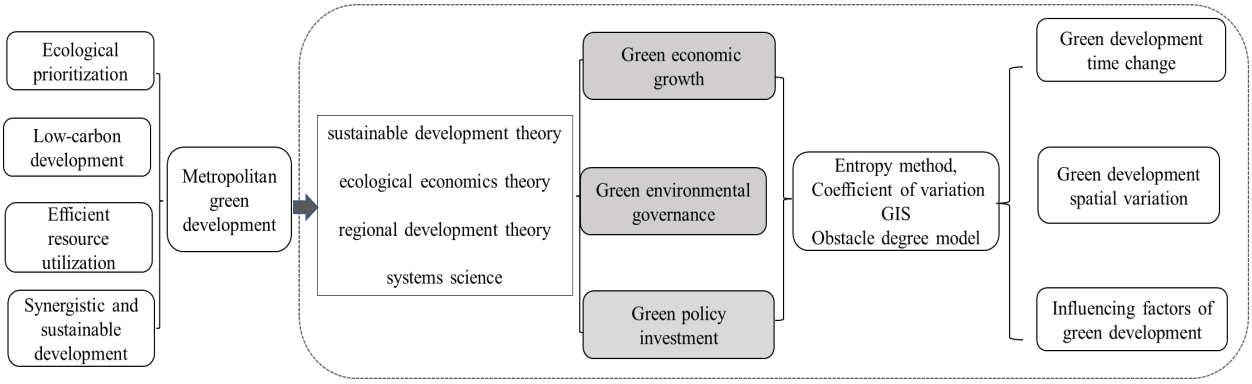

Figure 1. Research framework.

3.2 Evaluation System

In 2015, China put forward the concept of green development: the harmonious coexistence of human beings and nature is its value orientation; green, low-carbon, and recycling are its primary principles, and ecological civilization construction is its fundamental focus. Based on the theoretical foundation of green development, drawing on the green development index system constructed by the China Green Development Index Report in 2010, the green development index system jointly compiled by the National Development and Reform Commission and other departments in 2016, as well as the relevant literature [6, 8, 10, 43, 44], and according to the principles of data scientificity and accessibility, three guidelines of green economic growth, green environmental governance, and green policy investment were used to, the indicator system of green development level of Guangzhou metropolitan area was constructed, as shown in Table 1.

Table 1. Index system of green development level in the Guangzhou metropolitan area

Criterion	Indicator (unit)	Meaning	Properties	Weights
Green Economic Growth	*X1* Energy consumption per unit of GDP (tons/million yuan)	the level of energy consumption and energy saving and consumption reduction	Negative	0.044
	X2 GDP per capita (million yuan/person)	the overall level of economic development	Positive	0.110
	X3 Ratio of disposable income of urban and rural residents (million yuan)	the differences in the lives of residents	Negative	0.046
	X4 Value added of tertiary industry in GDP (%)	the characteristics of industrial structure	Positive	0.090
Green Environmental Governance	*X5* Forest cover (%)	the state of the forest ecosystem	Positive	0.069
	X6 Greening coverage rate of urban built-up areas (%)	the degree of greening in built-up areas	Positive	0.044
	X7 Ratio of good air quality days (%)	the air quality condition	Positive	0.032
	X8 Park green space per capita (m^3/person)	the degree of greening equity in the area	Positive	0.053
	X9 Centralized treatment rate of sewage treatment plants (%)	pollution control capacity	Positive	0.023
	X10 Harmless treatment rate of domestic garbage (%)	pollution control capacity	Positive	0.029
	X11 Population density (people/m^2)	population distribution	Negative	0.082
Green Policy Investments	*X12* Science, education, culture, and health expenditures as a share of fiscal spending (%)	the strength of investment decisions in public service governance	Positive	0.037
	X13 Investment in Landscaping as a Share of Fixed Assets (%)	the strength of greening investment decisions	Positive	0.140
	X14 Drainage Investment as a Share of Fixed Assets (%)	the strength of investment decisions in drainage	Positive	0.126
	X15 Agriculture, Forestry and Water Affairs Expenditures as a Share of Fiscal Expenditures (%)	the strength of investment decisions in agriculture	Positive	0.076

The green economic growth dimension reflects the overall level of the economy, economic efficiency, economic structure, living differences, and other indicators; the green environmental governance dimension mainly reflects the green infrastructure and human habitat creation in the process of regional development in a comprehensive manner, mainly including pollution treatment, air quality, forest green space, and other indicators; thirdly, the green policy investment reflects the degree of investment and focus on the policy in the green development. Third, green policy investment demonstrates the degree of policy investment and focuses on green development, mainly including investment in public service governance, green investment, drainage investment, and agricultural investment [45, 46]. Weights were calculated using the entropy method (Section 3.3).

3.3 Entropy method

The entropy value method can effectively eliminate the interference of subjective factors and scientifically and objectively reflect the state of regional green development. In the entropy value method, the higher the entropy value of information, the better the balance of the system structure is, and the smaller the change of the original data is. Therefore, the final entropy value can reflect the importance of each indicator [47]. It is assumed that n evaluation years and m evaluation indicators are involved in the *y* evaluation indicator levels in the indicator system of green development level in the Guangzhou metropolitan area, where *i* is the number of evaluation years and *j* is the number of evaluation indicators; *min{Xm}* and *max{Xm}* denote the minimum and maximum values in the *m* th evaluation indicator in all the years, respectively. The specific steps are as follows:

(1) Data standardization is carried out.

Positive indicator standardization calculation method:

$$X'_{nm} = （X_{nm} - min\{X_m\}）/（max\{X_m\} - min\{X_m\}） \tag{1}$$

Negative indicator standardization calculation method:

$$X'_{nm} = （min\{X_m\} - X_{nm}）/（max\{X_m\} - min\{X_m\}） \tag{2}$$

(2) The weight of the *m* th indicator in year *n* is calculated:

$$Y_{nm} = X'_{nm} / \sum_{n=1}^{i} X'_{nm} \tag{3}$$

(3) Calculate the information entropy value of the indicator:

$$e_m = -k \sum_{n=1}^{i} (Y_{nm} * \ln Y_{nm}), \quad k = \frac{1}{\ln i}, \ 0 \le e_m \le 1 \tag{4}$$

(4) Weighting of indicators:

$$w_n = 1 - e_m / \sum_{m=1}^{j} 1 - e_m \tag{5}$$

(5) Calculate the value of individual indicator ratings:

$$S_{nm} = w_n * X'_{nm} \tag{6}$$

(6) Calculate the overall value of the level of green development:

$$S_n = \sum_{m}^{i} S_{nm} \tag{7}$$

3.4 Coefficient variation method

The coefficient of variation can be used to calculate the degree of spatial difference in the level of green development in the Guangzhou metropolitan area [48]. The calculation formula is as follows:

$$CV = \frac{\delta}{|\bar{x}|} \tag{8}$$

$$\delta = \sqrt{\sum (S_n - \mu)^2 / n} \tag{9}$$

$$\mu = \sum S_n / n \tag{10}$$

Where *CV* denotes the coefficient of variation of the green development level of each city in the Guangzhou metropolitan area, δ denotes the standard deviation of the green development level of the Guangzhou metro area, and μ denotes the average value of the green development level of each city in the study area. The smaller the value of the coefficient of variation, the more balanced the level of green development in the Guangzhou metropolitan area, i.e., the smaller the gap.

3.5 Obstacle degree model

The model mainly adopts three indicators, namely factor contribution degree, indicator deviation degree, and obstacle degree, to judge the main obstacle factors of the green development level of the Guangzhou metropolitan area [49]. Among them, the factor contribution degree (F_{ij}) is the degree of influence of a single factor on the total goal, i.e. the weight of a single factor on the total goal; the indicator deviation degree (I_{ijt}) indicates the gap between a single indicator and the green development indicator; and the obstacle degree (O_{ijt}) means the value of the influence of a single indicator on the green development level. The specific calculation formula is as follows:

$$F_{ij} = W_i * W_{ij} \tag{11}$$

$$I_{ijt} = 1 - P_{ijt} \tag{12}$$

$$O_{ijt} = I_{ijt} * \frac{F_{ij}}{\sum_{j=1}^{15}(F_{ij} * I_{ijt})} * 100\% \tag{13}$$

4. Results

4.1 Temporal Changes

4.1.1 Overall level analysis

Facing the construction of a beautiful China and the target requirements and background of carbon peak and carbon neutrality, the overall level of green development in the Guangzhou metropolitan area shows an upward trend. However, there is a certain degree of volatility. Figure 2 shows a slight decrease in 2013, 2014, and 2021; the green development level is the lowest in 2014, with an evaluation value of 0.338, and the green development level is the highest in 2020, with an evaluation value of 0.446. From 2011 to 2021, the index of the level of green development in the Guangzhou metropolitan area grew from 0.330 to 0.434, with an increase value of 0.104, which is an increase of 31%. It indicates that the economic-social-ecological-policy coordination of the Guangzhou metropolitan area is constantly improving, the construction of ecological civilization has achieved new progress, and the quality of the environmental environment has continued to improve.

As shown in Figure 3, the average value of green development level of six cities in the Guangzhou metropolitan area from 2011 to 2021 is ranked from most significant to most miniature: Shaoguan City, Yunfu, Qingyuan, Zhaoqing, Guangzhou, and Foshan. Foshan is a traditional manufacturing city facing more significant industrial transformation and ecological construction challenges. Although the trend of green economic growth is evident, the average value of green environmental governance and green investment is low, which leads to the average value of Foshan City's green development level being the lowest among the six cities, so attention needs to be paid to the enhancement of green environmental governance and investment in green policies in the later stage. As the core city of the Guangzhou metropolitan area, Guangzhou's green development level encounters the same dilemma as Foshan. Guangzhou has the highest value for green economic growth and is at the middle level of green environmental governance. Still, the green policy investment aspect is not very satisfactory, affecting Guangzhou's overall green development level. This is mainly due to the high population density and economic density of Guangzhou City, which is low in terms of the proportion of green policy investment, and the green infrastructure construction and green policy investment can be increased in the later stage. In recent years, Guangzhou Municipality has practiced the concept of green development and harmonious coexistence of humans and nature, formulated and introduced several rules and regulations, constructed ecological and environmental safety defense, and achieved significant achievements in green policy and environmental control. As the fringe cities of the Guangzhou metropolitan area, Shaoguan, Yunfu,

Qingyuan, and Zhaoqing rely on a higher average value of green development level, and the green economic growth value of these cities is actually in the lower middle level, but higher than Guangzhou and Foshan in terms of green environmental governance and green policy investment.

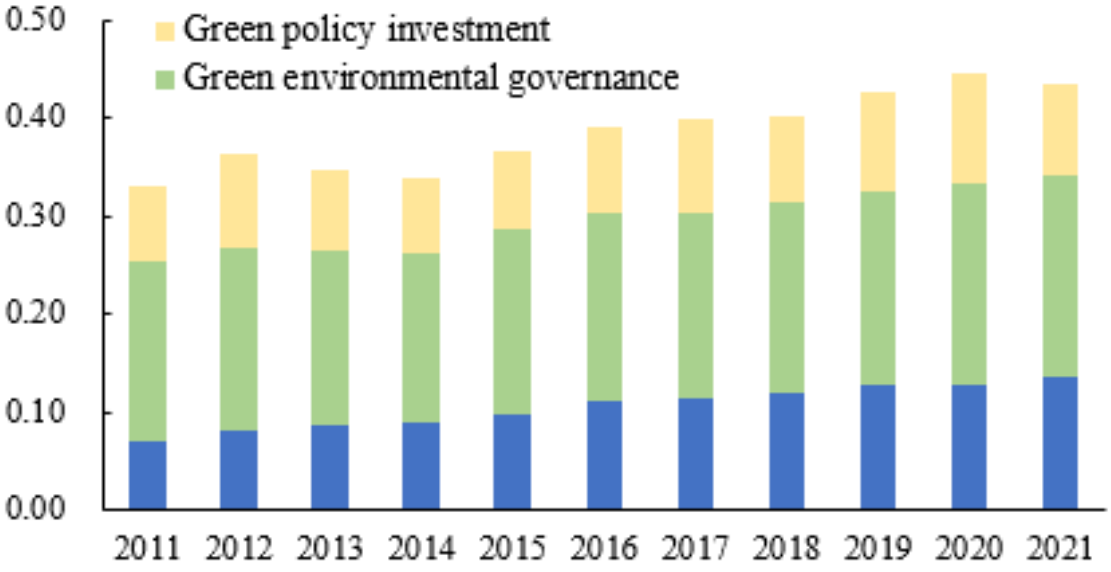

Figure 2. Overall level of green development in the Guangzhou metropolitan area (2011-2021).

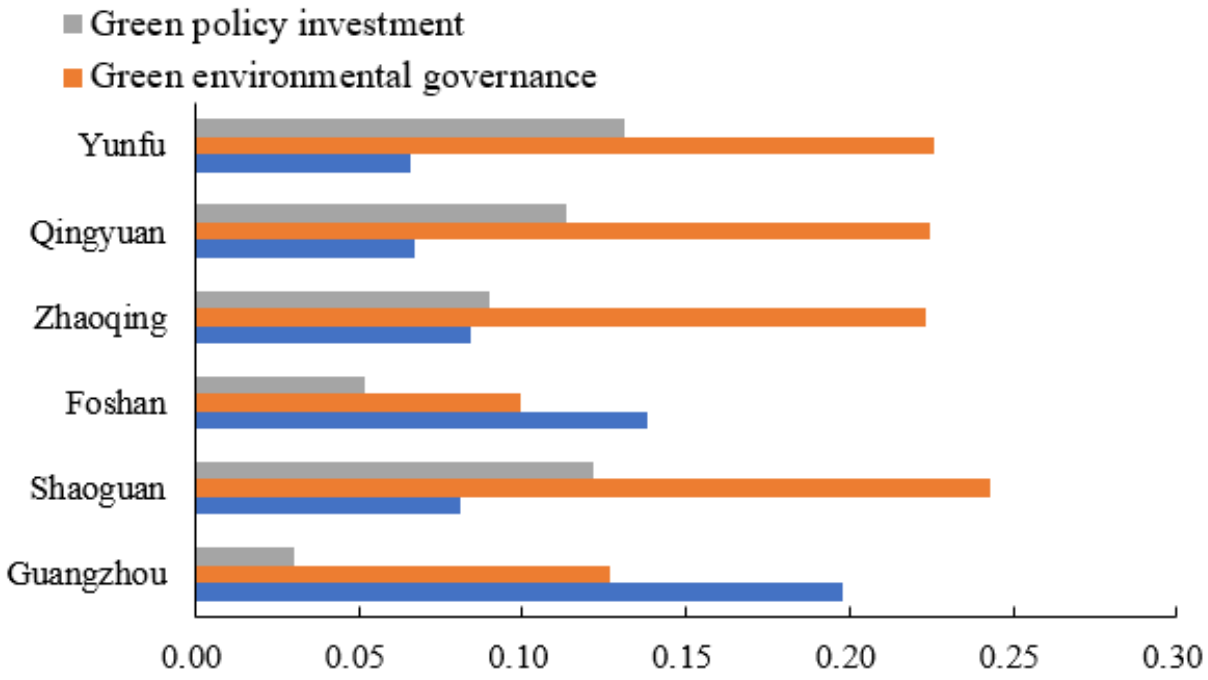

Figure 3. Average green development level in the Guangzhou metropolitan area (2011-2021).

4.1.2 Differences in the level of green development between municipalities

From 2011 to 2021, the level of green development in the six cities of the Guangzhou metropolitan area generally shows a fluctuating upward trend. As shown in Figure 4, the rising trend of the comprehensive level of green

development in Guangzhou is relatively gentle, and the extensive level of green development in Yunfu has a greater degree of fluctuation. The average growth rate from high to low is Foshan, Guangzhou, Qingyuan, Yunfu, Zhaoqing, and Shaoguan. At the same time, the difference between the highest and lowest comprehensive levels of green development of the six cities in the Guangzhou Metropolitan Area narrowed from 1.54 to 1.4, with a narrowing gap. In recent years, the growth rate of energy consumption per unit of industrial added value and GDP energy consumption of the cities in the Guangzhou Metropolitan Area has decreased significantly, which indicates that specific progress has been made in improving the energy structure and optimizing the industrial structure; at the same time, it has reduced the emission of the 'three wastes', increased the rate of urban sewage treatment and the rate of harmless treatment of urban rubbish, and continued to strengthen the construction of urban parks and green spaces, and improved the quality of the urban parks and green spaces. At the same time, it has reduced 'three wastes' emissions, increased the urban sewage treatment rate and the rate of harmless treatment of urban garbage, and continuously strengthened the construction of urban parks and green spaces, thereby improving the quality of the human environment and the quality of life.

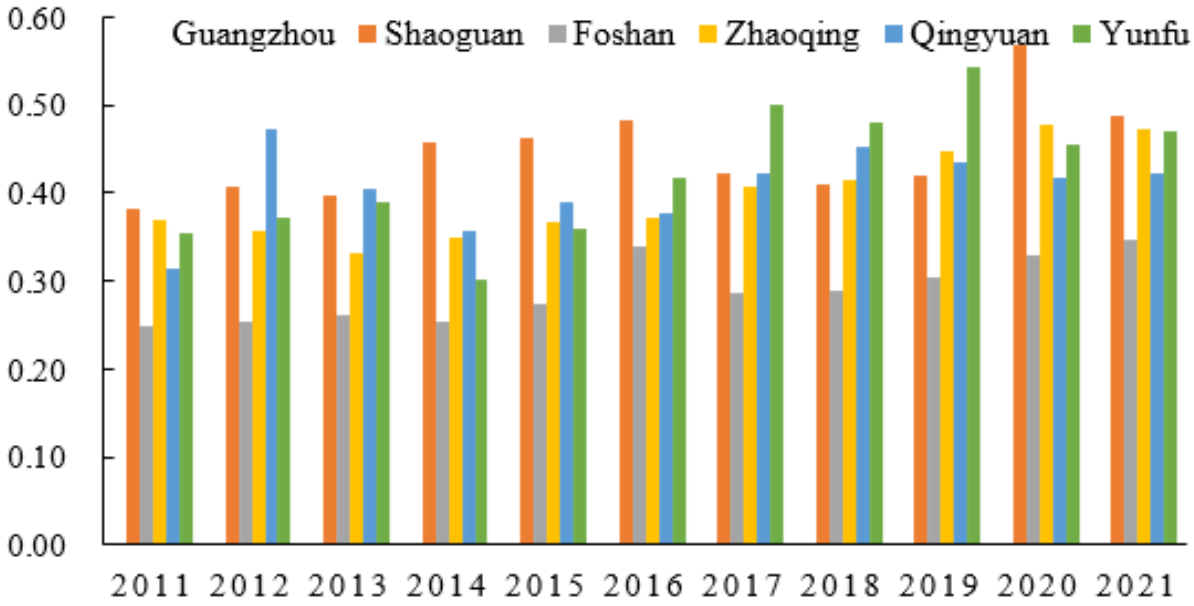

Figure 4. Trend of Green Development in the Guangzhou Metropolitan Area (2011-2021).

(1) Green economic growth

As shown in Figure 5, during 2011-2021, the green economic growth of the six cities in the Guangzhou metropolitan area generally indicates a steady upward trend, reflecting a good development trend. Among them, Guangzhou and Foshan have the highest level of green economic development. They are significantly higher than other cities, reflecting that Guangzhou and Foshan have made significant progress in the green economic growth and industrial structure transformation, and have played a good demonstration effect and driving role. Shaoguan, Zhaoqing, Yunfu, and Qingyuan cities' green economic growth development levels are generally closer. The ratio of the highest to the lowest level of green development of the six cities in the integrated level of the highest and lowest city from 6.32:1 narrowed to 2.85:1; the spatial difference is significant, and the gap is a narrowing trend. Although the green economic growth trend of the Guangzhou metropolitan area is better, it faces greater regional environmental control and governance requirements in optimizing the regional economic, spatial structure, and industrial network connection. Therefore, it is necessary to strengthen the advantage of giving full play to the rich ecological resources of Yunfu, Shaoguan northern ecological development area, and Zhaoqing to improve the overall environmental environment quality of the metropolitan area; on the other hand, enhance the ability of urban environmental collaborative governance, establish a long-term mechanism for the coordinated development of the ecological civilization and the economy, and jointly promote the level of green economic growth in the Guangzhou metropolitan area.

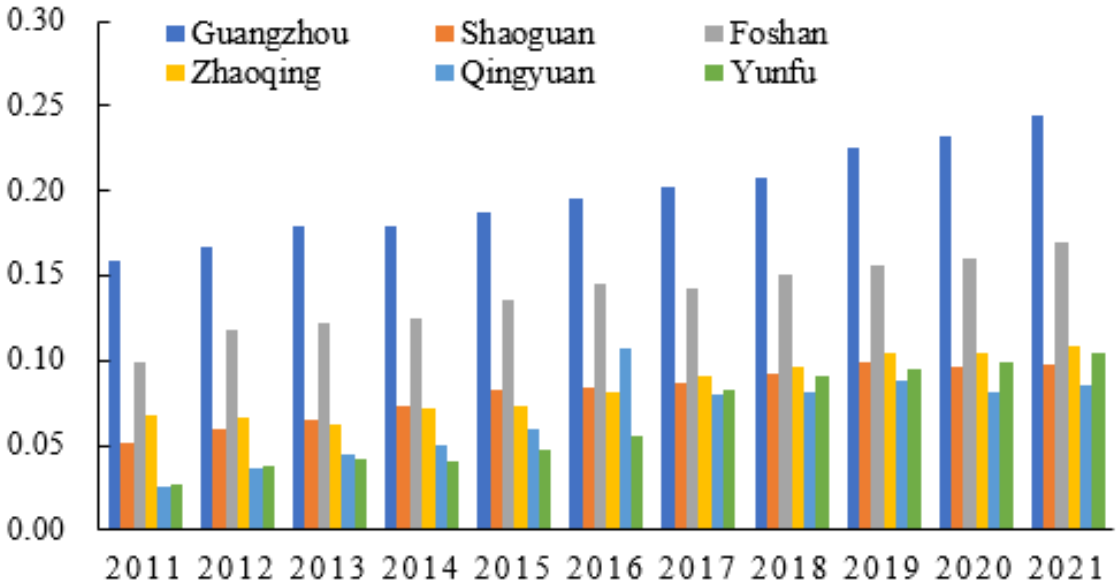

Figure 5. Trend of green economic growth in the Guangzhou metropolitan area, 2011-2021.

(2) Green environmental governance

As shown in Figure 6, the values of green environmental governance in the four cities of Shaoguan, Zhaoqing, Qingyuan, and Yunfu are higher than those of Guangzhou and Foshan. It is mainly because Yunfu and Shaoguan are in the northern ecological development area of Guangdong Province, and Zhaoqing and Qingyuan have rich environmental resources, which improve the air quality index and less pressure on pollution control; however, Guangzhou and Foshan have high population heights and high economic densities, large urban built-up areas, and small proportions of green and the forested regions, which make the task of environmental protection and pollution control higher. However, the growth rate of the development level of green environmental governance in Foshan City and Guangzhou City is still relatively obvious.

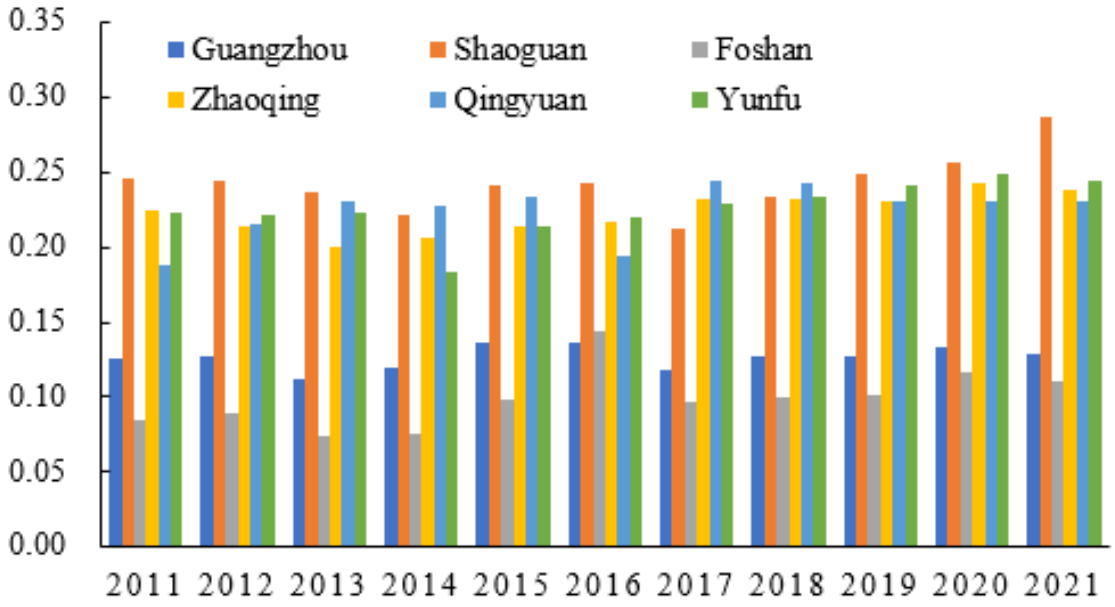

Figure 6. Trend of green environmental governance in the Guangzhou metropolitan area (2011-2021).

At the same time, the ratio of the highest to the lowest level of green ecological governance in the six cities of the Guangzhou metropolitan area has narrowed from 2.93:1 to 2.61:1, and the gap is narrowing. At a later stage, by deepening the reform of the ecological civilization system, the Guangzhou metropolitan area will further optimize and improve the ecological and environmental governance system, enhance the quality and efficiency of ecological and environmental protection, and provide a more solid ecological guarantee for green development.

(3) Green policy investment

From 2011 to 2021, the overall trend of green policy investment development level in the six cities of the Guangzhou metropolitan area has a greater degree of fluctuation.

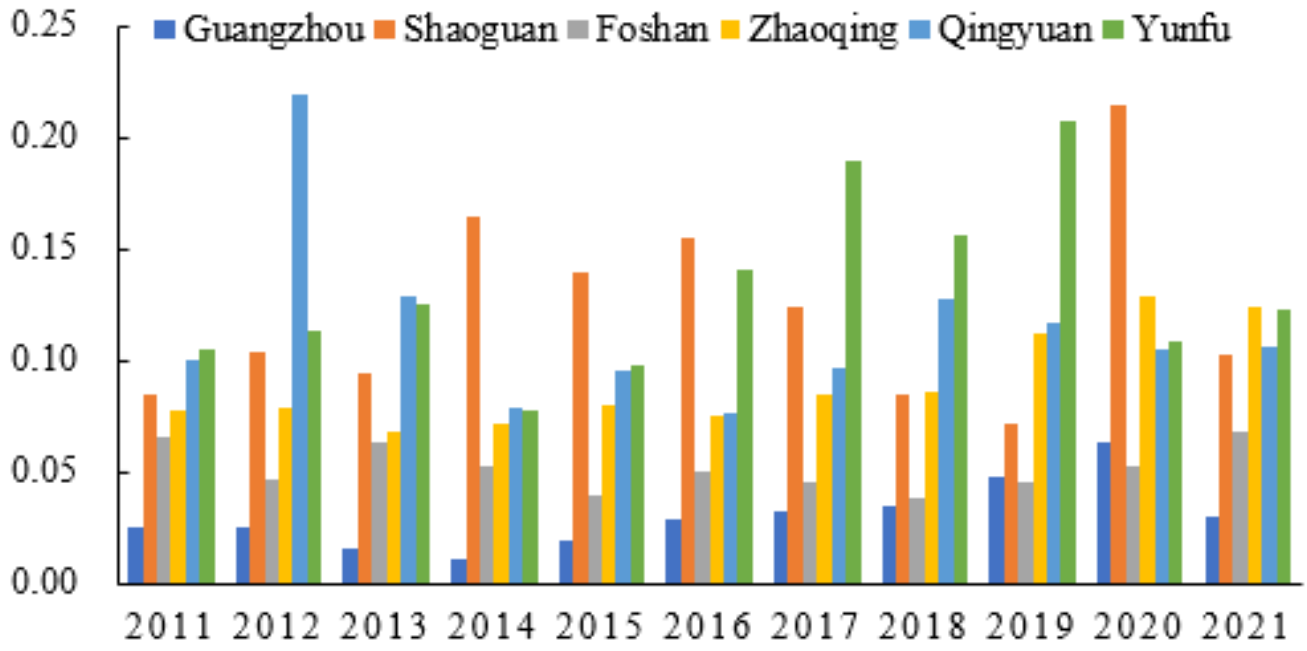

Figure 7. Trend of green policy in the Guangzhou metropolitan area (2011-2021).

As shown in Figure 7, Shaoguan, Qingyuan, and Yunfu cities have a greater degree of fluctuation in the level of green policy investment development; Guangzhou and Foshan have a lower value of green policy investment level. This is mainly because Guangzhou and Foshan have a larger economic development volume, and there is more pressure on green policy investment. In contrast, green investment primarily comes from local financial input; the degree of social public participation is not strong, and there is not enough diversification of the investment body. At the same time, there is a lack of intrinsic incentives for green investment [50]. Of course, Guangzhou and Foshan's green policy investment development level of the growth rate is more prominent in the economic development to improve the support of green development of the fiscal, financial, investment policies and standards system, focusing on the natural ecosystem and economic and social system of the virtuous cycle, and promoting the formation of a spatial pattern of resource conservation and environmental protection. However, the highest to lowest green policy investment development ratio in the six cities increased from 4.13:1 to 4.2:1, and the gap is widening. Therefore, the development of green investment policy in the Guangzhou metropolitan area in the later stage reflects more synergistic cooperation and needs to consider the policy's coordination, operability, and dynamics from a global and overall perspective, focusing on the synergistic effect of the policy. Based on regional differences and synergies, economic development should be combined with green and low-carbon transformation to optimize the efficiency of the government's guidance for green development and the overall quality of services.

4.2 Spatial Evolution Characteristics

Through the calculation of the coefficient of variation of green development level, it is found that the coefficient of variation of green development level of the Guangzhou metropolitan area decreased from 0.1365 in 2011 to 0.1129 in 2021, indicating that the regional difference of green development level of Guangzhou metropolitan area gradually changes from the characteristic of 'low level-with big gap' to the characteristic of 'high level-with small gap'. It shows that the regional difference in the green development level of the Guangzhou metropolitan area gradually changes from the characteristic of 'low level - large gap' to the characteristic of 'high level - small gap'. As can be seen from Figure 8, from the point of view of the composition of the evaluation system of the green development level in this study region, except for the coefficient of variation of green policy investment, which is more fluctuating and decreasing, the level of green economic growth and the level of green environmental governance are both in a steady state decreasing trend. Among them, the coefficient of variation of the green economic growth level is decreasing more significantly, indicating that the gap between the green economic growth levels of the six cities in the Guangzhou metropolitan area is continuously narrowing, and the synergy of the green economic growth is better.

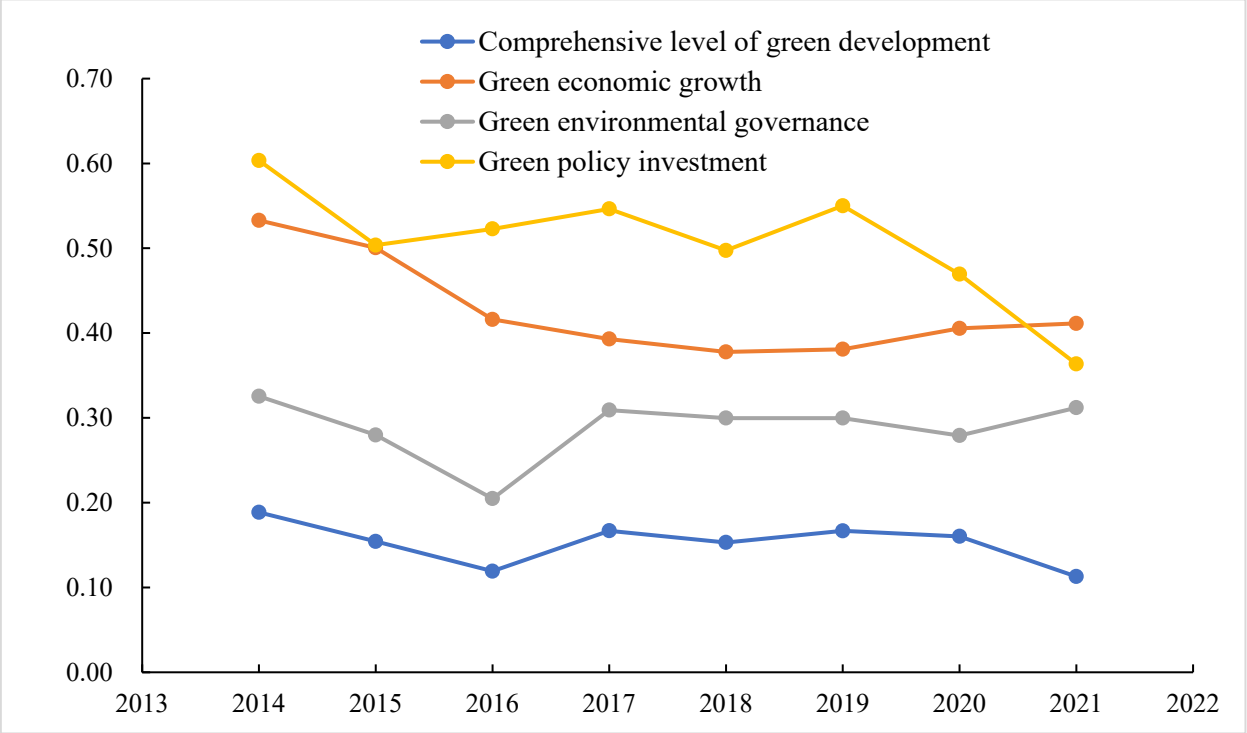

Figure 8. Coefficient variation of green development level in the Guangzhou metropolitan area (2011-2021).

To make the green development level situation of the six cities in the Guangzhou metropolitan area more intuitive, the spatial characterization of the green development level values of the towns in the Guangzhou metropolitan area was carried out by operating the ArcGIS software and using the natural intermittent point grading method, which is classified into three grades: low, medium, and high. Three-time nodes, 2011, 2016, and 2021, were selected to analyze the spatial evolution of the three dimensions and the composite index of the green development level of the six cities in the Guangzhou metropolitan area.

The spatial distribution of the green economic growth level in the Guangzhou metropolitan area changes little from 2011 to 2021, with the distribution of high-level and low-level regions relatively fixed, and only Zhaoqing changing from medium to low level, while the other five cities remain unchanged, presenting a spatial pattern of 'high in the middle and low on both sides'. Guangzhou, as the capital city of Guangdong Province, has always had the highest level of green economic growth and is far ahead of other cities. Foshan stays at the middle level, and Zhaoqing lags slightly behind in green economic development. In terms of the level of green environmental governance, the spatial

pattern of the Guangzhou metropolitan area changes relatively little from 2011-2021, except for Zhaoqing and Yunfu, which change from a high level to a medium level, the level of green development of the other cities remains unchanged, showing a spatial pattern of low in the southeast and high in the northwest. Among them, Shaoguan has a high level of green environmental governance. In contrast, Guangzhou and Foshan City have a low level, suggesting that rapid economic development may also bring ecological pollution problems and insufficient greening. The spatial distribution of green policy investment levels in the Guangzhou metropolitan area is relatively variable. Yunfu is always at a high level, Shaoguan is at a medium level, Guangzhou is at a low level, Qingyuan changes from a high level to a medium level, Zhaoqing changes from a high level to a medium level, and Foshan changes from a medium level to a low level. Qingyuan, Guangzhou, and Foshan have a relatively low percentage of investment in green policies during the study period, which needs to be paid more attention to.

The spatial pattern of the overall green development level of the Guangzhou metropolitan area in 2011 and 2021 is the same, with a pattern of 'low in the middle and high in the periphery', in which the green development level of Yunfu, Zhaoqing, and Shaoguan are all at a high level in the Guangzhou metropolitan area, followed by Qingyuan and Guangzhou, and Foshan is at a low level. In 2016, the green development level of Yunfu and Zhaoqing, was slightly reduced to a medium level. Comprehensively, the green development level index of Shaoguan is stable at a high level, Qingyuan and Guangzhou are ranked at a medium level, and the green development level of Foshan has been at a low level compared with the other five cities. The higher level of green development in the Guangzhou metropolitan area is the neighbouring cities, which have relatively low population density, high forest coverage and air quality, and better green environmental governance and green investment policies. Foshan is a substantial manufacturing base in China, with the 4th largest industrial scale in the country and a high level of economic development, but with a high population density, an industrial structure that favors high energy-consuming industries, and environmental protection that requires a more significant investment in management costs, which, to a certain extent, restricts its green development.

4.3 Analysis of Influencing Factors

The factors of green development in the Guangzhou metropolitan area are calculated through the barrier degree model, as shown in Table 2; the main factors are GDP per capita (*X2*), the proportion of investment in landscaping and greening to fixed assets (*X13*), the proportion of drainage investment to fixed investment (*X14*), the proportion of output value of the tertiary industry to GDP *(X4*), the proportion of expenditure on agriculture, forestry, and water affairs to fiscal expenditure (*X15*), and urban population density (*X11*). These main obstacle factors behave differently in different cities. Among them, Guangzhou mainly exists obstacle factors such as the proportion of agricultural, forestry and water affairs expenditures to fiscal expenditures, the proportion of investment in landscaping and greening to fixed assets, and the proportion of investment in drainage to fixed investment; Shaoguan mainly exists obstacle factors such as GDP per capita, the proportion of investment in landscaping and greening to fixed assets, the proportion of tertiary industry output value to GDP, and the proportion of investment in drainage to fixed investment; and Foshan mainly exists urban population density, Foshan city mainly exists urban population density, tertiary industry output value accounted for the proportion of GDP, landscaping investment accounted for the proportion of fixed assets, drainage investment accounted for the proportion of fixed investment, agriculture, forestry and water affairs expenditures accounted for the proportion of fiscal spending and other obstacle factors; Zhaoqing, Qingyuan and Yunfu are mainly exists per capita GDP, tertiary industry output value accounted for the proportion of GDP, landscaping investment accounted for the proportion of fixed assets, drainage investment accounted for the proportion of fixed investment and other obstacle factors.

Overall, the proportion of investment in landscaping to fixed assets (*X13*) and the proportion of investment in drainage to fixed investment (*X14)* have the highest frequency, indicating that the insufficient proportion of fixed investment in landscaping and drainage in the six cities of the Guangzhou metropolitan area is the most critical factor affecting the level of green development. Except for Guangzhou, the top three barriers to green development levels in the other five cities include the proportion of tertiary industry output to GDP. Hence, the industrial structure of each city needs to be adjusted.

Table 2. The top three obstacle factors and obstacle degree of green development level in the Guangzhou metropolitan area

	Guangzhou			Shaoguan			Foshan			Zhaoqing			Qingyuan			Yunfu		
2011	*X13*	*X14*	*X15*	*X13*	*X14*	*X2*	*X13*	*X14*	*X4*	*X13*	*X14*	*X2*	*X13*	*X14*	*X2*	*X13*	*X14*	*X2*
	21.64	18.02	10.86	25.45	19.78	14.63	19.66	17.12	9.94	22.88	21.55	13.76	23.10	18.26	13.12	24.61	16.75	14.77
2012	*X13*	*X14*	*X15*	*X13*	*X14*	*X2*	*X13*	*X14*	*X4*	*X13*	*X14*	*X2*	*X14*	*X2*	*X4*	*X13*	*X14*	*X2*
	22.20	18.87	10.58	25.53	19.21	14.85	20.70	18.67	9.78	24.14	21.04	13.24	27.79	17.48	10.92	22.62	18.20	14.91
2013	*X13*	*X14*	*X15*	*X13*	*X14*	*X2*	*X13*	*X14*	*X4*	*X13*	*X14*	*X2*	*X14*	*X13*	*X2*	*X14*	*X13*	*X2*
	21.87	18.87	10.60	25.99	19.56	14.19	18.82	17.71	9.61	23.12	20.96	12.30	21.47	18.56	14.88	20.12	19.86	15.00
2014	*X13*	*X14*	*X15*	*X13*	*X2*	*X8*	*X13*	*X14*	*X4*	*X13*	*X14*	*X2*	*X13*	*X14*	*X2*	*X13*	*X14*	*X2*
	21.43	18.99	11.42	29.41	15.76	9.15	19.65	18.20	9.82	23.90	20.94	12.24	23.28	21.96	13.37	22.58	20.32	12.79
2015	*X13*	*X14*	*X15*	*X13*	*X14*	*X2*	*X13*	*X14*	*X15*	*X13*	*X14*	*X2*	*X13*	*X14*	*X2*	*X13*	*X14*	*X2*
	22.57	19.96	11.41	29.41	15.64	15.63	20.04	18.41	9.61	24.64	20.85	12.29	24.58	23.17	13.91	24.60	22.15	13.70
2016	*X13*	*X14*	*X15*	*X13*	*X2*	*X14*	*X13*	*X14*	*X15*	*X13*	*X14*	*X2*	*X13*	*X14*	*X2*	*X13*	*X2*	*X4*
	23.30	19.13	11.96	28.64	15.98	15.64	21.68	20.18	10.90	24.75	22.11	12.02	24.91	22.40	13.08	27.25	14.85	11.73
2017	*X13*	*X14*	*X15*	*X13*	*X14*	*X2*	*X13*	*X14*	*X15*	*X13*	*X14*	*X2*	*X13*	*X14*	*X2*	*X14*	*X2*	*X4*
	22.62	18.58	12.17	24.76	17.94	13.86	21.19	18.96	10.43	25.29	21.81	12.29	26.88	21.74	14.00	28.83	17.18	9.64
2018	*X13*	*X14*	*X15*	*X13*	*X14*	*X2*	*X13*	*X14*	*X15*	*X13*	*X14*	*X2*	*X13*	*X14*	*X2*	*X13*	*X2*	*X14*
	23.47	17.96	12.40	26.42	22.09	13.08	21.51	19.28	11.09	26.34	23.03	12.04	27.98	21.85	14.56	27.18	16.00	14.26
2019	*X13*	*X14*	*X15*	*X13*	*X14*	*X2*	*X13*	*X14*	*X15*	*X13*	*X14*	*X2*	*X13*	*X14*	*X2*	*X13*	*X2*	*X4*
	24.77	16.71	13.07	26.73	23.74	12.81	21.92	19.12	11.20	28.12	17.82	12.37	25.84	20.96	13.70	34.07	17.90	10.04
2020	*X13*	*X14*	*X15*	*X13*	*X2*	*X4*	*X13*	*X14*	*X11*	*X13*	*X14*	*X2*	*X13*	*X14*	*X2*	*X13*	*X14*	*X2*
	25.50	14.80	13.60	25.40	17.44	10.02	21.89	19.86	11.30	28.82	15.62	12.94	26.87	21.36	12.97	27.96	21.00	14.12
2021	*X13*	*X14*	*X15*	*X13*	*X14*	*X2*	*X13*	*X14*	*X11*	*X13*	*X14*	*X4*	*X13*	*X14*	*X2*	*X13*	*X14*	*X2*
	24.67	18.84	13.47	30.14	23.09	13.42	20.22	19.98	11.75	29.40	17.28	11.74	23.02	22.55	12.45	25.78	21.99	13.94

5. Discussion

China's green development indicators have become an essential part of national policies, with green development as an important guiding concept for ecological civilization, the construction of a "Beautiful China," and global economic restructuring [34]. The level of green development refers to the comprehensive performance of a country or region that pays attention to environmental protection and pursues sustainable economic development. This concept covers resource conservation, environmental protection, ecological restoration, green industry, and technology. With the promotion of carbon peak and carbon neutral policies, as well as the United Nations' sustainable development goals, green development faces challenges such as economic growth remodeling, performance appraisal mechanisms, the update of energy-saving technologies, and public awareness of environmental issues. In the context of high-quality development, the enhancement of scientific and technological innovation thinking, and the high-speed development of big data, the concept, methodology, planning, and implementation of green development are being examined and reflected [51, 52]. This study seeks to construct a green development index system under the framework of "green economic growth—green environmental governance—green policy investment." It conducts a comprehensive study on the measurement, spatial evolution, and influence of the mechanism of green development level in the Guangzhou metropolitan area. However, due to the theoretical comprehensiveness of green development, the complexity of its extension, and differences in available statistics, the indicators of green development in the Guangzhou metropolitan area are different from standard indicators. Methodologically, the study applies spatial analysis and obstacle degree models, indicating potential for methodological diversity and precision. In the later stage, we will further consider the theoretical connotation of green development, focus on the systematic, comprehensive, and coordinated qualities, and improve the green development index system. Future research will compare methods across varying scales, carry out dynamic studies, and forecast green development levels to strengthen the empirical significance of green development research.

As one of the important metropolitan areas in Guangdong Province, the green development of the Guangzhou metropolitan area has achieved certain results, but it also faces some challenges. Strengthening the green transformation of industries and regional coordination, increasing difficulty in continuously improving air quality, arduous tasks in the green transformation of energy systems, and shortcomings in the circular economy system are all issues that need to be continuously addressed in the future. Aligning with national green development goals, our findings for Guangzhou highlight the critical role of policy investment and environmental governance.

Finally, updating the connotation of green development and constructing a scientific and comprehensive evaluation system are key to promoting green development in metropolitan areas. Currently, evaluations need to comprehensively consider multi-dimensional indicators such as economy, society, and environment, emphasizing data quality and multi-source integration, while optimizing models by combining quantitative and qualitative methods. In the future, big data and artificial intelligence should be leveraged to achieve intelligent evaluation and real-time monitoring. Regional collaboration and cooperation should be strengthened, public participation and environmental awareness should be enhanced, and international experiences should be drawn upon to improve the evaluation system. Through long-term tracking research and dynamic policy adjustments, the evaluation of green development in metropolitan areas will provide strong support for achieving sustainable, low-carbon, and livable urban agglomerations.

6. Conclusion and Recommendation

6.1 Conclusion

From the three perspectives of green economic growth, green environmental governance, and green policy investment, 15 indicators were selected to construct an evaluation index system for the green development level of the Guangzhou Metropolitan Area. Using the entropy method, the coefficient of variation method, and geographic information system (GIS), the changes and spatial differences in the green development level of the Guangzhou Metropolitan Area were analyzed. Based on the obstacle degree model, the influencing factors of the green development level in the Guangzhou Metropolitan Area were explored, and the following conclusions were drawn:

(1) The level of green development in the Guangzhou metropolitan area shows a general upward trend over the

study period; this reflects the fact that the Guangzhou metropolitan area is continuously strengthening its green economic growth, green environmental governance, and green policy investments, but there are still some differences within the metropolitan area. Foshan City consistently ranks the lowest in comprehensive green development levels, but has the highest growth rate. In addition, green economic growth is generally on a steady upward trend, while green environmental governance and green policy investment fluctuate with an upward trend, with a greater degree of fluctuation in the level of green policy investment. Guangzhou and Foshan lead in green economic growth levels green economic growth level, but lag behind in green environmental governance and green policy investment compared to the other four cities

(2) The coefficient of variation results show that the level of green development in the Guangzhou metropolitan area has been decreasing in spatial differences. The regional difference is changing a "low level-large gap" to a "high level-small gap," indicating better synergy in regional green development. However, there are still some spatial differences within the metropolitan area. The spatial distribution of green development level shows a pattern of 'low in the middle and high on both sides', with green development at a lower level in Foshan and a high level in Shaoguan. To a certain extent, these affect the implementation of the green synergistic governance system in the Guangzhou metropolitan area.

(3) Analyses of factors influencing green development help to identify the main issues and difficulties. Green environmental governance and green policy investment are the main dimensions that affect green development in the Guangzhou metropolitan area. Major influencing factors include the ratio of landscaping and greening investments to fixed assets and the ratio of drainage investments to fixed investments. Other factors include the proportion of tertiary industry output to GDP, per capita GDP, urban population density, and the proportion of agricultural, forestry, and water affairs expenditures to fiscal expenditure. All these factors are the main directions for low-carbon development, ecological construction, and environmental management in the Guangzhou metropolitan area.

6.2 Recommendations

6.2.1 Strengthen the linkage of the metropolitan area and build a regional green co-development mechanism

Under the opportunity of the current planning background, the Guangzhou metropolitan area establishes a reasonable green development guarantee system to share the development results among cities. It builds a mechanism suitable for the green development characteristics of the Guangzhou metropolitan area. Enhance the role of Guangzhou in driving the green economic growth in the neighborhood and promote the central city's radiation to drive the neighboring cities' joint development. Through mutual exchanges and collaboration among cities, promote the realization of industrial complementarity and green development among cities, formulate countermeasures suitable for the green development of their cities, to make the green development of the Guangzhou Metropolitan Area more balanced and gradually narrow the gap in the level of green development among cities, which will be conducive to the formation of a regional economic layout with complementary strengths and high-quality development. Establishing a strict green development management system, implementing green policies and investments according to the standard indicators, and improving the green social security system will enable the residents of the cities in the Guangzhou metropolitan area to share the fruits of green development.

6.2.2 Focus on green environmental governance and increase green investments

The Guangzhou metropolitan area needs to increase its green policy investment and put more effort into creating livable green urban space. In terms of green ecological governance and green policy investment, it is recommended that each city set up reasonable incentives and welfare benefits to attract more professionals and realize innovative eco-construction models in science and technology. Guangzhou and Foshan still have a lot of room for progress in green environmental governance and policy investment. In the future, it is necessary to strengthen the government's guidance and social participation, strengthen the government's role in planning and guiding green investment, regulating operations, service guarantee, etc., and establish a sound incentive and constraint mechanism to support the market-oriented and professional development of green finance. At the same time, we need to explore new modes of intelligent and refined management in green environmental governance.

6.2.3 Optimize the layout of the industrial structure and vigorously develop the green economy

The proportion of tertiary industry output to GDP is the main obstacle affecting most Guangzhou Metropolitan Area. Economic growth is the foundation and driving force of green development, and cities with a particular economic foundation can make more significant investments in environmental pollution control. To strengthen the structural adjustment of primary and secondary industries in the cities of Guangzhou Metropolitan Area, to increase the investment in science and technology, and to improve the production efficiency and energy utilization rate, the six towns of Guangzhou Metropolitan Area, which have an excellent ecological environment, should give full play to their advantages, and vigorously promote the development of tertiary industries. For example, Foshan City should emphasize the vital role and critical influence of ecological environmental protection on high-quality development and scientifically build a modern green development system.

Funding

This research was funded by the Philosophy and Social Science Planning Project of Guangdong Province (GD24XGL035); Guangdong General Colleges and Universities Characteristic and Innovative Projects (2024KTSCX126).

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material; further inquiries can be directed to the corresponding authors.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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