Research and evaluation of high-quality development of pearl River Delta and urban conglomeration based on energy consumption

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Abstract: In the framework of "dual carbon," the correlation between energy usage and the enduring advancement of the Pearl River Delta（PRD） urban cluster, emblematic of China's reform and opening policies, has garnered considerable interest across different segments of society. The problem of measuring regional high-quality development is related to many indicators and variables, and the quantitative measurement of this topic is a complex systematic project. Based on the high degree of specificity of the region, we have constructed a dynamic and comprehensive measurement system of advanced development for the nine cities in the PRD region using the degree of intensive socio-economic development, the construction of a regional social security system, the structure and efficiency of energy consumption, and the degree of harmony between human beings and the natural environment as the secondary indicators. Utilizing relevant data throughout the period spanning from 2005 to 2020, encompassing the nine cities within the PRD region. The study utilized various methodologies including the kernel density estimation model, GIS spatial model, Dagum Gini coefficient method, and simulation calculations to delve into the current status and trends of advanced development in the PRD urban conglomeration. It also examined the primary barriers to high-quality development in the PRD urban conglomeration and the mechanisms underlying internal coordination development within the urban conglomeration. The research suggests that enhancing the advanced development level in the PRD urban conglomeration relies on improving energy utilization efficiency, transitioning traditional industries, and promoting the development of eco-friendly industries. These findings offer decision-makers valuable insights and practical guidance for advancing high-quality development in the PRD urban conglomeration.

1. Introduction

Cities are significant achievements of human civilization, engines of socio-economic growth, and important carriers for people's pursuit of a better life. Since the launch of China's economic liberalization and international trade opening in 1978, urbanization has progressed rapidly, reaching a level of development that took the UK 200 years, the US 100 years, and Japan 50 years to achieve in just over 40 years. The "Outline Development Plan for the Guangdong-Hong Kong-Macao Greater Bay Area" was released by the CPC Central Committee and the State Council on Feb. 18, 2019. This plan targets the Guangdong-Hong Kong-Macao Greater Bay Area, encompassing cities like Guangzhou, Shenzhen, Zhuhai, and others within the PRD. This region covers an area of approximately 55,400 square kilometers. By the end of 2023, the total economic output reached 11.02 trillion yuan, and the permanent resident population was 78.2943 million. The region is distinguished as one of China's highly open and economically dynamic zones, playing a crucial strategic role in the country's broader developmental agenda. The urban cluster in the PRD exemplifies China's reform and opening-up policies in action, promoting the coordinated development of key regions in the country and establishing a new paradigm of urban conglomeration spearheaded by central cities and propelling regional development. It serves a significant function in strengthening interaction among regional groups and promoting development.

The planning of sustainable development in urban conglomerations is closely related to energy consumption, and it is an important research area in urban ecology. The connection between urban high-quality development and energy use has long been a hot topic of concern for various sectors of society and many scholars. Earlier researches on the comprehensive assessment of urban high-quality development from the energy consumption

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viewpoint predominantly concentrated on the subsequent aspects: ① Defining research themes - this involves defining the concept or understanding of high-quality development. For instance, in 1989, The World Commission on Environment and Development unveiled the concept of "sustainable development," defining it as development that meets current demands without hindering future generations' capacity to meet their own needs. [1-3]. ② Scope of research involvement: single cities or urban conglomerations (circles)[4-6], urbanization areas, rural areas[7-8], provincial autonomous regions[9-10], wetlands, lakes, river basins, etc[11-14]. ③ Regional research: studies on urban high-quality development across China have predominantly focused on the Yangtze River Delta urban conglomeration, with fewer examining the PRD. ④ Research methodologies: Mei Song[15] employed the elasticity coefficient method to forecast China's energy requirements and carbon footprint for the year 2020. Huaizhi Wang[16] studied artificial intelligence classification methods for deterministic solar power forecasting. Shijie Song[17] devised a set of measurement indices to gauge the standard of advanced development in coal mining regions and applied the Analytic Hierarchy Process and entropy weight approach to establish a measurement system for Shaanbei mining areas. Anton Nahman[18] crafted a detailed index for assessing green economic progress using 26 metrics across economic, social, and environmental dimensions.⑤ Impact mechanism or driving force: The UNSDC scrutinized the driving force behind urban ecological progress from the perspectives of driving force, state, and response[19-27]. The research indicates a two-way causal connection between economic growth and energy consumption, featuring reciprocal feedback loops. Furthermore, it asserts that sustainable energy usage contributes to economic expansion, with renewable energy driving both economic growth and environmental sustainability.

Through reviewing relevant research literature and their inspirations, this paper takes the nine cities in the PRD urban conglomeration of China as samples, Degree of intensive socio-economic development, construction of a regional social security system, structure and efficiency of energy consumption, and degree of harmony between human beings and the natural environment as secondary indicators, creates a comprehensive assessment framework for measuring high-quality development within urban conglomerations. Drawing on data from the sample area between 2005 and 2020, this research gauges the high-quality development level of both the urban conglomeration and its constituent cities employing the vertical and horizontal gap method. This involves techniques such as kernel density estimation, GIS spatial analysis, Dagum Gini coefficient, and others, the study employs simulation calculations to examine the spatial and temporal variations in high-quality development across the PRD region. It also analyzes the primary factors impeding the enhancement of high-quality development levels. This research scrutinizes variances, trends, and the evolution of spatio-temporal patterns concerning high-quality development and its influencing mechanisms. Additionally, it puts forward recommendations and strategies for optimizing energy consumption structures, aiming to augment and fortify the integrated sustainable development of the PRD urban conglomeration.

2. Research methods

2.1. Construction of Evaluation Index System

Urban development includes economic systems, social systems, energy systems, environmental systems, etc., all of which are intricately linked to energy consumption. Taking into account the requirements of the energy system for high-quality development and the factors affecting the structure of energy consumption, this paper opts for 21 assessment criteria spanning economic advancement, social stability, resource utilization, and the ecological environment from multiple dimensions and angles to comprehensively reflect the evaluation targets. The tiered measurement system for it is established, depicted in Table 1

Table 1. Tiered measurement system for Comprehensive Evaluation of Urban high-quality development

Target layer	The standard layer	Index layer	unit	Indicator attributes
The Urban high-quality development Index, A	Degree of intensive socio-economic development B1	Energy consumption of ten thousand yuan of GDP is C1	Tons of standard coal / ten thousand yuan	negative direction
		Per capita GDP C2	Yuan / person	forward direction
		R&D funds internal expenditure C3	100 million	forward direction
		The output value of the tertiary industry accounted for C4	%	forward direction
	Construction of a regional social security system B2	The typical noise level in the traffic surroundings is C5	decibel	negative direction
		The amount of road space per person is C6	m2	forward direction
		The extent to which urban areas have access to tap water is C7	%	forward direction forward direction

	The concentration of population is denoted by C8	People / km2	negative direction
	The rate at which urban sewage is treated is C9	%	forward direction
	The percentage of household garbage undergoing safe disposal is C10	%	forward direction
	The extent to which industrial solid waste is comprehensively utilized is denoted by C11	%	forward direction
	Industrial emissions of sulfur dioxide are represented by C12	Ten thousand tons	negative direction
	The capacity for industrial wastewater discharge is denoted as C13	million tons	negative direction
Structure and efficiency of energy consumption B3	C14 indicates the volume of fertilizer usage discounts	Ten thousand tons	negative direction
	C15 represents the overall area of land sown with crops	A thousand hectares	forward direction
	C16 stands for the daily per capita consumption of domestic water	rise	negative direction
	C17 denotes the green park area available per person	m^2	forward direction
	The green coverage rate within urban built-up areas is indicated by C18	%	forward direction
Degree of harmony between human beings and the natural environment B4	C19 represents the proportion of air quality graded as excellent	%	forward direction
	C20 signifies the extent of forest coverage	%	forward direction
	C21 stands for the emissions of carbon dioxide	megaton	negative direction

2.2 Evaluation Method and Basic Steps

Assessing the level of high-quality development urban conglomerations involves dynamically evaluating various factors. This study utilizes both horizontal and vertical grading techniques to assess indicators within these conglomerations. This approach improves the comparison of temporal data, offering a more intuitive depiction of the overall status in urban areas [28]. The detailed procedure is outlined as follows:

(1) Data standardization and processing involve applying Formula (1) to positive indicators and Formula

(2) to negative indicators.

$$x_{ij} = \frac{X_{ij} - \min(X_{ij})}{\max(X_{ij}) - \min(X_{ij})} \tag{1}$$

$$x_{ij} = \frac{\max(X_{ij}) - X_{ij}}{\max(X_{ij}) - \min(X_{ij})} \tag{2}$$

In the formula $X_{ij}(i = 1,2,\cdots,n; j = 1,2,\cdots,m)$, It represents the value of the j index for the i-th evaluation entity, and x_{ij} represents the index value after standardization treatment, $x_{ij} \in (0,1)$.

(3) Set up the evaluation function. The m evaluation indicators constitute n points in the m-dimensional evaluation space. The evaluation value can be regarded as the n points projected into a certain space, and each projection point is most scattered in this space, so as to maximize the difference between the evaluation objects. See the evaluation function set according to the panel dataFormula (3).

$$y_i(t_k) = \sum_{j=1}^{m} w_j x_{ij}(t_k) \tag{3}$$

Among them, $y_i(t_k)$ is the comprehensive evaluation value of the i-th evaluation object in period t_k, and w_j is the weight of the i-th evaluation index.

If it is written as $y_i = (y_1, y_2, \ldots, y_n)^T$ $w = (w_1, w_2, \ldots, w_m)^T$,

$$A_K = \begin{bmatrix} x_{11}(t_k) & x_{12}(t_k) & \cdots & x_{1m}(t_k) \\ x_{21}(t_k) & x_{22}(t_k) & \cdots & x_{2m}(t_k) \\ \cdots & \cdots & \cdots & \cdots \\ x_{n1}(t_k) & x_{n1}(t_k) & \cdots & x_{nm}(t_k) \end{bmatrix},$$

then equation (3) can be rewritten as $y = Aw$.

(4) Determine the weight. on the basis of w_j, The difference maximization principle between evaluation objects is solved, and this difference can be expressed by the total sum of squares: $y_i(t_k)$ and σ^2

$$\sigma^2 = \sum_{k=1}^{N} \sum_{i=1}^{n} [y_i(t_k) - \overline{y}]^2 \tag{4}$$

As a result of the normalization of the raw data, will $\bar{y}=0$, $y=Aw$ Transfer formula (4), get formula (5).

$$\sigma^2=\sum_{k=1}^{N}\sum_{i=1}^{n}[y_i(t_k)-\bar{y}]^2=\sum_{k=1}^{N}[w^T H w]=w^T\sum_{k=1}^{N}H_k w \quad (5)$$

Where, $H=\sum_{k=1}^{N}H_k$ $m\times m$ is the symmetric matrix and $H_k=A_k^T A_k\,(k=1,2,\cdots,N)$ is the real symmetric matrix. Obviously, the maximum value of formula (5) is the selection w, and $\max_{\|w\|=1} w^T H w=\lambda_{max}(H)$, $\sum_{j=1}^{m}w_j=1$. Solve the maximum eigenvalue of matrix H, calculate the corresponding eigenvector, and normalize w.

(5) Calculate the high-quality development based on Equation (3) for the urban conglomeration and each city.

2.3 The Dagum Gini coefficient

Utilizing the suggested Gini coefficient decomposition method, the spatial disparity in high-quality development levels across the PRD urban conglomeration is dissected, following Dagum[29]. The overarching Gini coefficient, G, can be broken down into contributions from intra-region disparity G_w, inter-region wealth disparity G_{nb}, hyper-variable density G_t, and their interrelationship conforms to certain criteria $G=G_w+G_{nb}+G_t$ ($G\in[0,1]$). Among them, G_w shows the difference in the development level of the three metropolitan areas in the PRD urban conglomeration, G_{nb} shows the disparity in the net value of the development level of the metropolitan areas, and G_t shows the contribution of the overlapping effect of the three metropolitan areas to the variance in development levels across the urban conglomeration. Typically, a smaller Gini coefficient suggests lesser regional disparities, while a larger one indicates the opposite, the larger the regional difference, the specific formula ref[30].

2.4 Obstacles degree model

This study explores the obstacle degree model is applied to identify factors hindering progress within the PRD urban conglomeration. According to the size of the obstacle degree, which reflects the influence of these factors, larger values indicate greater barriers to development, while smaller values suggest fewer impediments. The formula used is as follows:

$$P_{ij}=\frac{w_j(1-x_{ij})}{\sum_{j=1}^{m}w_j(1-x_{ij})}\times 100\% \quad (6)$$

Where, w_j represents the evaluation weight of the j indicator on the development level; x_{ij} represents the index value of the j index of the i city after standardization; P_{ij} represents the obstacle degree of the j index of the i city to the level of development; m represents the total number of evaluation indicators.

3. Study area and data sources

3.1 Overview of the study area

The nine urban centers forming the PRD metropolitan area situate themselves at the southern entrance of China. Together with the Hong Kong and Macao Special Administrative regions, they have become an important region for the GBA and China's economic and social development. The GBA resembles the San Francisco Bay Area, surrounded by mountains on three sides and facing the sea on one side, making it ideal for an export-oriented economy. The Greater Bay Area (GBA) consists of nine cities along with two special administrative regions.

3.2 Indicator system and data sources

High-quality development represents a mode of growth that achieves a harmonious balance among economic, social, and ecological systems under the restriction of resources and the environment highlighting the harmonization and synergy between economic development and environmental preservation by prioritizing minimal resource usage and reducing pollution emissions. The primary sources of data for this study are drawn from the China Urban Statistical Yearbook, Guangdong Provincial Statistical Yearbook, and China Urban Construction Statistical Yearbook, covering the period from 2005 to 2020， as well as Guangdong Rural Statistical Yearbook and relevant cities and relevant city statistical Bulletin of 2005-2020. Due to data acquisition restrictions, the missing data in some cities was scientifically corrected by interpolation. This article initiates its discussion by delving into the concept of high-quality development. Referencing Wang Yizhao[31] and WANG[32], it examines the evaluation indices for high-quality development specific to the PRD region. This analysis aligns with the "high-quality development index system" and the "assessment of ecological civilization construction system" published by the National Development and Reform Commission and other pertinent agencies. These initiatives were integrated with the ongoing construction efforts in the PRD National high-quality development Demonstration Area, from the degree of intensive socio-economic development, construction of a regional social security system, structure and efficiency of energy consumption, and degree of harmony between human beings and the natural environment four aspects to build the PRD urban conglomeration high-quality development evaluation index system (Table 2).

Table 2. Assessment framework for sustainable growth within the urban cluster of the PRD

Target layer	The standard layer	Index layer	unit	attribute	Indicator weight
high-quality development level in the Pearl River Delta urban conglomeration	Degree of intensive socio-economic developmentB1	The energy consumption per ten thousand yuan of GDP is denoted as C1	Tons of standard coal	—	0.0500
		Per capita GDP of C2	first	+	0.0464
		R & D funds internal expenditure C3	Wan Yuan	+	0.0429
		C4 represents the proportion of the tertiary industry's output value within the total	%	+	0.0462
	Construction of a regional social security system B2	Per capita road area of C5	square meter	+	0.0467
		Urban tap water penetration rate is C6	%	+	0.0543
		Population density of C7	Person / square kilometer	—	0.0509
		Urban sewage treatment rate is C8	%	+	0.0527
		C9 refers to the rate of harmless treatment of household garbage	%	+	0.0538
		C10 stands for the comprehensive utilization rate of industrial solid waste	%	+	0.0524
	Structure and efficiency of energy consumption B3	Industrial SO2 emissions of C11	ton	—	0.0523
		Industrial waste water discharge capacity: C12	Ten thousand tons	—	0.0538
		C13	ton	—	0.0511
		By year-end, the actual area of arable land is represented by C14	hectare	+	0.0460
		Per capita domestic water consumption is C15	rise	—	0.0510
		Per capita domestic electricity consumption is C16	Ten thousand kilowatt-hours	—	0.0517
	Degree of harmony between human beings and the natural environment B4	Green park area per capita is C17	square meter	+	0.0490
		Green coverage rate of the built-up area is C18	%	+	0.0500
		Days with good air quality: C19	sky	+	0.0516
		Forest coverage rate of C20	%	+	0.0474

4. Results and analysis

4.1 Analysis of the time evolution of the high-quality development level

Using the longitudinal-horizontal grade pulling method, the high-quality development levels among the nine cities within the PRD Urban Conglomeration from 2005 to 2020 were analyzed, as depicted in Figure 1. The general level of high-quality development in the PRD Urban Conglomeration exhibited a steady rise, climbing from 0.516 in 2005 to 0.701 in 2020, with only a slight decrease in 2013. Although there was a negative growth in 2003, the high-quality development level remained above 0.6. The rate of increase in the high-quality development level fluctuated around 1% between 2015 and 2020, entering a phase of stable growth. This was largely due to the execution of the "13th Five-Year Plan" for Environmental Protection in Guangdong Province, which led to continuous improvement in the environmental quality of the PRD region's ecology.

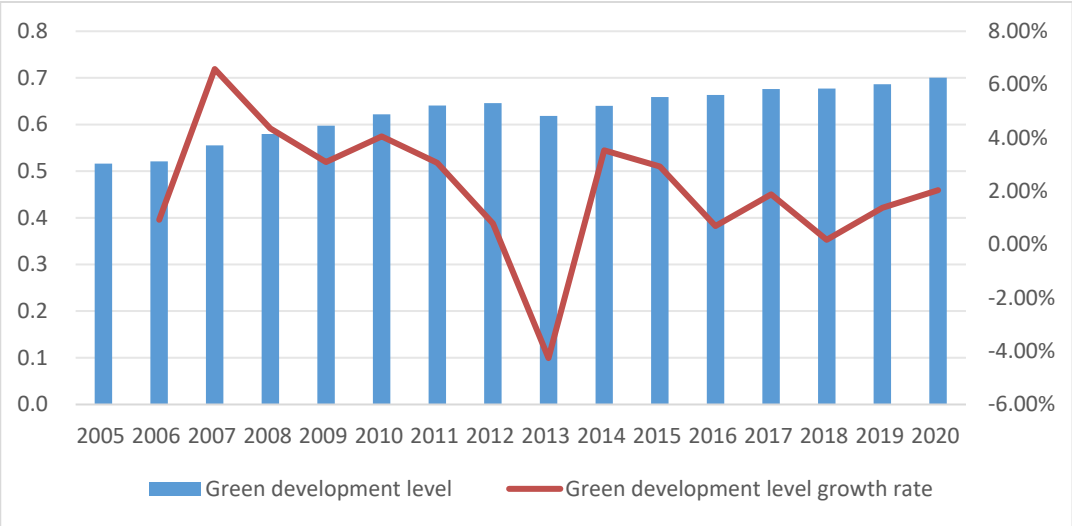

Figure 1. Evolution of development levels in the PRD urban conglomeration, 2005-2020

To more thoroughly analyze the dynamic changes in the development quality of the PRD Urban Conglomeration, density estimation curves at different time points were plotted using Stata (Figure 2). In 2005, the curve had a wide range of values with lower peaks, indicating significant disparities in the level of high-quality development across cities, with most cities being at a low level, exhibiting characteristics of "low level and imbalance." The range of values for the curves in 2010 and 2015 narrowed compared to 2005, with increased peak heights and narrower peaks, indicating an overall improvement in the high-quality development level of the urban conglomeration, with a growing number of cities achieving higher development tiers, showing characteristics of "relatively high level and relatively balanced." In 2020, the range of values for the density curve further narrowed, and the curve shifted noticeably to the right, indicating a further reduction in internal differences and exhibiting characteristics of "high level and balance."

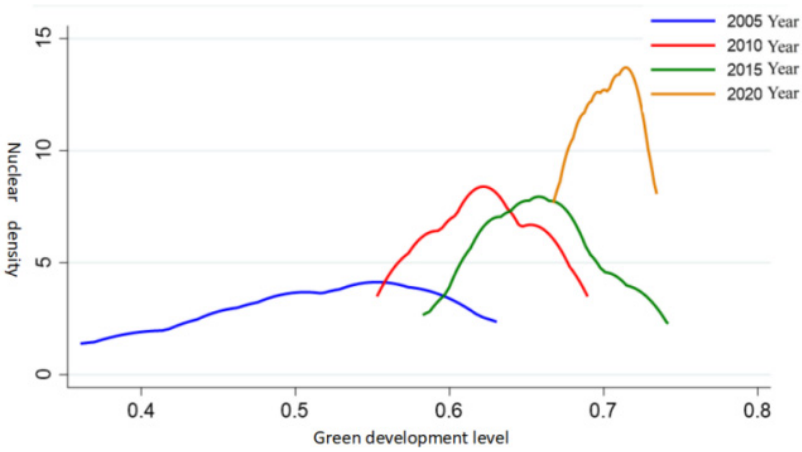

Figure 2. Nuclear density curve of the high-quality development level in the PRD urban conglomeration

4.2 The spatial pattern analysis of the high-quality development level

Four typical years, 2005, 2010, 2015, and 2020, were selected for spatial pattern analysis of the high-quality development level of the urban conglomeration. The cities were categorized into four levels based on their level values: high level [0.7, 1], medium level [0.65, 0.7), medium-low level [0.6, 0.65), and low level (0, 0.6). Spatial distribution maps were drawn using ArcGIS software (see Figure 3). It can be observed that the spatial distribution of development in the PRD Urban Conglomeration reflects a temporal pattern, with an upward trend in the development quality of internal cities. The spatial evolution of the PRD Urban Conglomeration exhibits a progressive pattern, showing a "middle-low, surrounded by high" distribution characteristic.

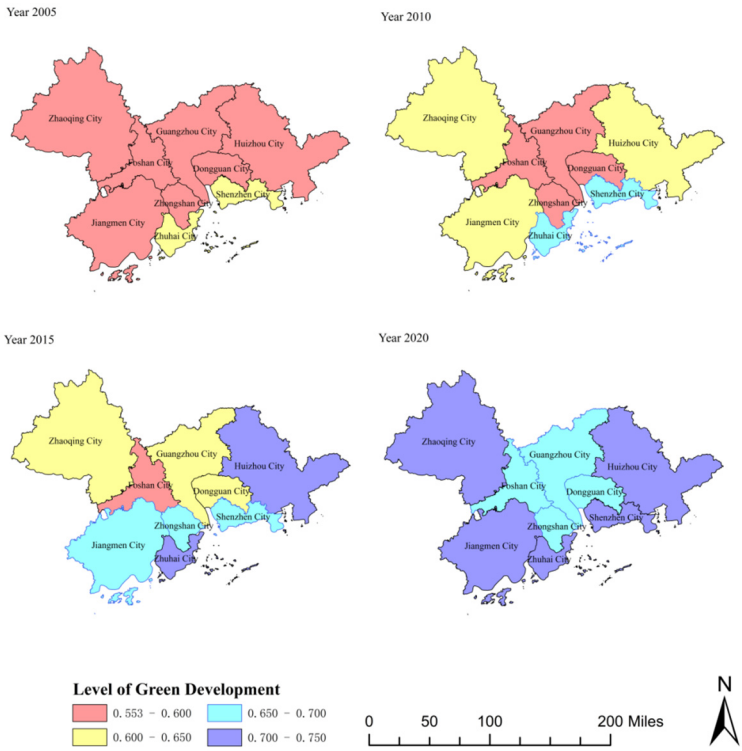

Figure 3. Spatial distribution pattern of high-quality development level in the PRD urban conglomeration

4.3 Regional difference analysis of high-quality development level

The preceding analysis demonstrates that the PRD urban conglomeration high-quality development has significant spatial points, in order to more clearly uncover the regional disparities within the urban conglomeration, this paper is divided into Guangzhou city circle, Shenzhen city circle, Zhuhai-West city circle three areas, and using the Dagum gini coefficient to examine regional difference size and specific sources, the findings depicted in Table 3 and Figure 4.

As shown in Table 3, the reduction in disparity levels from 2005 to 2008 occurred at a notably quick pace. From 2009 to 2014, the disparity level fluctuated slightly, with a slight increase. However, the disparity level decreased again in 2015, reaching a minimum value of 0.018 in 2020. This indicates that in recent years, the synchronized advancement of high-quality development in the PRD Urban conglomeration has attained notable accomplishments. In terms of inter-group differences, the trend of variations in the Gini coefficient among regions throughout the study period showed similarity, presenting a "first decline—then fluctuation rise—followed by decline again" pattern. In the early stages, the Gini coefficients between the Guangzhou Metropolitan Area and the Shenzhen Metropolitan Area, the Guangzhou Metropolitan Area, and the Zhuhai-West Metropolitan Area, and the Shenzhen Metropolitan Area and the Zhuhai-West Metropolitan Area took turns holding the top position. After 2009, the inter-group Gini coefficients between Guangzhou and the Zhuhai-West Metropolitan Area remained consistently high.

Table 3. The Gini coefficient of the high-quality development level of the PRD urban conglomeration

a particular year	ensemble	Differences within groups			Differences between groups		
		Guangzhou metropolis circle	Shenzhen metropolis circle	Zhuhai-West metropolis circle	Guangzhou metropolitan area VS Shenzhen Metropolitan Area	Guangzhou metropolitan area VS Zhuhai-West metropolitan area	Shenzhen metropolitan area VS Zhuhai-West metropolitan area
2005	0.092	0.049	0.113	0.045	0.111	0.102	0.098
2006	0.084	0.042	0.108	0.038	0.099	0.090	0.094
2007	0.058	0.048	0.076	0.023	0.070	0.053	0.066
2008	0.034	0.021	0.029	0.030	0.031	0.045	0.038
2009	0.035	0.018	0.030	0.025	0.046	0.048	0.029
2010	0.036	0.035	0.023	0.033	0.036	0.046	0.033
2011	0.036	0.035	0.036	0.021	0.039	0.040	0.035
2012	0.035	0.029	0.027	0.026	0.034	0.047	0.035
2013	0.046	0.009	0.031	0.040	0.056	0.069	0.044

2014	0.047	0.016	0.036	0.030	0.062	0.067	0.042
2015	0.038	0.023	0.021	0.030	0.050	0.055	0.032
2016	0.035	0.012	0.012	0.036	0.045	0.051	0.031
2017	0.021	0.018	0.009	0.019	0.026	0.031	0.017
2018	0.019	0.020	0.007	0.022	0.019	0.023	0.019
2019	0.022	0.017	0.014	0.027	0.018	0.028	0.024
2020	0.018	0.020	0.010	0.018	0.018	0.022	0.018

Based on the Gini coefficient decomposition results (Figure 4), it can be observed that from 2005 to 2017, the largest contribution to the Gini coefficient came from inter-group differences, being the main source of overall differences. After 2018, the proportion of the contribution made by super-variable density surpassed both intra-group and inter-group differences, emerging as the dominant factor driving the imbalance in these levels. Although showing a tendency of increasing in recent years, its value remained below 0.3.

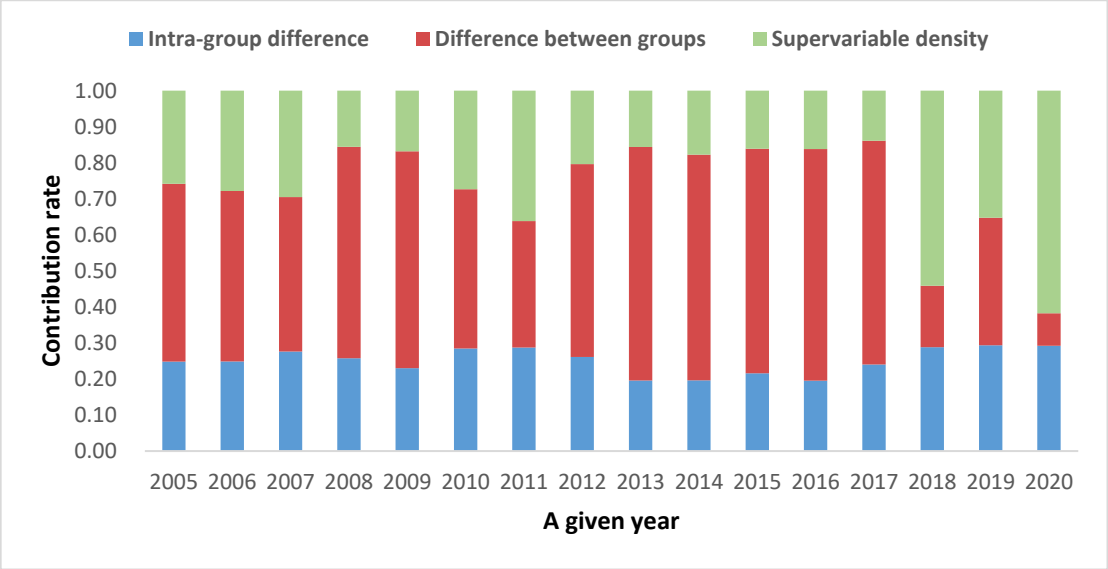

Figure 4. PRD urban conglomeration: decomposition the sources of regional variations in high-quality development levels

4.4 Analysis of Obstacles to high-quality development

To assess the development, the obstacle degree model was employed. The mean obstacle degree associated with the development index for the PRD urban conglomeration was computed over the period from 2005 to 2020. Given the multitude of indicators, the top six obstacle factors for each region were selected for analysis (see Table 4). The main barrier factor in the Guangzhou metropolitan area is road space per capita, with a barrier level of 7.94%, indicating that there is a shortage of public resources in the area. The main obstacles in the Shenzhen metropolitan area are social security and the ecological environment. The obstacle degrees of per capita road area and per capita park green area are 8.98% and 6.16% respectively, indicating poor performance in per capita public resource levels and resource endowment conditions in the Shenzhen, Dongguan, and Huizhou areas. The remaining main obstacles in the Pearl River West metropolitan area are reflected in the ecological environment, with obstacle degrees of per capita park green area and forest coverage rate reaching 7.04% and 10.05% respectively, showing that environmental quality issues are prominent obstacles to high-quality development in the Zhuzhongjiang area.

Table 4. Regional high-quality development indicators of the PRD urban conglomeration obstacle unit:%

region	project	Factor ranking					
		1	2	3	4	5	6
Guangzhou metropolitan area	obstruction factor	C3	C5	C2	C4	C13	C14
	Disorder degree	9.903	7.939	7.567	7.162	7.041	6.397
Shenzhen metropolitan area	obstruction factor	C14	C3	C5	C4	C2	C17
	Disorder degree	9.608	9.306	8.984	7.861	7.786	6.160
Zhuhai West metropolitan area	obstruction factor	C3	C20	C4	C14	C2	C17

	Disorder degree	12.163	10.054	9.639	9.371	8.858	7.036
Pearl River Delta city cluster	obstruction factor	C3	C14	C4	C2	C5	C20
	Disorder degree	10.457	8.459	8.221	8.070	7.862	7.286

5 Conclusion and Recommendations

5.1 Conclusion

In the context of this study, which examines panel data from 2005 to 2020 across the nine cities of the PRD urban conglomeration, an evaluation index system for high-quality development evaluation was constructed. Utilizing the horizontal method for assessing the urban conglomeration's development and its internal levels, the study integrates nuclear density estimation and GIS spatial analysis. The Dagum Gini coefficient was applied to explore development characteristics in the PRD. Subsequently, the barrier model was used to analyze the primary factors influencing high-quality development. The main findings can be outlined as follows:

(1) Over time, the high-quality development level of the PRD urban conglomeration increased markedly, rising from 0.516 in 2005 to 0.701 in 2020, showing a consistent upward trajectory. The disparity in high-quality development among the cities is decreasing annually, with an increase in the number of high-level cities and a decrease in low-level cities. This trend suggests that the urban conglomeration is moving towards balanced development, reflecting a healthy high-quality development mode.

(2) Considering spatial differentiation, the spatial distribution of high-quality development level in the PRD shows a temporal inheritance, with the high-quality development level of internal cities showing a stair-step upward trend. However, the spatial pattern of "low in the middle, high around" remains deeply rooted.

(3) Considering the barriers to high-quality development, per capita GDP, internal R&D expenditure, the share of the tertiary sector in total economic output, and the year-end cultivated land area are the main obstacles shared by the urban conglomeration and internal urban circles. It's evident that enhancing the high-quality development level in the PRD should prioritize economic growth and optimizing resource utilization.

5.2 Recommendations

Through the above analysis, it is known that to promote the stable growth of high-quality development level in the PRD urban conglomeration and the coordinated development of regional high-quality development, It's crucial to implement a collaborative approach involving multiple parties, led by the government, while incorporating social oversight and public participation. Continuously optimizing the structure of energy consumption and driving the integration of regional ecological and superior quality development is vital. Here are the proposed recommendations:

(1) Promote the development of circular economy strategies to improve energy efficiency and consistently optimize the energy consumption structure within the economic framework. Implement principles of "reduction, reuse, and energy conversion" to reduce pollution emissions through effective resource recycling. Maintain standards of "resource conservation" and "environmental friendliness" throughout all processes.

(2) Advocate green culture and build a reasonable social structure to continuously enhance the efficiency of energy consumption within the social system. Foster amiable, organic social connections to cultivate a lifestyle and consumption habits that are lower in carbon emissions, environmentally sustainable, and promote better health. Improve environmental protection awareness throughout society and achieve coordination in education, health care, employment, social security, social fairness, and protection.

(3) To foster regional high-quality growth, it is imperative to elevate the development and exploitation of renewable and pristine energy sources while persistently improving the energy consumption architecture within the energy system. Tailored strategies based on the resource endowment of each region are essential. This includes increasing the deployment of renewable energy such as solar, nuclear, and wind， and implementing a distributed multi-energy operational model to optimize energy consumption patterns.

(4) Consider environmental resources as integral components of socio-economic development and consistently refine the energy consumption framework within the environmental system. The government plays a crucial role in this by effectively steering through macroeconomic policy regulation, establishing a fair and equitable institutional framework, continuously enhancing relevant laws and regulations on energy consumption and fostering market competition. Advocating for green and low-carbon consumption patterns is essential, along with ongoing efforts to optimize the energy consumption structure.

(5) Adhere to innovation-driven development and build a green industrial system. Currently, aside from developed cities like Shenzhen, innovation capabilities and industrial structures are significant impediments to high-quality development in other cities within the PRD urban conglomeration. Moving forward, the PRD should advocate for the transformation and upgrading of industrial high-quality development, increase investment in scientific investigation and development, and boost autonomous creativity skills to offer robust backing for the superior development of the urban conglomeration.

(6) Achieve complementary advantages and promote regional coordinated development. Cities within the PRD urban conglomeration exhibit disparities in their

economic development foundation, industrial structure, ecological environment quality, and resource endowment. It is necessary to implement high-quality development strategies taking into account the unique strengths and advantages of each city, give full play to the innovative research and development capabilities of cities such as Guangzhou and Shenzhen, and the advantages of complete industrial chains in cities such as Foshan, Zhaoqing, Dongguan, Zhuhai, and Zhongshan, to promote regional coordinated high-quality development.

(7) Enhance infrastructure development to facilitate the optimization of public resource distribution. The shortage of high-quality public resources is a prominent barrier to high-quality development in the PRD urban conglomeration. The per capita levels of public resources such as green space, roads, education, and medical care are relatively low. Therefore, government departments should tailor fiscal policies according to the development status and population of individual cities, aiming to ensure a logical and efficient distribution of public resources within the region.

Considering the intricate, inclusive, cohesive, and ever-evolving nature of energy usage and societal progress systems in regional urban clusters, a comprehensive index system for assessing urban high-quality development was formulated. Building upon the assessment of the this level within this urban conglomeration and internal cities using the longitudinal and transverse grade method, in this study, various methods including kernel density estimation, GIS spatial analysis, Dagum Gini coefficient, etc., were employed to investigate the temporal and spatial disparities in high-quality development across the PRD. Finally, the obstacle degree model was utilized to scrutinize the primary factors constraining the enhancement of high-quality development levels, delving into the dynamics and spatial distribution pattern of high-quality development within this region. The research results of this study, including theoretical, methodological, model, and algorithm design, in the application research in relevant fields, are worthy of recognition and expectation. Given space constraints, further exploration of this topic will serve as our forthcoming objectives and investigative outlook.

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References

1. Daly D J. A History of the Economics Branch of the Department of Trade and Commerce[J]. Canadian Business Economics, 1997.
2. Ruggerio C A. Sustainability and sustainable development: A review of principles and definitions[J]. Science of the Total Environment, 2021, 786: 147481.
3. Ruggerio C A. Sustainability and sustainable development: A review of principles and definitions[J]. Science of the Total Environment, 2021, 786: 147481.
4. Tian Y, Wang R, Liu L, et al. A spatial effect study on financial agglomeration promoting the high-quality development of urban conglomerations[J]. Sustainable Cities and Society, 2021, 70: 102900.
5. Li L, Ma S, Zheng Y, et al. Integrated regional development: Comparison of urban conglomeration policies in China[J]. Land Use Policy, 2022, 114: 105939.
6. Kii M. Projecting future populations of urban conglomerations around the world and through the 21st century[J]. npj Urban Sustainability, 2021, 1(1): 10.
7. Hu Caiyun. Study on urbanization and Coordination with Ecological environment in Heilongjiang Province [D]. Harbin Normal University, 2015.
8. Zhang Jixiang. Assessment of rural environmental quality in Hunan Province [D]. Hunan Normal University, 2014.
9. Liu Y, Zhang X, Pan X, et al. The spatial integration and coordinated industrial development of urban conglomerations in the Yangtze River Economic Belt, China[J]. Cities, 2020, 104: 102801.
10. Li Z, Jiang W, Wang W, et al. Ecological risk assessment of the wetlands in Beijing-Tianjin-Hebei urban conglomeration[J]. Ecological Indicators, 2020, 117: 106677.
11. Zhang Z, Jiang W, Peng K, et al. Assessment of the impact of wetland changes on carbon storage in coastal urban conglomerations from 1990 to 2035 in support of SDG15. 1[J]. Science of The Total Environment, 2023, 877: 162824.

12. Ventzislav Karamfilov, Dimitar Berov, Panayotis Panayotidis.Using Zostera noltei biometrics for evaluation of the ecological and environmental quality status of Black Sea coastal waters[J]. Regional Studies in Marine Science, 2019, (27): 1-11s.
13. Gao Z, Li C, Zou S, et al. Riverine wetland dynamics and health assessment: A case study in the urban conglomerations along the Yellow River in China's Ningxia Hui Autonomous Region[J]. Ecological Indicators, 2024, 162: 111965.
14. Kundu S, Rana N K, Mahato S. Unravelling blue landscape fragmentation effects on ecosystem services in urban conglomerations[J]. Sustainable Cities and Society, 2024, 102: 105192.
15. Mei Song; Zong Yuan Lin; Yan Qing Zuo; Tao Chen.Optimization Research on Carbon Emissions and Energy Structure of Responding to Climate Change.Applied Mechanics and Materials, Trans Tech.2013(10).291-294.
16. Huaizhi Wang, Yangyang Liu, Bin Zhou, Canbing Li, Guangzhong Cao, Nikolai Voropai, Evgeny Barakhtenko, Taxonomy research of artificial intelligence for deterministic solar power forecasting, Energy Conversion and Management, Volume 214, 2020, 11 A. 2,909.
17. Shi Jie Song; Jin Suo Zhang; Wei Zhang.Study on the Measurement Index System of Green Development Degree in Coal Mining Area Based on Comprehensive Environmental Capacity.Advanced Materials Research.2015(10).
18. Anton Nahman; Brian K.Mahumani; Willem J.de Lange.Beyond GDP: Towards a Green Economy Index.Development Southern Africa, Taylor & Francis.2016(10).215-233.
19. Su Y, Fan Q M. Renewable energy technology innovation, industrial structure upgrading and high-quality development from the perspective of China's provinces[J]. Technological Forecasting and Social Change, 2022, 180: 121727.
20. Cheng Z, Wang H, Xiong W, et al. Public–private partnership as a driver of sustainable development: Toward a conceptual framework of sustainability-oriented PPP[J]. Environment, Development and Sustainability, 2021, 23: 1043-1063.
21. Wang Y, Niu Y, Li M, et al. Spatial structure and carbon emission of urban conglomerations: Spatiotemporal characteristics and driving forces[J]. Sustainable Cities and Society, 2022, 78: 103600.
22. Ren S, Li L, Han Y, et al. The emerging driving force of inclusive green growth: does digital economy agglomeration work?[J]. Business Strategy and the Environment, 2022, 31(4): 1656-1678.
23. Kwatra S, Kumar A, Sharma P. A critical review of studies related to construction and computation of Sustainable Development Indices[J]. Ecological Indicators, 2020, 112: 106061.
24. Ruan F, Yan L, Wang D. The complexity for the resource-based cities in China on creating sustainable development[J]. Cities, 2020, 97: 102571.
25. Martín Martín J M, Calvo Martínez S, Guaita Martínez J M, et al. Qualitative analysis on the driving force behind upcycling practices associated with mobile applications: Circular economy perspective[J]. Operations Management Research, 2022, Early-access.
26. Moallemi E A, Malekpour S, Hadjikakou M, et al. Achieving the sustainable development goals requires transdisciplinary innovation at the local scale[J]. One Earth, 2020, 3(3): 300-313.
27. Dai J, Ahmed Z, Alvarado R, et al. Assessing the nexus between human capital, green energy, and load capacity factor: policymaking for achieving sustainable development goals[J]. Gondwana Research, 2024, 129: 452-464.
28. Zhang Feng, Song Xiaona, Dong Huizhong. Analysis of green competitiveness index measurement and evolution characteristics of manufacturing industry in the Guangdong-Hong Kong-Macao Greater Bay Area [J]. China Soft Science, 2019 (10): 70-89.
29. Loizia P, Voukkali I, Zorpas A A, et al. Measuring the level of environmental performance in insular areas, through key performed indicators, in the framework of waste strategy development[J]. Science of the Total Environment, 2021, 753: 141974.
30. Yang Xinmei, Huang Heping, Zhou Ruihui. Evaluation of urban high-quality development level in China [J/OL]. Journal of Ecology, 2023 (04): 1-13 [2023-02-11].
31. Semeraro T, Scarano A, Buccolieri R, et al. Planning of urban green spaces: An ecological perspective on human benefits[J]. Land, 2021, 10(2): 105.
32. Ghasemian S, Faridzad A, Abbaszadeh P, et al. An overview of global energy scenarios by 2040: identifying the driving forces using cross-impact analysis method[J]. International Journal of Environmental Science and Technology, 2020: 1-24.