

Study on the Spatio-temporal Heterogeneity of Green Finance Development Level and Its Influencing Factors in the Guangdong-Hong Kong-Macau Greater Bay Area: An Empirical Analysis Based on Entropy Method and GTWR Model

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ABSTRACT

Against the background of global climate change and China's "dual carbon" goals, the development of green finance in the Guangdong-Hong Kong-Macau Greater Bay Area has strategic demonstration significance for the whole country. However, there is a significant imbalance within the region. This study focuses on 9 inland cities in the Greater Bay Area from 2016 to 2022. It builds an evaluation system covering 7 dimensions including green credit and green investment, uses the entropy method to calculate the green finance index, and combines the GTWR model to explore the spatio-temporal heterogeneity of 5 core influencing factors. The findings indicate that green finance in the Greater Bay Area exhibits notable spatial and temporal differences. In terms of time, the index rises with fluctuations, and the growth rate increases after 2019. Guangzhou and Shenzhen have become a "dual-core" driving force. In terms of space, the pattern has changed from "isolated dual-core" to "dual-core and dual-belt". The eastern bank of the Pearl River Estuary is more strongly driven by the coordination of Guangzhou and Shenzhen. Green patents have a continuous positive driving effect. Industrial structure and economic development mainly have negative impacts. The impacts of government intervention and energy consumption intensity are different between the eastern and western banks of the Pearl River Estuary. In addition to providing empirical support for developing distinct green finance policies and advancing regional coordinated development, this study also closes the theoretical gap in the spatio-temporal differentiation of regional green finance.

KEYWORDS

Guangdong-Hong Kong-Macau Greater Bay Area; Green Finance; Entropy Method; GTWR Model

1. INTRODUCTION

1.1. Research Background and Significance

In the realm of global climate change, green financing has become an essential tool for enabling the transition to low-carbon practices, positioning it as a fundamental element of international competition and cooperation. The proposal of China's "dual carbon" goals requires the financial system to accelerate its transformation towards green and low-carbon development. The Guangdong-Hong Kong-Macau Greater Bay Area, known for its high openness and robust economic activity in China, plays a strategically significant role in demonstrating green finance development for the entire nation. In 2019, the "Development Plan for the Guangdong-Hong Kong-Macau Greater Bay Area" clearly listed green finance as a key task. In 2020, the "Opinions on Financial Support for the Construction of the Guangdong-Hong Kong-Macau Greater Bay Area" issued by four departments

including the People's Bank of China further proposed the establishment of a cross-regional cooperation mechanism.

However, the development of green finance within the Greater Bay Area is significantly imbalanced. Over the years 2016 to 2022, the nine inland cities of the Greater Bay Area saw their environmental protection project loans grow to over 50 billion yuan. Still, industrial cities like Foshan and Jiangmen have made some efforts in environmental pollution control investment, environmental protection project credit, and green bond issuance, but their total level of growth is relatively low when compared to Guangzhou and Shenzhen. This spatial and temporal diversity highlights the difficulties in achieving regional coordination in green finance development and offers a typical case for studying the impact mechanisms of green finance in depth.

As a national strategic region, the development of green finance in the 9 inland cities of the Greater Bay Area is crucial to regional coordination and the realization of the "dual carbon" goals. This study identifies the development shortcomings of different cities and the spatiotemporal characteristics of influencing factors. It can provide empirical basis for formulating differentiated green finance policies, promoting regional coordinated development, and accelerating green transformation. It also helps to enhance the competitiveness of green finance in the Greater Bay Area and serve the national high-quality development strategy. In existing studies, the majority of current research on green finance is concentrated at the national, provincial, or city level. Limited research has been conducted on the nine inland cities of the Guangdong-Hong Kong-Macau Greater Bay Area, with inadequate focus on the spatial and temporal variability of their influencing factors. This study uses the entropy method to objectively measure the green finance development level of the 9 inland cities, and combines the GTWR model to reveal the spatiotemporal dynamic differences of influencing factors. It can fill the theoretical gap in the spatiotemporal differentiation of regional green finance, enrich the dynamic analysis framework of the green finance impact mechanism, and provide a new perspective for the theoretical research on regional green finance differentiation.

1.2. Literature Review

In recent years, there have been many studies on green finance at home and abroad, which can be mainly divided into the following three categories.

The first category is research on the effect of green finance. For example, Zhou, Y., & Chen, F. (2023), Mao, X., & Wang, R. (2024), and Xie, F., & Zhou M. (2023) utilized the entropy method to compute the regional green finance index. Then, through verification with models such as the mediating effect model and the Difference-in-Differences (DID) model, they discovered that green finance has the potential to boost green total factor productivity (GTFP), promote new-quality productive forces and energy efficiency by reducing carbon emission intensity, and this effect exhibits regional heterogeneity [1-3]. Liu, H., & He, C. (2021) used green credit data to represent the development level of green finance. They developed a dynamic GMM model and applied the entropy method to compute indicators. The study found that green finance can promote the high-quality economic development of cities [4]. Zhou, X., Jia, M., & Zhao, X. (2023) built a tripartite evolutionary game model and the DID model to analyze indicators such as green patents. They discovered that green credit, a type of green finance, can foster increased green innovation among polluting enterprises [5]. Zhang, S., & Ren, C. (2024) measured the green finance index of each province by building a comprehensive evaluation index system. Then they used the SBM-GML model and mediating effect model to analyze indicators such as. The findings indicate that green finance influences agricultural green total factor productivity through an 'inverted U-shaped' threshold effect, which involves a mechanism and displays heterogeneity [6]. Xu, Q., Yao, L., Shi, K., Zhou, W., & Tang, X. (2025) used the GTWR model to analyze data of cities in China and indicators such as carbon intensity, green credit, and government support. They found that green credit and green insurance significantly reduce carbon intensity, and this effect has significant regional differences [7].

The second category involves studying the development traits and factors affecting green finance. For example, Zhou, J. (2022) used the entropy method to build a green finance index, the GTWR model to analyze influencing factors, and the spatial autocorrelation (Moran's I) method. He analyzed the green finance data and influencing factor data of 31 provinces in China. The research indicated that green finance development is more advanced in the south compared to the north. Policy support and urbanization are the main driving factors, while environmental pollution and public dissatisfaction have negative impacts, and there is spatio-temporal heterogeneity [8]. Yuan, H., Feng, Y., Lee, J., & Liu, H. (2020) used the DPSIR model to build a green development index, the BLISA model to analyze the spatial connection between financial agglomeration and green development, and the GTWR model to reveal the spatio-temporal differences of the effect of financial concentration on green development. They analyzed the economic, financial, and Environmental data from 285 prefecture-level cities in China and relative indicators. The study discovered a strong favorable spatial link between financial agglomeration and green development. The influence of financial agglomeration on green development exhibits regional variation, diminishing from the southeastern coast to the northwestern interior [9]. Zhou, Y., Liu, H., Wang, J., Yang, H., Liu, Z., & Peng, G. (2022) employed the entropy approach to construct a green finance index for analyzing data from statistical yearbooks and environmental statistical yearbooks across 30 provinces and cities in China. They also used the SAR model (spatial autoregression) to explore its influencing factors. The study found that the absolute difference of green finance in China is expanding, while the relative difference is narrowing. Financial development and environmental governance facilitate the advancement of green finance, whilst economic expansion and energy use impede it [10].

The third category is research on policies and specific fields related to green finance. For example, Zhang, C., Cheng, X., & Ma, Y. (2022) utilized the 2017 pilot zone as a quasi-natural experiment and employed methodologies like the difference-in-differences (DID) approach to examine metrics related to green innovation. The study found that the pilot zone promotes regional green innovation, environmental regulation has a regulatory effect, and the robustness test is reliable [11]. Wang, J., Wang, H., & Gou, A. (2024) employed the extreme entropy weight method and linear weighting method to compute the ecological resilience index for 9 cities in the Greater Bay Area. They also used the GTWR model and spatial autocorrelation analysis method to analyze its influencing factors. According to the study, there is regional variability and the Greater Bay Area's ecological resilience varies and increases with resilience and adaptation acting as the primary drivers. The central region has high adaptability, and the western region has high resilience. Among the influencing factors, green space area has a positive impact on resilience, while GDP per unit area has a negative impact, and the spatiotemporal differences are obvious [12].

Looking at the existing studies, scholars usually use methods such as the entropy method and global principal component analysis to measure the green finance development level in the research area. This can provide references for this study in terms of indicator selection and measurement methods. Models like the SAR model, SDM model, and GTWR are frequently used by researchers to analyze the determinants of green financing. This can provide method references for the analysis of this study. Despite the aforementioned research validating the variety of green financing across regions and temporal dimensions, a comprehensive spatio-temporal evolution study using GTWR for the nine inland cities within the Greater Bay Area urban agglomeration remains absent.

1.3. Research Content

Based on the current research status and its gaps, this study aims to: (1) Integrate green finance evaluation indicators from existing literature, build an objective green finance comprehensive evaluation index system, then use the entropy method to objectively compute the green finance index of 9 inland cities in the Guangdong-Hong Kong-Macau Greater Bay Area from 2016 to 2022; (2) Select indicators that may affect green finance from existing studies as explanatory variables, take the calculated green finance index of each city as the explained variable, and use the GTWR model

(Geographically and Temporally Weighted Regression Model) to calculate the parameters of each influencing factor in each city at different times to reflect its impact degree; (3) Examine the computed outcomes and propose specific policy recommendations based on these findings. The innovations of this study are: (1) Focus on the 9 inland cities of the Greater Bay Area to provide micro-analysis at the regional level; (2) Consolidate current research, pick indicators from seven dimensions to establish a novel complete evaluation index system for green finance, therefore enabling a more objective and thorough assessment of the green finance development levels in the 9 inland cities of the Guangdong-Hong Kong-Macau Greater Bay Area; (3) Employ the GTWR model to examine the determinants of green finance advancement in the Guangdong-Hong Kong-Macau Greater Bay Area, and elucidate its heterogeneity more comprehensively from temporal and spatial perspectives.

2. MATERIALS AND METHODS

2.1. Research Area and Data Sources

This study examines 9 inland cities within the Guangdong-Hong Kong-Macau Greater Bay Area: Guangzhou, Shenzhen, Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen, and Zhaoqing. The research time span is from 2016 to 2022. The main considerations are as follows: First, due to the differences in systems and policy environments between China's inland and Hong Kong and Macao regions, as well as the differences in statistical standards of various data and indicators between inland cities and Hong Kong and Macao regions, to avoid deviations in research results caused by such differences, this study focuses on the 9 inland cities of the Guangdong-Hong Kong-Macau Greater Bay Area; Second, green finance is receiving a lot of attention because of the rules that were released in 2019 and 2020. Additionally, 2022 is the last year for which comprehensive data is available.

Among the research data, green finance data mainly comes from the "Guangdong Statistical Yearbook", "China Financial Statistical Yearbook", "China Industrial Statistical Yearbook", "China Ecological Environment Status Bulletin", and statistical yearbooks of various cities. The explanatory variable data of the GTWR model mainly comes from the "China Urban Statistical Yearbook", "Guangdong Statistical Yearbook", and statistical yearbooks and statistical bulletins of various cities.

2.2. Research Methods

2.2.1. Construction of Green Finance Comprehensive Evaluation System

Combined with existing studies [1-3, 6, 7, 9], this study builds a green finance comprehensive evaluation index system from 7 dimensions (Table 1), to more comprehensively reflect the green finance development level of 9 inland cities in the Guangdong-Hong Kong-Macau Greater Bay Area.

Table 1. Green Finance Comprehensive Evaluation Index System

First-level Indicators	Second-level Indicators	Explanation
Green Credit	Proportion of Credit for Environmental Protection Projects	Total credit for environmental protection projects in the province / Total credit of the province
Green Investment	Proportion of Environmental Pollution Control Investment in GDP	Environmental pollution control investment / GDP
Green Insurance	Promotion Degree of Environmental Pollution Liability Insurance	Income from environmental pollution liability insurance / Total premium income
Green Bonds	Development Degree of Green Bonds	Total issuance of green bonds / Total issuance of all bonds
Green Support	Proportion of Fiscal Expenditure on Environmental Protection	Fiscal expenditure on environmental protection / General budget expenditure
Green Funds	Proportion of Green Funds	Total market value of green funds / Total market value of all funds
Green Equity	Development Depth of Green Equity	(Carbon trading + Energy use right trading + Emission right trading) / Total trading volume of the equity market

2.2.2. Calculation of Green Finance Index by Entropy Method

The entropy method is an impartial weighting technique. It ascertains the weight by calculating the information entropy of indicators, so effectively mitigating the bias of subjective weighting. This research used the entropy approach to assess the green finance index of nine inland cities in the study area from 2016 to 2022. The precise steps are as follows:

(1) Standardize each indicator value.

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

$$X'_{ij} = X_{ij} + \theta \quad (2)$$

In the formulas, x_{ij} and X_{ij} are the original value and preliminary standardized value of the j -th indicator of the i -th city respectively. $\max(x_{ij})$ and $\min(x_{ij})$ are the maximum and minimum values of the original values of the j -th indicator respectively. To eliminate the impact of zero values, add a minimum unit value θ to all preliminary standardized values to meet the calculation requirements. Take $\theta = 0.0001$, and the final standardized value X'_{ij} is obtained.

(2) Employ the entropy method to ascertain the weight of each indicator.

$$p_{ij} = \frac{X'_{ij}}{\sum_{i=1}^n X'_{ij}} \quad (3)$$

$$e_j = -\frac{1}{\ln(n)} \sum_{i=1}^n p_{ij} \ln(p_{ij}) \quad (4)$$

$$W_j = \frac{1 - e_j}{\sum_{j=1}^m (1 - e_j)} \quad (5)$$

In the formulas, W_j is the weight coefficient of the j -th indicator; e_j is the entropy value of the j -th indicator; p_{ij} is the proportion of the standardized value of the i -th city in the j -th indicator; n is the number of samples; m is the number of indicators.

(3) Calculate the green finance index by weighted summation.

$$Gf_i = \sum_{j=1}^m W_j \times X'_{ij} \quad (6)$$

In the formula, Gf_i is the green finance index of the i -th city. The value range of Gf_i is (0,1), and a larger value indicates a higher level of green finance development.

2.2.3. Construction of Index System for Influencing Factors of Green Finance Development

Combined with existing studies [14-15, 17], this study selects 5 core influencing factors: industrial structure, government intervention degree, economic development level, number of green patents granted, and energy consumption intensity, to build an index system for influencing factors of green finance development (Table 2). To accurately reflect the impact of each indicator on green finance development, this study conducts a multicollinearity test on them. The results show that their variance inflation factors (VIF) are all less than 5 (Table 3). This indicates that the degree of multicollinearity between the indicators is relatively low, the interference to the subsequent regression model is small, and it can well reflect the stability and reliability of the subsequent model parameter estimation.

Table 2. Index System for Influencing Factors of Green Finance Development

Indicator Name	Variable Name	Explanation
Industrial Structure	Inds	Added value of the secondary industry / GDP
Government Intervention Degree	Gos	Local fiscal expenditure / GDP
Economic Development Level	ED	Natural logarithm of per capita GDP
Number of Green Patents Granted	GP	Natural logarithm of the number of green patents granted
Energy Consumption Intensity	ECI	Energy consumption per unit of GDP

Table 3. VIF Test Results of Influencing Factors of Green Finance Development

	Inds	Gos	ED	GP	ECI
VIF	1.313	1.599	3.385	4.216	4.337

2.2.4. Construction of Geographically and Temporally Weighted Regression (GTWR) Model

The Geographically and Temporally Weighted Regression (GTWR) model is a refined version derived from the Geographically Weighted Regression (GWR) model, with the notable addition of the temporal dimension. Distinct from the GWR model, the GTWR model can account for both spatial and temporal heterogeneity inherent in data by establishing a spatio-temporal weight matrix. Owing to this capability, it becomes a fitting tool for examining the dynamic spatio-temporal evolutionary traits of regional economic phenomena. In this research, the GTWR model is utilized to delve into the spatio-temporal fluctuations in the determinants that drive green finance development across 9 inland cities within the Greater Bay Area. The fundamental formulation of the model is presented as:

$$Gf_{it} = \beta_0(u_i, v_i, t) + \sum_{k=1}^5 \beta_k(u_i, v_i, t)X_{kit} + \varepsilon_{it} \quad (7)$$

In the formula, Gf_{it} is the green finance index of the i -th city in the t -th year (explained variable); X_{kit} represents the observed value of the k -th influencing factor related to green finance development in the i -th city during the t -th year, acting as the explanatory variable; (u_i, v_i, t) signifies the spatio-temporal coordinate of the i -th city in the t -th year, where u_i , v_i , and t are the longitude, latitude, and the year of each city respectively; $\beta_k(u_i, v_i, t)$ is the regression coefficient of the observation value of the k -th influencing factor of green finance development at the spatio-temporal coordinate (u_i, v_i, t) ; $\beta_0(u_i, v_i, t)$ is the constant term of the model; ε_{it} is the residual of the model.

3. RESULTS

3.1. Spatio-temporal Evolution Features of Green Finance in 9 Inland Cities of the Guangdong-Hong Kong-Macau Greater Bay Area

The entropy method is adopted to calculate the green finance index of 9 inland cities in the Guangdong-Hong Kong-Macau Greater Bay Area spanning from 2016 to 2022. This is done to reflect their green finance development level, relying on a comprehensive evaluation system for green finance development that has been established. It is found that the results exhibit specific spatio-temporal evolution features.

3.1.1. Temporal Change Trend

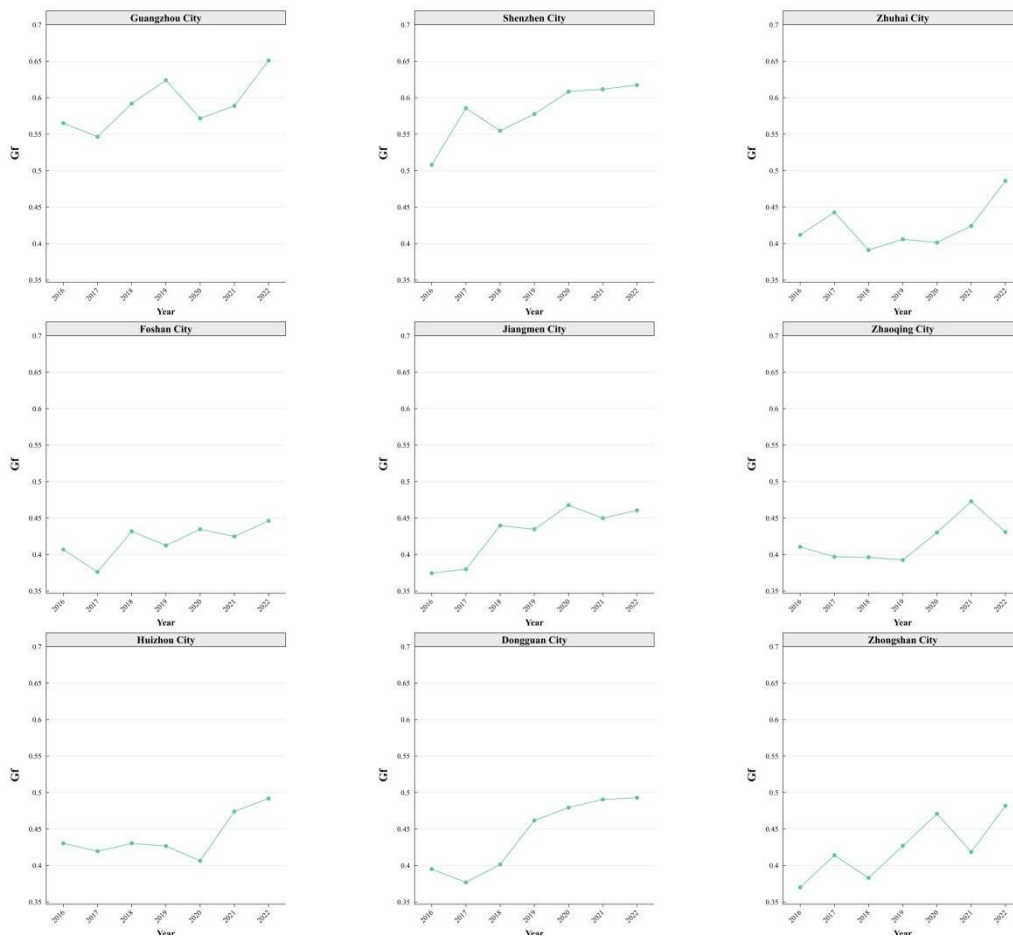


Figure 1. Temporal Change Diagram of Green Finance Index of Inland Cities in the Guangdong-Hong Kong-Macau Greater Bay Area from 2016 to 2022 [Owner-draw]

From the perspective of temporal evolution characteristics (Figure 1), the green finance index of each city shows a fluctuating upward trend within the research time span. The advancement of green

finance in major cities exhibits a "stable and progressive" trajectory: Guangzhou's green finance index fluctuated from 0.565 in 2016 to 0.651 in 2022. During this period, it reached a phased high of 0.624 in 2019, and then briefly adjusted to 0.572 in 2020 may be due to factors such as the epidemic, before quickly recovering growth. Shenzhen's green finance index continued to rise from 0.508 in 2016 to 0.617 in 2022. Among them, it exceeded Guangzhou's 0.546 for the first time with 0.586 in 2017, forming a dual-core competition pattern in the region. Other cities show differentiated growth characteristics: Dongguan has the most significant growth, with its green finance index jumping from 0.395 in 2016 to 0.493 in 2022. After 2019, the growth rate slowed down, entering a relatively stable growth period with high values. Zhuhai fluctuated in the range of 0.40-0.44 from 2016 to 2020, but after 2021, possibly driven by the policy of the Hengqin Guangdong-Macao In-Depth Cooperation Zone, the index increased from 0.424 in 2021 to 0.486 in 2022, an increase of 14.6% in one year. Zhongshan and Jiangmen show a step-by-step upward trend. Zhongshan's green finance index increased from 0.370 in 2016 to 0.482 in 2022, and Jiangmen's increased from 0.374 to 0.461. Both cities exceeded the 0.45 threshold in 2020.

In general, from the perspective of policy node effect, following the issuance of the "Development Plan for the Guangdong-Hong Kong-Macau Greater Bay Area" in 2019, the average growth rate of the green finance index of the 9 cities has been relatively stably improved, and the policy-driven effect is relatively significant. Among them, the policy effect of Huizhou and Zhuhai is particularly obvious.

3.1.2. Spatial Change Trend

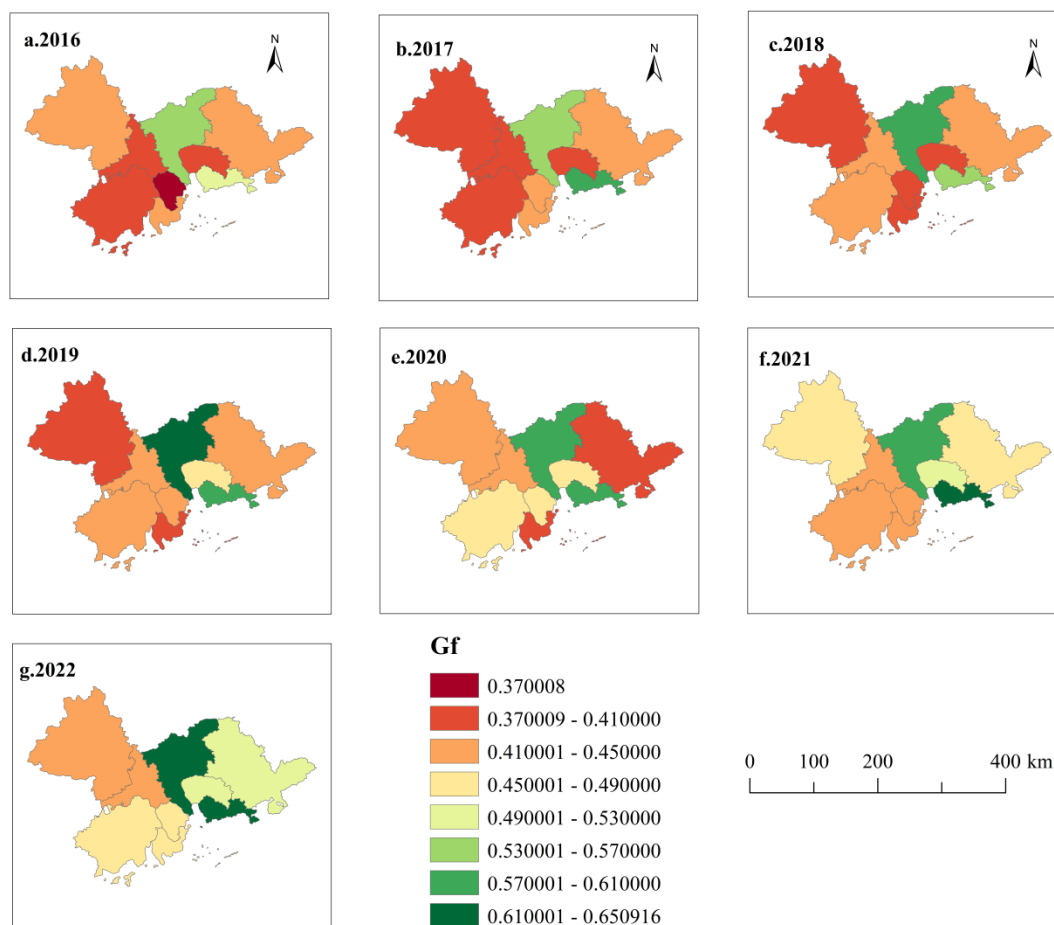


Figure 2. Spatial Change Diagram of Green Finance Index of 9 Inland Cities in the Guangdong-Hong Kong-Macau Greater Bay Area from 2016 to 2022 [Owner-draw]

From the standpoint of spatial distribution features (Figure 2), the advancement of green finance in this region exhibits a spatial pattern of "core agglomeration and gradient diffusion". In 2016, high-value areas were only concentrated in Guangzhou (0.565) and Shenzhen (0.508), forming an "isolated dual-core" situation. Even though Shenzhen's green finance index increased significantly in 2017, this situation still did not ease. After 2018, the spatial diffusion effect appeared. The index of manufacturing cities in the Pearl River Delta such as Dongguan and Zhongshan gradually increased, and the scope of high-value areas spread to cities on both sides of the Pearl River Estuary. In 2022, the spatial pattern showed the characteristics of "dual-core and dual-belt": Guangzhou and Shenzhen are still the two core cities (both $G_f > 0.5$). On the eastern bank, there is a secondary belt with Dongguan and Huizhou ($0.45 < G_f < 0.49$), and on the western bank, there is a potential belt with Foshan, Zhongshan, Zhuhai, Jiangmen, and Zhaoqing ($0.41 < G_f < 0.49$). The reason may be that the cities on the eastern bank of the Pearl River Estuary are more affected by the joint driving effect of Guangzhou and Shenzhen, especially the driving effect of Shenzhen. However, the cities on the western bank are mainly driven by Guangzhou, and due to geographical location, the driving effect of Shenzhen is relatively not obvious.

Overall, this result not only echoes but also expands the existing research conclusions on regional green finance heterogeneity. It is similar to the "high in the south, low in the north" spatial pattern found by Zhou Jie (2022). The green finance in the Greater Bay Area shows the characteristics of "core agglomeration and gradient diffusion", which verifies the radiation effect of economically core cities on green finance. However, the detailed pattern of "dual-core and dual-belt" highlights the uniqueness of the geographical and economic connections between the two banks of the Pearl River Estuary.

3.2. Spatio-temporal Heterogeneity Mechanism of Influencing Factors of Green Finance Development in 9 Inland Cities of the Guangdong-Hong Kong-Macau Greater Bay Area

In the overall information estimated based on the GTWR model (Table 4), the R^2 reaches 0.86 and the adjusted R^2 is 0.829. The fitting effect of the local regression is good. The AICc and residual sum of squares are -247.12 and 0.048 respectively. All these factors suggest that the model's estimation findings are exceptionally reliable. The estimation findings of the GTWR model indicate that the strength and direction of the influence of 5 primary determinants on green finance development exhibit significant spatio-temporal variation. Among them, the spatial heterogeneity is more prominent, while the temporal dimension shows a gradual adjustment trend (Figures 3 and 4).

Table 4. Overall Information of GTWR Model Estimation

Name of Information	Value
R^2	0.860433
Adjusted R^2	0.829431
AICc	-247.11709
Residual sum of squares	0.048268

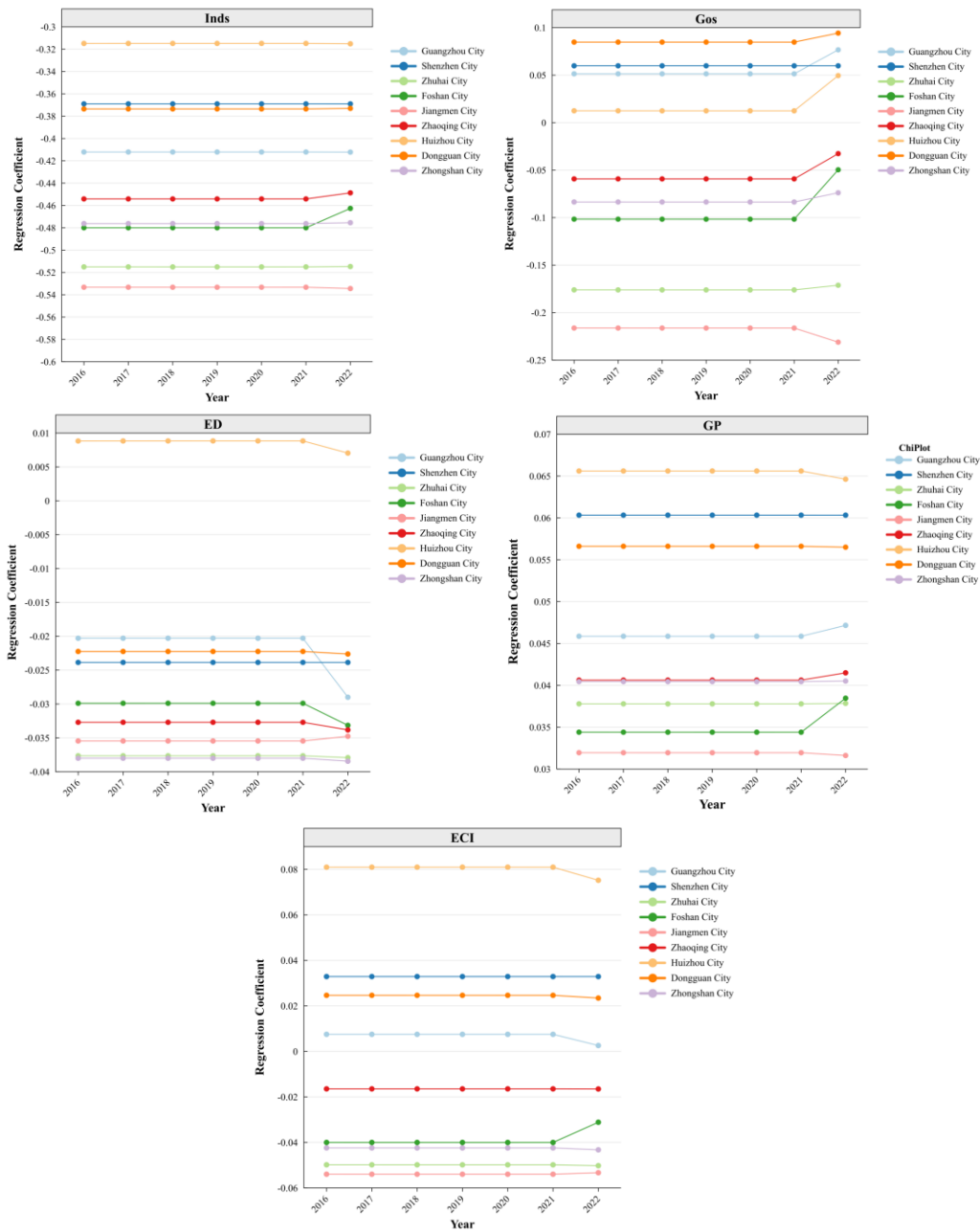


Figure 3. Temporal Change Diagram of Influencing Factors of Green Finance Development in 9 Inland Cities of the Guangdong-Hong Kong-Macau Greater Bay Area from 2016 to 2022 [Owner-draw]

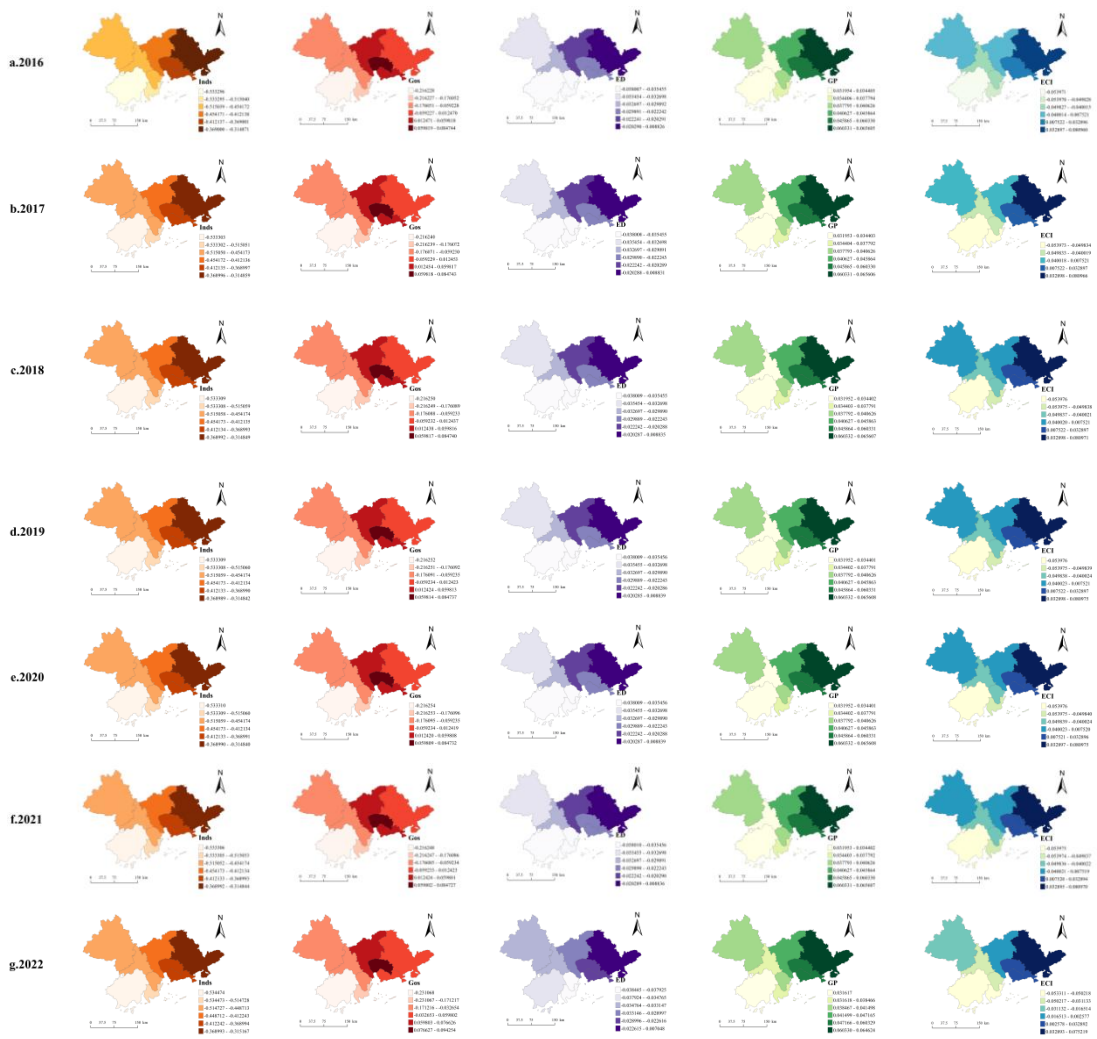


Figure 4. Spatial Change Diagram of Influencing Factors of Green Finance Development in 9 Inland Cities of the Guangdong-Hong Kong-Macau Greater Bay Area from 2016 to 2022 [Owner-draw]

(1) Industrial Structure

The detrimental impact of Inds is considerable, and its severity exhibits a pattern of convergence with time. From 2016 to 2018, the average regression coefficient of Inds was about -0.436. The prevalence of the secondary sector in manufacturing cities like Foshan and Dongguan may hinder the advancement of green financing. In 2022, the average coefficient rose to -0.433. This shows that the industrial transformation of manufacturing cities (such as the greening of the electronic information industry in Dongguan) has weakened the restrictive effect, but the negative impact is still obvious. The change of industrial structure constrains the advancement of green finance and necessitates sustained and ongoing optimization.

The spatial distribution characteristic of the Inds regression coefficient is that the negative impact is strong in cities on the western bank of the Pearl River Estuary and weak in cities on the eastern bank. For manufacturing cities on the western bank such as Foshan and Jiangmen, the Inds coefficient has been lower than -0.45 for a long time, and the high proportion of the secondary industry has a significant restrictive effect. For Shenzhen and Huizhou on the eastern bank, the coefficient is relatively higher. The industrial transformation towards light industry or high-tech industry has made the restriction weaker. The spatial difference of industrial structure directly leads to different degrees of restriction on green finance development.

(2) Government Intervention Degree

The impact of Gos is negative and relatively significant in most cities. Its spatio-temporal evolution characteristic is that the positive impact is strengthened and the negative impact is weakened. In cities such as Guangzhou and Shenzhen, the Gos regression coefficient has always been positive, and the positive effect has been strengthened after 2021. It reflects that under the promotion of policies, fiscal expenditure may increase investment in environmental protection, thus supporting green finance. However, in most cities such as Zhaoqing and Jiangmen, the Gos coefficient is negative. It reflects that the fiscal influence capacity of these cities is limited, the intervention effect is not good, and even the misallocation of resources restricts the development of green finance. The coordination with policies needs to be improved, but the negative effect has shown a weakening trend after 2021.

Regarding the features of geographical distribution, it demonstrates that cities have a detrimental effect on the Pearl River Estuary's western bank and a beneficial one on its eastern bank. Cities like Guangzhou, Shenzhen, and Dongguan on the Pearl River Estuary's eastern bank have all positive Gos coefficients, and the policy-driven effect creates high-value locations. Among them, Dongguan's coefficient has always been the highest, reaching the highest value in the whole time period in 2022 (0.094). For cities on the western bank such as Zhaoqing and Jiangmen, the coefficient is negative. The difference in fiscal influence capacity leads to the imbalance of policy support. The eastern bank cities have the characteristics of strong intervention and strong support, while the western bank cities have the characteristics of weak intervention, weak support, or even negative effect. The spatial differentiation is significant.

(3) Economic Development Level

ED predominantly exerts a detrimental influence, with just a limited number of cities exhibiting a marginal beneficial effect. During the research period, the ED coefficient is mostly negative, and only Huizhou has a weak positive impact (Huizhou's ED coefficient was 0.007 in 2022). Although Shenzhen and Guangzhou have high economic aggregates, the absolute value of the coefficient is small. The quality of economic development is more crucial to the advancement of green finance than the overall economic aggregate. Initially, economic development depends on traditional sectors, which inadequately supports green finance. The attributes of high-quality development manifest, and the beneficial impact can be progressively realized. The synchronized advancement of the general economy and green finance remains in its early phase.

The negative influence is significant in cities on the western bank of the Pearl River Estuary and weak in cities on the eastern bank, according to the geographical distribution characteristic of the ED regression coefficient, with the exception of Huizhou, which has a positive value. Especially in cities such as Jiangmen and Zhuhai in the southwest, the ED coefficient is about -0.035, which is the area most affected by the negative impact of ED in the region.

(4) Number of Green Patents Granted

GP shows a continuous positive driving effect and a strengthening trend. From 2016 to 2022, the regression coefficient of GP is positive in all cities, that is, the positive effect is significant, and the positive effect of some cities has shown an upward trend after 2021. In innovative cities such as Shenzhen, the GP coefficient is at a relatively high level. It indicates that green technological innovation can drive the demand for green finance and stimulate supply through pledge financing and project returns. The role of innovation-driven development will become more significant with the passage of time.

Its agglomeration on the eastern side and dispersion on the western bank are characteristics of its spatial distribution. The GP coefficients of Shenzhen and Huizhou on the eastern bank are among the highest (Huizhou reached 0.064 in 2022), forming a high-value innovation zone, which can enhance the advancement of green financing. For Foshan and Zhongshan on the western bank, although they have a good manufacturing foundation, the GP coefficient is low (Jiangmen was 0.032 in 2022), and

the conversion efficiency of green technology is low, so the promoting effect on green finance is weak. The spatial agglomeration of innovative resources makes the green finance on the eastern bank more driven by innovation.

(5) Energy Consumption Intensity

ECI has a positive impact on some cities and a negative impact on others, and these impacts have shown a weakening trend over time. The coefficients of cities such as Shenzhen and Huizhou have been positive for a long time (Huizhou remained at about 0.08). These cities possess a solid foundation for industrial greening, attracting the concentration of green financial resources and exerting a beneficial influence. However, the coefficients of cities such as Foshan and Jiangmen have been negative (Foshan was about -0.031 in 2022). The significant characteristics of high energy consumption are attributed to the dominance of traditional industries. High energy consumption intensity increases environmental costs and increases the capital pressure for transformation, which restricts the development of green finance to a certain extent. In general, from 2016 to 2022, regardless of positive or negative impact, the absolute value of the coefficient has shown a narrowing trend. The energy transformation under the "dual carbon" objectives has yielded results, the influence of ECI on green finance appears to be mild, and the compatibility between green finance and the energy system has been enhanced.

The spatial distribution exhibits coordination on the eastern side of the Pearl River Estuary and limitation on the western bank. The ECI regression coefficients of eastern bank cities such as Guangzhou, Shenzhen, and Huizhou are all positive, producing a positive impact and forming a coordination zone between energy and green finance. Relying on the advantage of low-energy-consuming industries, Huizhou's ECI positively promotes green finance. Shenzhen and Guangzhou rely on technological and management optimization to weaken the negative impact of high energy consumption. Combined with economic and innovative resources, the sensitivity of green finance to energy consumption intensity is low, and it is easier to achieve the coordinated development of the two. However, the ECI coefficients of western bank cities such as Foshan, Jiangmen, and Zhuhai have been negative for a long time, forming a restriction zone between energy and green finance. Traditional industrial cities such as Foshan and Jiangmen have developed high-energy-consuming industries, which leads to the restrictive effect of energy consumption intensity on green finance. It is difficult for green financial resources to flow in, which further hinders energy transformation and may fall into the dilemma of high energy consumption and low financial support.

To sum up, the five core influencing factors of green finance development in the 9 inland cities of the Greater Bay Area have had a relatively continuous and stable impact on each prefecture-level city from 2016 to 2022, and there has been no change in direction. However, relatively large changes have occurred after 2021, showing a certain positive change trend. The industrial structure and level of economic growth exert negative influences, whereas the quantity of issued green patents has a favorable effect; additionally, the extent of government participation and energy consumption intensity yield both negative and positive effects. The effects of these five factors differ markedly across cities, predominantly indicating that the negative impact is less pronounced and the positive impact is more robust in cities situated on the eastern bank of the Pearl River Estuary, whereas the negative impact is more pronounced and the positive impact is less significant in cities on the western bank.

Compared with existing studies, it is found that the continuous positive driving effect of green patents is consistent with the role of green technological innovation emphasized by Xu, Q. et al. (2025). The spatial characteristics of innovation agglomeration on the eastern bank enhance the comprehension of the impact mechanism of innovative resource allocation on financial support. The adverse effect of economic development on green finance aligns with Zhou, Y. et al. (2022), who assert that economic growth hinders the advancement of green finance. However, the varying effects of energy consumption intensity and the disparities between the eastern and western banks contrast with their

perspective that energy consumption hinders the advancement of green finance. This indicates that the positive impact of energy transformation promoted by the "dual carbon" policy has emerged in recent years, and also reveals the key impact of the adaptability between green finance and the energy system, providing detailed basis for the formulation of regional differentiated policies.

4. CONCLUSIONS

This study takes 9 inland cities of the Guangdong-Hong Kong-Macau Greater Bay Area from 2016 to 2022 as the research object. It establishes a thorough green finance evaluation framework encompassing 7 dimensions: green credit, green investment, green insurance, green bonds, green support, green funds, and green equity. It employs the entropy approach to objectively compute the green finance index and integrates the GTWR model to systematically examine the spatio-temporal heterogeneous effects of 5 core elements (industrial structure, government intervention degree, economic development level, number of green patents granted, and energy consumption intensity) on green finance development, and reveals the law of regional green finance development. The main research conclusions are as follows:

(1) Spatio-temporal Evolution Law of Green Finance Development in the Greater Bay Area

The green finance index of all 9 cities exhibits a variable rising trajectory over time. Following the publication of the "Development Plan for the Guangdong-Hong Kong-Macau Greater Bay Area" in 2019, the growth rate experienced a substantial increase. Among them, the green finance index of Guangzhou and Shenzhen is often the highest in the region, forming a "dual-core competition" pattern. Cities such as Dongguan and Zhuhai show differentiated growth characteristics at different stages. For example, driven by the policy of the Hengqin Guangdong-Macao In-Depth Cooperation Zone, Zhuhai's index growth rate accelerated from 2021 to 2022. In terms of space, the pattern has changed from the "isolated dual-core" of Guangzhou and Shenzhen in 2016 to the "dual-core and dual-belt" in 2022. With Guangzhou and Shenzhen as the core, a secondary belt has been formed in Dongguan and Huizhou on the eastern bank, and a potential belt has been formed in Foshan, Zhongshan, Zhuhai, and other cities on the western bank. The synergistic driving influence of Guangzhou and Shenzhen on the eastern bank is markedly more potent than that on the western side. This detailed pattern highlights the uniqueness of the geographical and economic connections between the two banks of the Pearl River Estuary.

(2) Spatio-temporal Heterogeneity Mechanism of Influencing Factors of Green Finance Development

From the perspective of impact direction and intensity, the five core factors have significant spatiotemporal differentiation characteristics, and the spatial heterogeneity is more prominent:

The number of green patents granted (GP) is the only factor with a continuous positive driving effect. After 2021, the positive effect of some cities (such as Shenzhen and Huizhou) has been further strengthened. The eastern bank has formed a high-value belt due to the agglomeration of innovative resources, while the western bank has a low conversion efficiency of green technology, so the driving effect is weak.

Industrial structure (Inds) and economic development level (ED) mainly have negative impacts. Among them, manufacturing cities on the western bank such as Foshan and Jiangmen have a high proportion of the secondary industry and a strong dependence on traditional industries, so their negative restrictive effect is significantly stronger than that of cities on the eastern bank. ED has a weak positive impact only in Huizhou, which indicates that the quality of economic development, rather than the aggregate, is more critical to supporting green finance.

The degree of government intervention (Gos) and energy consumption intensity (ECI) show differences between the eastern and western banks. For Gos, the coefficients of cities on the eastern bank such as Shenzhen and Dongguan are positive, and the positive support effect has been

strengthened after 2021. However, cities on the western bank such as Zhaoqing and Jiangmen still have a negative impact due to the misallocation of fiscal resources, but the negative effect has shown a weakening trend after 2021. For ECI, Shenzhen and Huizhou on the eastern bank have formed an "energy-finance" coordination zone (with positive coefficients), while Foshan and Jiangmen on the western bank have formed a restriction zone (with negative coefficients) due to the high proportion of high-energy-consuming industries. From 2016 to 2022, the absolute values of ECI coefficients in both types of regions have narrowed, reflecting the effective energy transformation under the "dual carbon" policy.

In light of the aforementioned research findings, the subsequent policy recommendations are proposed: (1) Create a platform for cross-regional green finance cooperation, capitalize on the radiation capability of the Guangzhou and Shenzhen dual cores, and encourage the transfer of creative resources from the eastern bank to the western bank. For cities within the prospective belt on the western bank, enhance policy orientation towards green credit and green bonds, and draw upon the policy experiences of the Hengqin Cooperation Zone in Zhuhai to mitigate the developmental disparity between the eastern and western banks and bolster regional coordinated development. (2) Guide manufacturing cities on the western bank such as Foshan and Jiangmen to accelerate the green transformation of industries. Establish dedicated funds to offer subsidies for green technology upgrades in cities with a significant secondary industry presence, optimize the industrial structure, and progressively mitigate the constraining impact of high-energy-consuming industries on green finance. Cities on the eastern bank should maintain the favorable impetus of fiscal investment in environmental conservation and augment the magnitude of financial assistance for green initiatives. Cities on the western bank should optimize the structure of fiscal expenditure, establish a performance evaluation mechanism for environmental protection expenditure, avoid the misallocation of resources, and strengthen the coordination between fiscal policies and green finance policies. Focus on the innovation agglomeration advantage of the eastern bank, establish a special green patent fund, support Shenzhen, Huizhou, and other cities to build green technology innovation and financial docking platforms, and promote cooperation between cities on the western bank and universities and scientific research institutions on the eastern bank to improve the conversion efficiency of green patents. Cities on the eastern bank should rely on technological advantages to deepen the coordination between energy consumption and green finance, and promote the green finance support model for low-energy-consuming industries in Shenzhen and Huizhou. Cities on the western bank should implement specialized loans for the conversion of high-energy-consuming enterprises, alleviate the constraints on energy consumption intensity in green finance, and resolve the paradox of high energy consumption coupled with inadequate financial assistance.

However, this study also has certain limitations: (1) The scope of the research area is limited. Due to the differences in systems between inland and Hong Kong and Macao, and the inconsistency in statistical standards, the study only focuses on 9 inland cities and does not include Hong Kong and Macao. As international financial centers, the green finance practices of Hong Kong and Macao are crucial to regional coordinated development. The lack of this part of the analysis may weaken the explanatory power of the regional overall coordination mechanism. (2) The index system has data-dependent deviations. Although the green finance evaluation indicators cover 7 dimensions, which is more comprehensive than previous studies, they do not include emerging tools such as green trusts and green leases. In addition, the disclosure of data on green funds and green equity transactions in some cities is incomplete, which may also affect the comprehensiveness of the evaluation. To address these limitations, the following solutions can be further explored in the future: (1) By unifying statistical standards, conducting cross-regional data docking, or using case comparison analysis, supplement the research on the spillover effect of green finance in Hong Kong and Macao on inland cities. (2) Expand data sources, connect with special data from local financial regulatory authorities, and introduce the expert weighting method to supplement subjective correction, so as to improve the completeness and accuracy of the index system.

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