Original Research Article

A Study on the Spatio-Temporal characteristics and enhancement pathways of the green economic competitiveness of the Guangdong-Hong Kong-Macao greater bay area under the dual carbon goals

Wei Gao

Hainan Vocational University of Science and Technology, Haikou city, Hainan Province, 571126, China

Abstract: The rapid advancement of urbanization has brought about traffic congestion and environmental pollution, highlighting the tension between livability and development pace in cities. Against this backdrop, as people increasingly pursue higher quality of life, ecological city development has emerged as a crucial direction for promoting sustainable development. As one of China's most economically developed and innovative regions, the Yangtze River Delta plays a pivotal role in advancing ecological civilization goals and national development plans through enhancing its ecological city development standards.

Against the backdrop of the "dual carbon" goals, this paper focuses on enhancing the green economic competitiveness of the Guangdong-Hong Kong-Macao Greater Bay Area. It constructs a three-dimensional evaluation system encompassing economic momentum, ecological resilience, and social welfare. Employing methods such as Gini coefficient decomposition and kernel density estimation, the study systematically examines the spatiotemporal characteristics and improvement pathways of the region's green economic competitiveness from 2005 to 2022. Results indicate: The comprehensive green economic competitiveness index of the Greater Bay Area grew at an average annual rate of 3.2%. However, regional disparities exhibited a gradient pattern of "inter-cluster variation (50.23%) > super-variability density (31.41%) > intra-cluster variation (18.36%)". The kernel density distribution evolved from unipolar dominance to multipolar symbiosis, with low-level cities experiencing a "club convergence" effect. The decline in the spatial σ convergence coefficient indicates gradually narrowing regional disparities. However, the competitiveness of the ecological subsystem (2.7% annual growth) lags behind that of the economic subsystem (4.2%). Core cities exhibit a carbon intensity over-limit rate of 12%, creating a mismatch between "economic polarization and ecological dilution." Research identifies three core constraints: path dependence in industrial structure (traditional manufacturing exceeding 40% share), insufficient policy coordination among three regions (non-uniform carbon accounting standards), and ecological-economic imbalance (core cities' ecological deficit rate of 12% vs. peripheral ecological surplus of 8.3%).

This paper innovatively constructs a three-dimensional "goal-system-foundation" evaluation framework to reveal the nonlinear linkage mechanism among economic, ecological, and social subsystems. It proposes a trinity strategy of "inter-group coordination-industrial transformation-ecological compensation," which integrates cross-regional factor sharing, carbon intensity control coupled with ecological compensation, and the dual-platform development of green technology banks and carbon account blockchains. This approach provides theoretical reference and practical paradigms for the green coordinated development of the Greater Bay Area and the green transformation of urban clusters nationwide.

Keywords: Green economic competitiveness; Nuclear density; Three-dimensional assessment

1. Introduction

As China's most economically developed and open region, the green economic development of the Guang-

dong-Hong Kong-Macao Greater Bay Area is not only crucial for the region's sustainable growth but also holds significant strategic importance for the nation. The introduction of the "dual carbon" goals (carbon peak and carbon neutrality) provides clear policy guidance for advancing green economic development in the Greater Bay Area.

Exploring pathways to enhance the green economic development of the Guangdong-Hong Kong-Macao Greater Bay Area will help optimize the regional industrial structure, improve resource utilization efficiency, reduce environmental pollution, and achieve coordinated economic and environmental development. Simultaneously, this will provide robust support for achieving the national "dual carbon" goals and offer valuable experience and models for green economic development in other regions.

2. Current status and challenges of green economic development in the Guangdong-Hong Kong-Macao greater bay area

2.1. Current status of green economic development

The Guangdong-Hong Kong-Macao Greater Bay Area has achieved remarkable progress in green economic development. In terms of green industry growth, the clean energy sector has flourished, with multiple large-scale photovoltaic power stations and wind farms constructed across the region, leading to increased utilization of solar and wind energy. Significant improvements have been made in optimizing the energy structure, and the nuclear energy industry is actively planning and constructing facilities to provide stable energy supply. Ecological and environmental protection has also advanced, with overall water quality improving in some areas.

Despite these achievements, the green economy in the Greater Bay Area still faces numerous challenges. These include difficulties in industrial restructuring, a persistent reliance on traditional high-input growth models, and consequently slow industrial transformation. Policy coordination remains inadequate, with prominent administrative barriers hindering unified policy formulation across Guangdong, Hong Kong, and Macao. Reforms to the low-carbon policy framework and institutional mechanisms are urgently needed. Regional development imbalances persist, with cities like Zhaoqing and Jiangmen exhibiting low per capita GDP and high manufacturing sector shares, posing challenges for enhancing carbon productivity. These issues are closely tied to regional development disparities and administrative systems.

2.2. Challenges to green economic competitiveness

2.2.1. The reasons behind the challenges

From an economic perspective, long-established industrial path dependencies have resulted in high transformation costs and significant challenges for enterprises, leaving them lacking the motivation to transition. Socially, public awareness and engagement with the green economy require enhancement, and the green consumption market remains underdeveloped. At the policy level, the lack of coordinated policy formulation across the three regions has failed to generate effective synergistic effects. Furthermore, insufficient enforcement and oversight of low-carbon policies hinder the implementation of certain measures. Additionally, regional development imbalances—marked by significant disparities in resources, technology, and talent between economically advanced and relatively underdeveloped areas—Further impede the overall advancement of the green economy.

As the green economy emerges as a hot topic in global research, scholars from diverse disciplinary backgrounds worldwide have conducted in-depth explorations of green economic competitiveness across multiple dimensions and scales. To comprehensively grasp the research progress on green economic competitiveness in urban clusters globally, this paper first employs knowledge graph analysis to systematically organize relevant literature. Knowledge graphs, which focus on specific knowledge domains, effectively mitigate the subjective

influence of inductive reasoning. By visualizing research progress and structural relationships, they demonstrate scientific rigor and objectivity[1].

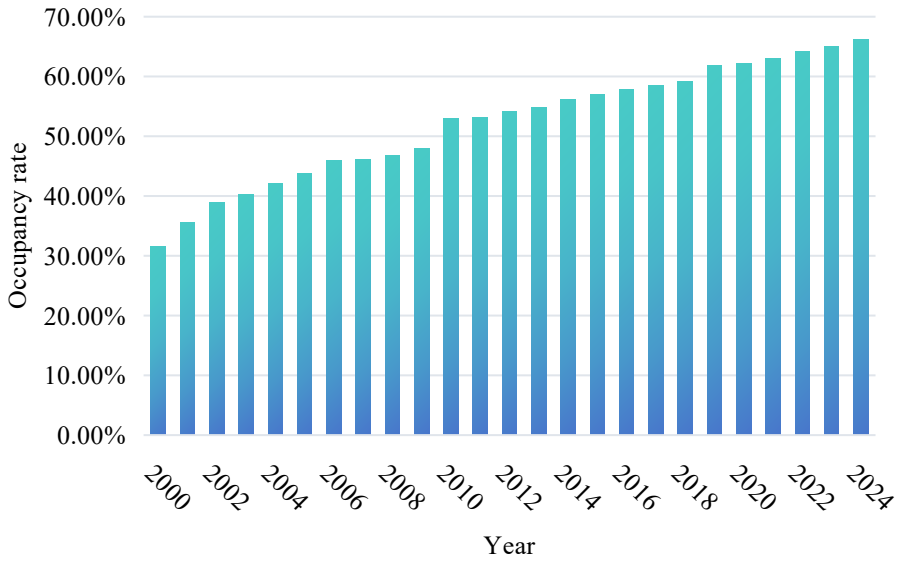

Figure 1. Urbanization rate of permanent residents nationwide, 2000–2024.

The "low-carbon economy" is a core topic in current research. Based on an objective cluster analysis of domestic and international journal literature, this study systematically reviews research progress in the field. It integrates research themes to examine the conceptual definition and evaluation indicator system of green economic competitiveness, analyzes influencing factors, and explores strategies for enhancing competitiveness.

2.2.2. Evolution of green competitiveness

Construct an evaluation model for measurement assessment. First, establish a national and regional competitiveness evaluation model. The concept of competitiveness was introduced by Chamberlin, and Porter systematically elaborated its micro, meso, and macro theories.

Table 1. IMD and WEF national competitiveness evaluation systems.

Research	Element	Essential Elements
IMD	Economy	Domestic, International, Investment, Employment, Prices
	Government	Finance, Policy, Law, Society
	Enterprise	Productivity, Labor Force, Finance, Practice, Values
	Facilities	Infrastructure, technological facilities, scientific facilities, healthy environment, education
WEF	Essential Elements	Institutional framework, stability, health education
	Efficiency	Higher education training, commodity markets, labor markets, financial markets, technology maturity ratio, market size
	Innovation	Product Maturity, Innovation

Porter's Diamond Model encompasses key dimensions such as production factors, market demand, related industries, and corporate strategic position, along with two supplementary elements: government regulation and external opportunities. National competitiveness emerged as a focal point at the 1980 Davos European Economic Forum, prompting the IMD and WEF to evaluate the competitiveness of numerous countries and regions. In 1993, the EEA introduced the DPSIR model, analyzing the interrelationships among "environment-economy-society" through the logical chain of "Drivers-Pressures-State-Impacts-Responses" and implementing measurement[2]. This study constructs an evaluation indicator system and employs measurement methods for assessment. The construction of the evaluation indicator system is divided into single-factor and

comprehensive approaches.

3. Multi-dimensional evaluation and analysis of the green economic competitiveness of the Guangdong-Hong Kong-Macao greater bay area

3.1. Research methods

This chapter will utilize the Gini coefficient to decompose disparities within the Guangdong-Hong Kong-Macao Greater Bay Area, examining differences among cities in the region and analyzing overlapping situations within each unit.

The overall disparity decomposition expression is:

$$G = \frac{\sum_{j=1}^{q} \Sigma_{h=1}^{q} \sum_{l=1}^{n_j} \sum_{r=1}^{n_h} \left| Y_{jl} - Y_{hr} \right|}{2n^2 \overline{Y}} \quad \text{Formula (1)}$$

In the formula: Y_{jl} represents the green economic competitiveness index of a city, q denotes the quantity within the region, n indicates the number of 11 cities in the Guangdong-Hong Kong-Macao Greater Bay Area, and $\overline{Y}$ signifies the average green economic competitiveness of the 11 cities in the Greater Bay Area.

The Gini coefficient for inter-city variation is:

$$G_{jj} = \frac{\frac{1}{2Y_j} \sum_{l=1}^{n_j} \sum_{r=1}^{n_j} \left| Y_{jl} - Y_{jr} \right|}{n_j^2} \quad \text{Formula (2)}$$

$$G_{jh} = \frac{\sum_{l=1}^{n_j} \sum_{r=1}^{n_h} \left| Y_{jl} - Y_{hr} \right|}{n_j n_h \left(\overline{Y}_j + \overline{Y}_h \right)} \quad \text{Formula (3)}$$

In the formula, $\overline{Y}_j$ and $\overline{Y}_h$ reflect the average levels of green economic competitiveness in regions j and h. Based on this, the differences between each region and the corresponding expressions can be derived:

$$G_w = \sum_{j=1}^{q} G_{jj} P_j S_j \quad \text{Formula (4)}$$

$$G_{nb} = \sum_{j=2}^{q} \sum_{h=1}^{j-1} G_{jh} D_{jh} \left(P_j S_h + P_h S_j \right) \quad \text{Formula (5)}$$

$$G_t = \sum_{j=2}^{q} \sum_{h=1}^{j-1} G_{jh} \left(P_j S_h + P_h S_j \right) \left(1 - D_{jh} \right) \quad \text{Formula (6)}$$

In the formula, the sum of the three components equals G. D_{jh} denotes the green competitiveness influence of regions j and h, while d_{jh} represents the green economic competitiveness differential. p_{jh} signifies the super-transformed first-order distance, serving as the mathematical expectation of the aforementioned values.

3.2. Analysis of regional differences in urban areas

Based on the above content, we projected green competitiveness data for each city in the Greater Bay Area, thereby identifying regional disparities within the Guangdong-Hong Kong-Macao Greater Bay Area. These dis-

parities exhibit phased changes, enabling us to determine both the differences in green economic competitiveness across the Greater Bay Area and the evolving trends in these disparities.

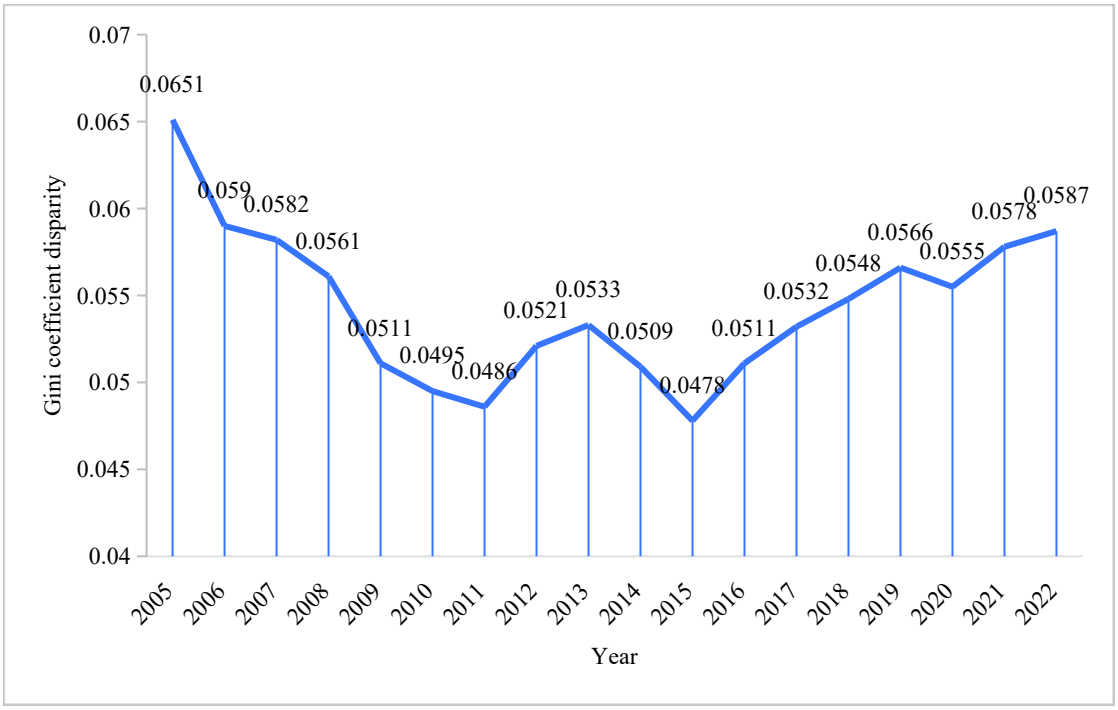

Figure 2. Overall differences in the Gini coefficient of green economic competitiveness in the Guangdong-Hong Kong-Macao greater bay area.

Figure 2 illustrates the green economic competitiveness of the Guangdong-Hong Kong-Macao Greater Bay Area. It is evident that the overall Gini coefficient for this green competitiveness has remained stable within the range of 0.0478 to 0.0651, with an average of 0.0544. From an initial value of 0.0651 in 2005 to 0.0587 in 2022, it exhibits a W-shaped trajectory overall, indicating a trend of continuous improvement in spatial coordination. This reveals the spatial disparities within the Guangdong-Hong Kong-Macao Greater Bay Area from 2005 to 2022. The figure indicates that inter-regional differences are the primary contributing factor, accounting for an average contribution rate of 50.23% during the study period. This is followed by super-variable density, with an average annual contribution rate of 31.41%, while intra-regional differences contribute the least at 18.36%. This indicates a diminishing trend in the distribution pattern: "interregional differences > hyper-variable density > intraregional differences." The overall disparity in the Greater Bay Area's green economic competitiveness primarily stems from differences among urban clusters, with weak inter-cluster synergies suggesting significant potential for spatial collaborative governance. Therefore, urban clusters should further eliminate regional barriers, strengthen cross-regional resource sharing and cooperation, and enhance inter-cluster spillover effects to elevate overall green economic competitiveness.

This study decomposes the composition of disparities in the Guangdong-Hong Kong-Macao Greater Bay Area from 2005 to 2022 (as shown in Figure 2), revealing its three-dimensional spatial differentiation characteristics: inter-cluster differences emerge as the dominant factor with an average contribution rate of 50.23%, while hyper-variable density (31.41%) and intra-cluster differences (18.36%) constitute secondary and auxiliary explanatory dimensions respectively. This gradient distribution—"inter-cluster differences > hyper-variability density > intra-cluster differences"—indicates that the unevenness in the Greater Bay Area's green economic competitiveness primarily stems from systemic isolation between urban clusters. This reflects that inter-cluster coordination mechanisms have yet to achieve economies of scale, urgently requiring spatial governance innovation to unlock cross-regional cooperation potential. Accordingly, we propose establishing a "dual-circulation"

coordination framework: externally, dismantling administrative barriers to create cross-cluster factor-sharing platforms; Internally, strengthen networked governance to amplify the radiating capacity of core cities.

The significant contribution (>30%) of the hyper-variability density indicator reveals a spatial nesting effect: inefficient units within high-competitiveness clusters may underperform compared to efficient units in low-competitiveness clusters. This heterogeneous structure maps onto two major contradictions—the siphoning-inhibition effect between core cities and their hinterlands, and gradient barriers to inter-cluster factor flows. This necessitates establishing differential compensation mechanisms to promote cross-cluster value chain restructuring through enclave economic models, while implementing a gradient development strategy of "core empowerment and hinterland upgrading."

The persistently low level of intra-cluster differentiation (<20%) validates the "club convergence" hypothesis: spatial stickiness effects arising from geographic proximity, policy homogeneity, and cultural commonality drive developmental convergence among cities within clusters. To break through the low-level equilibrium trap, three major mechanism transformations are needed: 1) governance paradigm shift from administrative-area-based to cluster-based economies; 2) resource allocation upgrade by establishing cross-cluster factor trading markets; 3) institutional innovation breakthroughs to build a collaborative governance system featuring "joint decision-making, co-developed standards, and shared benefits." Through dual-pronged efforts of "intra-cluster optimization and inter-cluster coordination," the Greater Bay Area will ultimately achieve a systemic leap in green competitiveness.

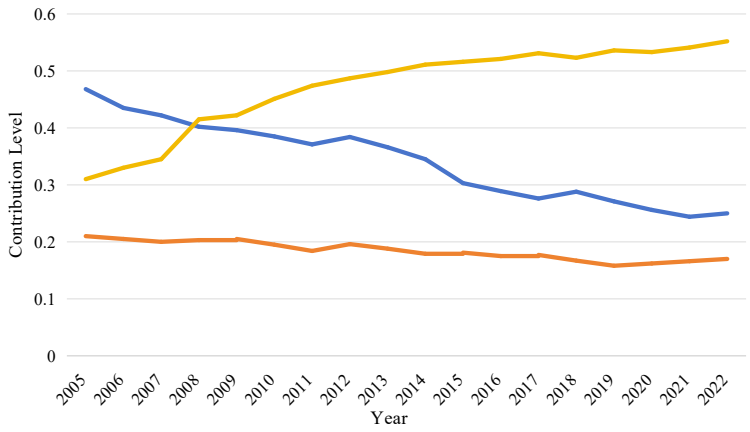

Figure 3. Contribution of sources to Gini coefficient differences in green economic competitiveness of the Guangdong-Hong Kong-Macao greater bay area.

3.3. Assessment and analysis of dynamic evolution characteristics

Based on the above content, kernel density estimation will be employed to analyze dynamic evolution characteristics. As a nonparametric estimation technique, this method utilizes a smooth density function to accurately model the distribution of the sample. By examining the displacement of the density curve, the number and height of peaks, the width, and the characteristics of the curve's tails, one can concisely observe attributes such as the location, shape, and diffusivity of the distribution.

The expression for kernel density in absolute difference analysis is:

$$f(x) = \frac{1}{Nh}\sum_{i=1}^{N} K\left(\frac{X_i - \overline{x}}{h}\right) \qquad \text{Formula (7)}$$

The results obtained indicate the density function of the green economic competitiveness index for the Guangdong-Hong Kong-Macao Greater Bay Area. Here, N represents the number of observations, and variable X denotes the observed data. This result follows an independent and identically distributed (i.i.d.) distribution.

The value of h reflects the precision and smoothing level of the density. A higher value of h indicates a smaller variance in the kernel density, resulting in a smoother curve for the density function, but at the cost of reduced precision. Conversely, a lower value of h yields a less smooth curve but higher precision. Subsequently, a Gaussian function is introduced to estimate this distribution, analyzing the distribution and corresponding morphology of the Guangdong-Hong Kong-Macao Greater Bay Area.

Regarding the spatial distribution within the Greater Bay Area, this reflects the region's green economic competitiveness capacity, thereby influencing fluctuation frequency and precision values. The number of peaks can be used to analyze polarization phenomena within the city[3].

4. Conclusions and outlook

Against the backdrop of the dual carbon goals, this study systematically investigates the spatiotemporal characteristics and enhancement pathways of the Guangdong-Hong Kong-Macao Greater Bay Area's green economic competitiveness from 2005 to 2022. This is achieved by constructing a three-dimensional evaluation system encompassing economic momentum, ecological resilience, and social welfare, and integrating methodologies such as Gini coefficient decomposition and kernel density estimation. The primary findings are as follows:

4.1. Regional variations and dynamic evolution characteristics

4.1.1. Intergroup differences drive regional imbalances

The annual average growth rate of the Greater Bay Area's green economic competitiveness composite index stands at 3.2%, yet regional disparities exhibit a gradient pattern of "inter-cluster variation (50.23%) > hyper-density variation (31.41%) > intra-cluster variation (18.36%)", confirming the shortcomings in collaborative governance under the "core-periphery" structure. The core-density distribution evolves from unipolar dominance toward multipolar symbiosis. Markov chain analysis confirms a "club convergence" effect among lower-tier cities. The decline in the spatial σ convergence coefficient indicates gradually narrowing regional disparities. However, the competitiveness of the ecological subsystem (2.7% annual growth) significantly lags behind that of the economic subsystem (4.2%). with core cities exceeding carbon intensity standards at a rate of 12%, creating a mismatch between "economic polarization and ecological dilution."

4.1.2. Key constraints identified

Path dependence in industrial structure (traditional manufacturing accounting for over 40%), insufficient policy coordination among Guangdong, Hong Kong, and Macao (non-uniform carbon accounting standards), and ecological-economic imbalance (core cities with a 12% ecological deficit rate vs. peripheral cities with an 8.3% ecological surplus) constitute core bottlenecks hindering competitiveness enhancement. These issues underscore the urgency for cross-regional governance and institutional innovation.

4.2. Theoretical and practical contributions

Methodological Innovation: The constructed "Objective-System-Foundation" three-dimensional evaluation framework breaks through the limitations of traditional single-dimensional indicators, revealing the nonlinear interconnection mechanisms among economic, ecological, and social subsystems. This provides a replicable analytical paradigm for regional green competitiveness research.

Policy Implications: The proposed trinity strategy of "inter-regional coordination-industrial transformation-ecological compensation" drives green technology transfer through cross-regional resource-sharing platforms, establishes "carbon intensity control + watershed carbon sink compensation" mechanisms, and facili-

tates industrial upgrading via dual platforms of "green technology banks + carbon account blockchains." This offers practical pathways for coordinated development in the Greater Bay Area and green transformation across China's urban clusters.

This study provides theoretical and empirical support for the coordinated green economic development of the Greater Bay Area. Future efforts should continue to monitor regional dynamics and policy innovations, contributing a "Chinese solution" to the global green transformation of bay area economies.

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