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EVOLUTION AND INFLUENCING FACTORS OF THE GREEN DEVELOPMENT SPATIAL ASSOCIATION NETWORK IN THE GUANGDONG-HONG KONG-MACAO GREATER BAY AREA

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Abstract. Accurately grasping the structural characteristics and influencing factors of green development spatial association are significant for green coordinated development and ecological civilization construction in the Guangdong-Hong Kong-Macao Greater Bay Area (GBA). This study evaluates the GBA's green development performance from 2015 to 2019 based on duality theory, and uses social network analysis to explore the structural characteristics and evolution of the green development spatial association network, and then uses the exponential random graph model to reveal the influencing factors of network formation. we find that: (1) the GBA's green development is steady. Its spatial association network became increasingly complex, and tends to be tight. (2) As important hubs, Guangzhou, Shenzhen, and Hong Kong have the dominant positions in the GBA's green development spatial association network. Huizhou, Jiangmen, Zhaoqing, and Macao are at the edge of the network, and their interoperability with other cities is relatively weak. (3) Four subgroups exist in the GBA during different periods, with obvious gradient characteristics between them, and the multilevel transmission mechanism of the green development network gradually forms. (4) Economic development and urbanization level, ecological environment endowment, and geographical, institutional, and industrial proximity all have significant impacts on the formation of the GBA's green development spatial association network.

Keywords: Guangdong-Hong Kong-Macao Greater Bay Area, green development, spatial association network, social network analysis, duality theory, exponential random graph model.

JEL Classification: Q56, R11, R12.

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Introduction

Green development is a common choice for all global economies, and an inevitable requirement for the construction of China's ecological civilization and sustainable economic development (Liu & Yu, 2020). Since China's reform and opening-up, China has achieved rapid economic growth as well as resource shortages and environmental pollution caused by high energy consumption and emissions, bringing tremendous pressure to sustainable economic and social development. The "2020 Environmental Performance Index Report" shows that of the 180 participating countries, China ranks 120th, with 37.3 points (Wendling et al., 2020). Under such a severe environmental situation, the traditional economic and social development model must be transformed and upgraded. Compared with the traditional "black" development mode of high energy consumption and emissions, the core of green development is the coordination and unification of "green" with "development" to emphasize the harmonious coexistence of human and nature, and alleviate the contradiction between economic growth and resources and environment and ecology without breaking the limit of environmental supply (Qiu et al., 2021).

The Guangdong-Hong Kong-Macao Greater Bay Area (GBA), in the lower reaches of the Pearl River Basin, is a leader in China's economic strength and regional competitiveness, and is a pioneer in China's green development. In February 2019, the Central Committee of the Communist Party of China and the State Council issued the "Outline of the Development Plan for the GBA" with the strategic position of building a beautiful bay area that had "ecological safety, beautiful environment, social stability, and cultural prosperity," thus highlighting the importance of green development. However, while the GBA is one of the world's four largest bay areas, its green development level lags behind the other three areas. The Pearl River Delta, an important part of the GBA, is the first area in China to open-up. Its rapid urbanization and industrialization processes have made regional, compound, and compressed environmental problems increasingly prominent, and regional ecological security and green development has become increasingly serious (Wu et al., 2021). Simultaneously, insufficient internal environmental management coordination in the GBA, lack of linkage mechanisms, and poor communication with Hong Kong and Macao's institutional systems have further hindered the GBA's green development (Xu & Ma, 2020). Green development space is a carrier for green development, a focal point for promoting solutions to ecological and environmental problems, and the supporting foundation and constraint conditions for green development. Therefore, on the basis of improving the quality of green development output in each city, how to scientifically arrange the green development production space in the GBA and promote the interaction, mutual references, and complementary advantages among cities are the key to promoting coordinated green development and supply-side structural reform, improving the quality of economic growth, and building a beautiful bay area.

This study proposes three research questions: What is the GBA's current state of green development? What are the network structure characteristics and evolutionary trends of the green development spatial association network in the GBA? What factors have important impacts on the formation of the green development spatial association network in the GBA? These issues are of great significance for optimizing the overall spatial network pattern of green development in the GBA, improving the level of green development, and promoting coordinated regional development and the construction of ecological civilization. Accordingly, it is necessary to study the spatial evolution and influencing factors of the GBA's green development spatial association network. This study evaluates the GBA's green development performance from 2015 to 2019 based on duality theory. From the "relationship" perspective, the improved gravity model is used to identify the spatial relationship of green development in the GBA. It constructs a green development spatial association network, uses social network analysis (SNA) to analyze the spatial evolution characteristics of the green development spatial association network, and constructs an exponential random graph model (ERGM) to empirically analyze the important factors that affect the formation of the spatial association network. This study can provide a scientific basis and reference for the GBA's green development and ecological civilization construction.

This study is organized as follows: Section 1 introduces the literature review. Section 2 introduces the research area and data sources. Section 3 describes our research design. Section 4 shows the empirical analysis results. In final section, the conclusion is given.

1. Literature review

With the continuous expansion of cities and increasing demand for energy resources, green development has become the consensus of human development (Liu et al., 2019). In 1989, Pierce first proposed "green economy" to enable the exploration of green development. He advocated for "sustainable economic growth" and believed that economic development should fully consider the bearing capacity of the natural ecological environment (Pearce et al., 1989). There has since been much research on the concepts of green economy and green growth, and the voices calling for green development have increased (Reardon, 2007; United Nations Economic and Social Commission for Asia and the Pacific [UNESCAP], 2006). The UN Environment Programme states that green development is an economy that improves human well-being and social equity, while significantly reducing environmental risks and ecological scarcity. In 2011, the Organization for Economic Cooperation and Development (OECD) put forward a formal definition of green development: it means that while the economy grows, it can ensure that nature continues to provide resources and environmental supplies to meet the needs of human beings for a happy life. At the 2012 Rio+20 summit, a consensus was reached on green development, with its promotion based on the need to invest in resource-saving and environment-friendly sectors, increase ecological capital, and reduce natural capital consumption. In 2015, the United Nations Climate Conference signed the Paris Agreement, which emphasized that green development is the only choice for mankind's future development. Therefore, from the theoretical exploration and practical evolution of green development, it can be seen that with the deepening of understanding of the relationship between economic activities and resources and the environment, green development is transitioning from one-dimensional to multidimensional, from simple to complex, and from the early focus on the ecological environment to the recent focus on coordinated and unified of economy, society, and ecology.

Recent research on green development has provided relatively rich results in the following aspects:

1. The evaluation of green development performance. It is mainly carried out from two aspects. One is to build a green development evaluation index system to evaluate the level of green development or green development capabilities. For example, Kim et al. (2014) established the evaluation index system of green economic growth, and evaluated the green growth situation of 30 countries. Huang and Li (2020) established a green development capability index to measure the green development level of participating countries in the Belt and Road initiative. Weng et al. (2020) constructed an urban green development performance evaluation index system based on the "five-circle" model, and used a combination of subjective and objective weights to conduct comprehensive evaluation of green development performance in Beijing-Tianjin-Hebei cities from 2006 to 2017. Li et al. (2020) proposed an evaluation method based on the S-type cloud model to assess the green development level of 13 cities in Beijing-Tianjin-Hebei.

The other is to measure the green development efficiency (GDE) based on the perspective of input and output. For example, Kortelainen (2008) used DEA analysis method to compare and analyze the environmental performance of 20 Eu member states from 1990 to 2003. Based on panel data from 2003 to 2016, Guo et al. (2020) used the SBM-DEA model to estimate the GDE of 34 cities in northeast China. Based on a provincial-level panel dataset from 2007 to 2017, Zhang et al. (2020) used a three-hierarchy meta-frontier SBM-DEA model and the global Malmquist index to estimate the green total factor productivity of China's chemical sub-industries. Huang et al. (2021) used the interval slacks-based global Malmquist-Luenberger index model to measure the green total factor productivity of China's provincial regions from 2000 to 2018. Overall, existing research on urban green development performance (especially for the GBA) is less, and mainly measures urban green development capability (focusing on the measurement of green development scale and output) or green development efficiency (focusing on the measurement of the green development process), yet this cannot reflect the overall picture and overall performance of the urban green development.

2. The spatial pattern of green development. With the deepening of the research on green development, some scholars have attempted to analyze the spatial pattern of green development from a spatial perspective. In comparison, empirical research in this area are mainly conducted in China, but there are very few literatures that take foreign regions as research object. For example, Glazyrina and Zabelina (2018) presented the results of a comparative spatial analysis of the regions of the Russian Federation in the context of the concept of a green economy with the use of two quantitative factors that characterize the well-being of the population. Sun et al. (2018) divided China's green development level into levels and analyzed the spatial differentiation characteristics of China's green development levels from spatial and temporal perspectives. Liu et al. (2021b) analyzed the spatiotemporal evolution characteristics of industrial GDE in China through ESDA. Cui and Lui (2021) took 13 cities in the Beijing-Tianjin-Hebei region of China as the research object, using the coefficient of variation and Global Moran's I to analyze the temporal and spatial differentiation characteristics of GDE from 2003 to 2017. Overall, the existing research on the spatial pattern of green development has been almost limited to the analysis of the differences in the spatial distribution of green development, and in-depth research on the possible complex spatial relationships of urban green development is rare.

3. The influencing factors of green development. At present, there have been extensive researches on the influencing factors of green development at home and abroad. Copeland and Scott (1994) explored the relationship between FDI and green development level by taking the United States as a sample and found that the two were negatively correlated. Starting from the relationship between green development efficiency and per capita income, Yoeruek and Zaim (2005) found a significant U-shaped relationship between the two. Chiou et al. (2011) analyzed that market and industrial structures would have impacts on the level of green development. Feng et al. (2017) conducted research on 165 countries (regions) around the world, and found that green development performance is positively correlated with living altitude, energy structure, and comprehensive oil price, and negatively correlated with ecological carrying capacity. Xiang et al. (2021) investigated the influencing factors of GDE of the paper industry in the Yangtze River Economic Belt, and found that the scale of enterprises, technological investment, and industrial structure had significant positive impact on GDE, yet environmental regulations and the intensity of foreign investment had significant negative impact. Si et al. (2021) conducted research through 30 prefecture-level cities in Northwest China, and found that economic development, population density, traffic conditions, and education investment can significantly improve the urban GDE; however, the proportion of industries significantly hindered GDE improvement. Zhou et al. (2020) found that the economic strength, industrial structure, openness, and climate conditions positively promoted urban GDE in China. Overall, most existing research mostly use traditional measurement models when analyzing the influencing factors of green development, failing to take the influence of spatial factors into consideration. Some research uses spatial econometric models to verify the spatial spillover effects of green development based on geographic proximity. However, these researches are mainly limited to the spatial quantification of "attribute data", and it is difficult to accurately describe the spatial association network structure of green development. Moreover, the spatial econometric models cannot explain whether the formation of spatial association is due to the self-organizing structure effect of the network, the attributes of network nodes, or the influence effects of exogenous networks, and thus cannot fully reveal the formation mechanism of spatial association network.

In a word, the previous research provides a reference for this study while providing room for further expansion. Accordingly, based on previous research, this study supplements or expands previous studies, thus forming the novelty and originality of this study, which is different from existing literature. First, it defines and evaluates urban green development performance using the new perspective of duality theory by describing the dual characteristics of urban green development, dividing the dual image subsystems, and quantifying and characterizing them to provide a comprehensive measurement of the GBA's green development performance. Second, it reveals the spatial relationship of green development in the GBA. Based on the spatial association and complex network perspectives, this study conducts in-depth analysis of the structural characteristics and evolution of the green development spatial association network in the GBA from three aspects (overall network structure, individual centrality, and cohesive subgroups), and explores the factors that influence the formation of the green development spatial association network in the GBA. Third, it applies the ERGM to empirically analyze the factors affecting this formation from multiple dimensions such as network endogenous structural variables, node attribute variables, and network covariates.

2. Research area and data sources

2.1. Study area

The GBA is composed of the two special administrative regions of Hong Kong and Macao and the nine cities of Guangzhou, Shenzhen, Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen, and Zhaoqing in the Pearl River Delta. As the region with the highest degree of openness and strongest economic vitality, the GBA has an important strategic position for the overall development of China. Due to historical reasons, the GBA has formed the unique management structure of "one country, two systems, and three tariff zones". In 2019, the permanent population of the GBA is 72,649,200, with 64,468,900 people in the Pearl River Delta, 75,007 in Hong Kong, and 679,600 in Macao. The GDP is RMB 11.62 trillion, with RMB 8.69 trillion for the Pearl River Delta (accounting for 80.7% of Guangdong Province) and RMB 134,800 per capita GDP; RMB 2.8682 billion for Hong Kong and RMB 382,000 per capita GDP; and RMB 434.67 billion for Macao and RMB 639,600 per capita GDP. However, compared with other world-class bay areas, the challenges faced by the GBA have become more severe due to rapid economic growth, industrialization, and urbanization in recent decades.

2.2. Data sources

This study uses 11 cities in the GBA urban agglomeration as the research object. The sample span is from 2015 to 2019. The data are mainly from the Guangdong Province Statistical Yearbook, Hong Kong Statistical Yearbook, Macao Statistical Yearbook, and China City Statistical Yearbook over the years. Part of the data are from environmental bulletins issued by the local statistical bureaus in nine cities in mainland China, as well as relevant survey data published by the official websites of the Hong Kong Census and Statistics Department, Macao Statistics and Census Bureau, and the World Bank, which use unified currency units for the main economic indicators of Guangdong Province, Hong Kong, and Macao, and the annual average exchange rate is used for conversion. The exchange rate uses the official average exchange rate of the Hong Kong dollar and Macao pataca against RMB for the year.

3. Research design

3.1. Evaluation of the green development performance based on the duality theory

Green growth, in the general sense, may be just a "step-in-place" economic mode; that is, under the condition that the total economic volume has not increased, the reduction of pollutant emissions is considered as achieving green growth. Green development does not only include green economic growth, but also includes economic efficiency improvement, industrial structure upgrades, and social welfare improvement, and is a more advanced form of green growth (Feng & Chen, 2018; Wang & You, 2016). Therefore, urban green development must reflect the total output and benefits of urban green development (scale status indicators) as well as the improvement of urban green growth methods and efficiency (process quality indicators). To comprehensively and objectively evaluate the GBA's green development performance, this study uses duality theory.

The duality theory believes that a system can be divided into two corresponding subsystems: one virtual and one real. One subsystem is the overall mapping of the other subsystem, forming a unity of opposites (Gao & Xu, 2007). Based on duality theory, the GBA's green development is a dynamic system. It presents the characteristics of both state and process in the process of green development, where "state" is a static description of the system, and "process" is a dynamic reflection of the system. Therefore, the GBA's green development can be divided into the state subsystem and the process subsystem of green development. The former is the real image subsystem of objective reality, and the latter is the virtual image subsystem composed of the attributes mapped by the real image subsystem. In the evolution process of the GBA's green development, the state and process subsystems are opposites and maintain a relationship that is both competitive and cooperative, mutually reinforcing and restraining, restricting and synergistic; that is, dualistic.

To comprehensively and objectively measure and evaluate the GBA's green development performance, the development level of the two subsystems must first be measured. The evaluation of the green development state subsystem focuses on the measurement of green development output and benefits, which measures the overall quantity and scale of green development output. This study uses green development benefits (GDB) to evaluate the green development state subsystem's development level. Measures included economic, social, and environmental benefits, with seven specific indicators (see Table 1 column 3, lines 6–12). The entropy method is adopted to evaluate and compare GDB in the GBA.

The evaluation of the green development process subsystem mainly focuses on measuring the efficiency improvement and transformation of green development methods; that is, whether the subsystem can achieve resource conservation and pollution reduction while achieving economic growth, and can promote the transformation of economic growth to a green development model with low input, low emissions, and high output. Therefore, this

Table 1. Evaluation index system for green development in the GBA

Indicator type	First-level index	Second-level index	Unit
Input	Capital	Total investment in fixed assets	100 million yuan
	Labor	Total number of employees	Ten thousand people
	Resources	Annual water consumption	One hundred million cubic meters
		Annual electricity consumption	Billion kilowatt hours
Output	Economic benefits	GDP (constant price in 2015)	100 million yuan
	Social benefits	Number of primary school teachers per 10,000 people	People
		Number of doctors per 10,000 people	People
		Unemployment rate	%
	Environmental benefits	Inhalable particle (PM10)	Micrograms per cubic meter
		Municipal solid waste generation	Ten thousand tons
		Sewage discharge	Ten thousand cubic meters

study uses GDE to measure the development level of the green development process subsystem; specifically, it uses the Super-SBM model based on undesired output. Before using the Super-SBM model, the input and output (including desirable output and undesired output) indicators are determined for the GBA's green development. This study referred to the previous research (Cui & Liu, 2021; Ding et al., 2016; Zhao & Yang, 2017; Wang et al., 2021; Wu et al., 2021) and comprehensively consider the actual situation of the GBA and the availability of indicators, and then determined the specific indicators seen in Table 1 (see column 3, lines 2–12).

The overall level of green development performance in the GBA depends on the level of development and coordination of its two subsystems. Therefore, the formula for the green development performance of the cities in the GBA constructed in this study is:

$$GDP_{it} = GDB_{it} * GDE_{it} . \quad (1)$$

3.2. Construction of the green development spatial association network

The previous literature has generally used the gravity model and VAR Granger causality test to determine the spatial relationship of each node. Considering that the VAR Granger causality model is too sensitive to the selection of lag order (Liu & Xiao, 2021), it reduces the accuracy of the spatial association network structural description to a certain extent. Further, it is often only applicable to data with a long-time span (He et al., 2020). The gravity model can comprehensively consider other factors such as economic development, distance, population, and so on when describing the relationship between two cities, and can also use cross-sectional data to reflect the changing trend of spatial association network. Therefore, by referring to relevant literature (Fan & Xiao, 2021), this study uses the improved gravity model to measure the green development spatial association network in the GBA. The specific model is as follows:

$$R_{ij} = K_{ij} \frac{\sqrt[3]{P_i S_i G_i}\,\sqrt[3]{P_j S_j G_j}}{d_{ij}^2},\ K_{ij} = \frac{S_i}{S_i + S_j}, \quad (2)$$

where R_{ij} is the relative intensity of green development space between city i and city j; K_{ij} is the contribution rate of city i to the relative intensity of green development of city i and city j; P_i and P_j are the populations of city i and city j, respectively; S_i and S_j are the green development performance of city i and city j, respectively; G_i and G_j are the GDP of city i and city j, respectively; and d_{ij} represents the geographic distance between city i and city j.

From the improved gravity model, the green development spatial association matrix of the GBA is obtained, and binarization is performed according to the degree of correlation. Using the "average principle method" (Zhang & Guo, 2020), the mean of all elements of the association matrix in 2015 is used as the segmentation value. If the value is greater than or equal to the value indicating strong association, there is spatial association, and the value is 1; if the value is less, then it indicated weak correlation, spatial association is ignored, and a value of 0 is assigned. Finally, the green development spatial association matrix of the GBA is obtained.

3.3. Characterization of the green development spatial association network

SNA has been used in several disciplines (Aplin et al., 2015; Lee et al., 2014; Marra et al., 2017; Nabiafjadi et al., 2021) to study the relationship between actors in a society or network (Liu et al., 2021c). This study inputs the spatial association matrix into UCINET 6.0 software, and uses SNA to analyze the evolution characteristics of the green development spatial association network in the GBA from three aspects: the overall network structure characteristics, individual centrality, and cohesive subgroups analysis.

1. The overall network structure characteristics analysis of the green development spatial association network in the GBA is characterized by indicators such as network size, total number of connections, average distance, cohesion index, and network density. Network size refers to the number of network nodes and the number of cities in the network. The total number of connections refers to the number of lines connecting nodes in the network, reflecting the interconnected relationship between the green development of two cities. The average distance refers to the average of the shortest distance between two cities, reflecting the smooth flow of green development between cities. The cohesion index can be obtained based on the average distance, and measures the cohesion of the network. Network density refers to the closeness of the connections between the members of the network, reflecting the city density characteristics of connections between city nodes.
2. Individual centrality analysis measured the degree, closeness, and betweenness centrality to describe the individual centrality of the spatial association network of green development in the GBA. Through individual centrality, the status and role of each city in the network can be analyzed. Degree centrality indicates the degree to which a node is connected to all other nodes in the network, and can measure the central position of each city in the green development spatial association network. Closeness centrality represents the proximity of a node to all other nodes in the network, and examines the average length of the shortest path from a certain node to all other nodes. Betweenness centrality represents the number of times that a node acts as an intermediary to help any other two nodes to communicate with each other using the shortest path. The more times a node in the network acts as an "intermediary", the greater the betweenness centrality (Wang & Zhang, 2021).
3. Cohesive subgroup analysis can explain the substructure within a group. It is essentially a subgroup of actors who have relatively strong, direct, close, frequent, or positive relationships (Li et al., 2018). This study uses the iterative correlation convergence CONCOR method in the UCINET 6.0 software to analyze the cohesive subgroups. By repeating the correlation coefficients between rows (or columns) in the matrix, individuals with the same correlation coefficients can be divided into a subgroup (Fan & Xiao, 2021). This method can reveal which cities in the GBA have closer green development spatial connections, and can then analyze the position of each subgroup in the green development spatial association network.

3.4. ERGM model to discover influencing factors of the green development spatial association network

3.4.1. ERGM model

The ERGM is a statistical model centered on a network structure, and can explain the observed characteristics of the network structure similar to a logistic regression (Chong & Pan, 2020; Liu et al., 2021a; King et al., 2020). An ERGM can comprehensively consider the influence of network's internal and external factors on the generation of network connections, and has been widely used in the study of the formation mechanism of network connections. The specific model is:

$$\Pr\left(Y=y|\theta\right)=\frac{1}{k}\,exp\left\{\sum_{H}\theta_{H}^{T}g_{H}\left(y\right)\right\}, \quad (3)$$

where y is the actual observation network; Y is the network constructed by the ERGM; H is the factor that affects the formation of the network; $\Pr\left(Y=y|\theta\right)$ represents the probability that y appears in the matrix Y under the condition θ; $g_H\left(y\right)$ is the network statistics related to the structural model H, such as network endogenous structure statistics, node attribute statistics, network covariate statistics, and so on; and k is a constant to ensure that the equation conforms to the probability distribution. The Markov chain Monte Carlo (MCMC) maximum likelihood estimation method is often used to test the model estimation. This study uses the statnet package in R to construct the ERGM.

3.4.2. ERGM variable selection

The ERGM allows a variety of factors that may affect the formation of the relationship between nodes to be incorporated, and usually includes network endogenous structural variables, node attribute variables, and network covariates, as follows:

1. Network endogenous structural variables. The self-organization effect of the network endogenous structure can analyze the special endogenous structure that affects the realization probability of the network and discover the more important network local relationship construction process. An ERGM can incorporate a variety of network endogenous structure variables, such as edges, mutuality, convergence, expansibility, transitivity, interactive K triangle, interactive K path, and others. These statistical variables explain the interdependence of the spatial network from multiple angles to reveal its role in the formation of the network. If the spatial network has strong agglomeration, then the triangular structure variables in the ERGM's estimation results may face approximate degradation and parameter non-convergence problems (Handcock et al., 2008). According to the experimental results, when triangular structural variables such as expansibility, transitivity, and interactive K triangle are added to the model, the estimation results are not ideal. Therefore, this study only uses edges (Edges) and mutuality (Mutual) in the model.

2. Node attribute variables. A city's factors, such as its economic and social characteristics and ecological environmental conditions, may impact the formation of green development spatial association. Based on the existing research results (Liu & Yu, 2020), this study introduced variables such as economic development level (Econ), urbanization level (Urban), and ecological environment endowment (Ecol) into the ERGM, and analyzed whether a city with the stronger of these attributes in the GBA's green development spatial association network would be more likely to form a spatial relationship with other cities. Econ is measured by GDP, Urban is measured by the rate of urbanization, and Ecol is measured by the rate of forest coverage.

3. Network covariates. Compared with traditional measurement methods, the ERGM's advantage is that network variables can be included in the analysis to directly examine the interdependence characteristics and trends of different types of spatial binary relations. To test the impact of network variables on the formation of the green development spatial association network, this study introduced geographic distance, economic distance, technological gap, industrial gap, and institutional difference as network covariates into the ERGM to verify geographic (GP), economic (EP), technological (TP), industrial (IdP), and institutional (InP) proximity on the formation of the GBA's green development spatial association network.

GP refers to the distance between nodes in the green development spatial association network regarding geographic space. This study calculated the geographic distance between each node according to the city's latitude and longitude.

EP refers to the distance between nodes in the economic space in the green development spatial association network. This study uses the GDP gap between nodes to calculate:

$$Ecogap_{ij} = \left| eco_i - eco_j \right|, \tag{4}$$

where *eco* represents the total GDP of each node.

TP is measured by the gap in the number of patents granted per capita among different nodes in the green development spatial association network:

$$Tecgap_{ij} = \sqrt{\left| tec_i - tec_j \right|}, \tag{5}$$

where *tec* represents the number of patents granted per person of each node.

IdP is measured by the industrial structure gap between different nodes in the green development spatial association network. Due to the multicollinearity between the primary, secondary, and tertiary industry gaps, this study only incorporated the tertiary industry gap into the model:

$$Indgap_{ij} = \sqrt{\left| ind_i - ind_j \right|}, \tag{6}$$

where *ind* represents the proportion of tertiary industry in the GDP of each node.

Considering that there are multiple administrative system environments in the GBA, and different institutional environments may impact innovation cooperation, this study uses institutional difference between nodes to measure InP:

$$Insgap_{ij} = \left| ins_i - ins_j \right|, \tag{7}$$

where *ins* represents the institution assignment of each node. Using the dummy variable method, according to the administrative affiliation of a city, a prefecture-level city is assigned a value of 1, a provincial capital city and a special economic zone are assigned the value of 2, and a special administrative region is assigned the value of 3.

4. Empirical analysis results

4.1. Results and analysis of green development

Table 2 shows the green development performance of the cities in the GBA, the development levels of the state subsystem, and the process subsystem of green development (i.e., GDB and GDE). Overall, the GBA's green development performance increases from 0.253 in 2015 to 0.436 in 2019, with an average annual growth rate of 9.222%. Specific to the 11 cities in the GBA, most of their green development performances fluctuate and increase from 2015 to 2019, and only Zhaoqing experiences a significant decline from 2015 to 2017. Regarding the average green development performance rank of each city, Shenzhen (0.282), Hong Kong (0.263), and Guangzhou (0.203) are at the top, while Foshan (0.088), Zhaoqing (0.061), and Jiangmen (0.019) are at the bottom. There is a large gap between the green development performance of the top- and bottom-ranked cities, which shows that the GBA's green development suffers from imbalance and insufficiency between cities.

Furthermore, cities dominated by producer services rank high. For example, Shenzhen's pillar industries are cultural, high-tech, logistics and financial industries. Hong Kong's pillar industries are mainly finance, trade and logistics, professional and industrial and commercial support services, and tourism. The green development performance of these two cities ranks first and second in the GBA. However, the green development performance of cities dominated by traditional manufacturing ranks low. For example, Foshan's advantageous industries mainly include household appliances, ceramic building materials, metal products, textile and clothing industries. Dongguan's five pillar industries include electronic information manufacturing, electrical machinery and equipment manufacturing, textile, apparel, footwear, and hat manufacturing, food and beverage processing, and paper and paper products. The green development performance of these two cities ranks 8th and 9th in the GBA, respectively. It is not difficult to see that industrial structure has a significant impact on the green development performance. Only by optimizing and adjusting the urban industrial structure, developing

Table 2. Evaluation results of the GBA's green development performance

	2015	2016	2017	2018	2019	Mean	Rank
Guangzhou	0.307	0.328	0.366	0.611	0.625	0.203	3
Shenzhen	0.539	0.601	0.629	0.614	0.718	0.282	1
Zhuhai	0.153	0.403	0.410	0.414	0.429	0.164	6
Foshan	0.066	0.074	0.076	0.305	0.446	0.088	9
Huizhou	0.357	0.398	0.296	0.432	0.455	0.176	4
Dongguan	0.064	0.078	0.083	0.375	0.406	0.091	8
Zhongshan	0.171	0.372	0.237	0.344	0.420	0.140	7
Jiangmen	0.040	0.031	0.033	0.033	0.075	0.019	11
Zhaoqing	0.270	0.152	0.052	0.077	0.123	0.061	10
Hong Kong	0.482	0.515	0.556	0.653	0.689	0.263	2
Macao	0.334	0.376	0.365	0.376	0.413	0.169	5
Mean	0.253	0.302	0.282	0.385	0.436	–	–

emerging industries and services, and phasing out industries with high pollution and energy consumption, can the urban green development performance be further improved.

Regarding the development levels of the state and process subsystems for the green development of the cities in the GBA (i.e., the comprehensive performance of different cities in terms of GDB and GDE), the average of the two can be used as the classification threshold. The 11 cities in the GBA are divided into four types (see Table 3).

Type 1 cities include those whose development levels of the state and process subsystems are higher than the average level of the GBA; that is, the cities' green development has both excellent scale benefits and quality improvement. Shenzhen and Hong Kong belong to this category from 2015 to 2019, while Guangzhou remains stable in this category from 2017 to 2019. These three cities are benchmarks for green development in the GBA, and have obvious advantages in green development.

Type 2 cities include those whose development levels of the green development state subsystem are higher than the average level of the GBA, while the development levels of the green development process subsystem are lower than the average level of the GBA; that is, the green development has certain comparative advantages in terms of scale benefits, but there are certain shortcomings in terms of GDE improvement and process quality. Guangzhou belongs to this type from 2015 to 2016.

Type 3 cities include those whose development levels of the state subsystem and process subsystems are lower than the average level of the GBA; that is, their green development shows a "double-poor" dilemma in terms of scale benefits and process quality. The overall level of green development is poor. Jiangmen, Zhaoqing, Foshan, and Dongguan are relatively stable in this category from 2015 to 2019. These four cities must be guided by the concept of green development and actively take measures to promote low consumption, low carbon, and green development.

Type 4 cities include those whose development levels of the green development process subsystem are higher than the average level of the GBA, while the development levels of the

Table 3. Type distribution of green development in the GBA based on duality

	Type 1	Type 2	Type 3	Type 4
2015	Shenzhen, Hong Kong	Guangzhou	Jiangmen, Dongguan, Zhongshan, Foshan, Zhuhai	Zhaoqing, Macao, Huizhou
2016	Shenzhen, Hong Kong	Guangzhou	Jiangmen, Zhaoqing, Dongguan, Foshan	Zhongshan, Macao, Zhuhai, Huizhou
2017	Shenzhen, Hong Kong, Guangzhou		Jiangmen, Zhaoqing, Foshan, Dongguan	Zhongshan, Macao, Huizhou, Zhuhai
2018	Shenzhen, Hong Kong, Guangzhou		Jiangmen, Zhaoqing, Foshan	Dongguan, Macao, Zhongshan, Zhuhai, Huizhou
2019	Shenzhen, Hong Kong, Guangzhou		Jiangmen, Zhaoqing	Macao, Dongguan, Zhongshan, Zhuhai, Foshan, Huizhou
Mean	Shenzhen, Hong Kong, Guangzhou		Jiangmen, Foshan, Zhaoqing, Dongguan	Macao, Zhongshan, Zhuhai, Huizhou

urban green development state subsystem are lower than the average level of the GBA; that is, the green development has certain comparative advantages in terms of efficiency improvement and process quality, but there are certain shortcomings in terms of the output of the scale benefits of green development. Zhongshan, Macao, Zhuhai, and Huizhou are relatively stable in this category. These four cities have better green development process effectiveness, and their green development has certain process advantages and potential.

4.2. Evolution of the GBA's green development spatial association network

4.2.1. Overall structural characteristics

This study constructed a network based on the improved gravity model and created a spatial association network diagram for the GBA's green development (see Figure 1). It simultaneously calculated the scale, total number of connections, density, and other indicators of the green development spatial association network in the GBA, and the results are shown in Table 4. It can be seen from Figure 1 that compared with 2015, the connections established by nodes in the network in 2019 have become more and more abundant, indicating that the green development connections between cities in the GBA have become tighter, and the green development spatial association network has shown a good development trend.

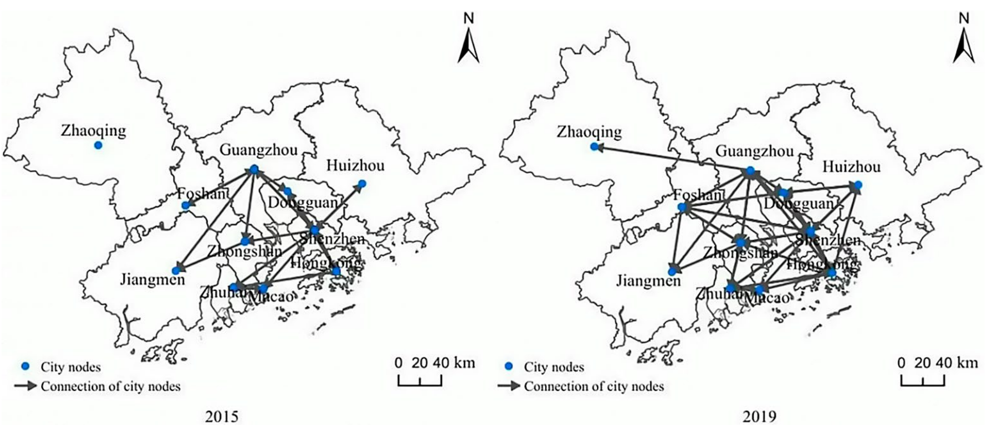


Figure 1. The green development spatial association network in the GBA in 2015 and 2019

Table 4. Structural characteristics of the GBA's green development spatial association network

Years	Network size	Total number of connections	Average distance	Cohesion index	Network density
2015	10	20	1.750	0.297	0.182
2016	10	27	1.778	0.433	0.246
2017	10	26	1.673	0.356	0.236
2018	11	36	1.744	0.554	0.327
2019	11	44	1.622	0.595	0.400

Regarding network size, this includes 10 cities, except Zhaoqing from 2015 to 2017. After 2018, the network size achieves full coverage in 11 cities, and the network size stabilizes, while the connections between cities constantly increase. From 20 connections in 2015 to 44 connections in 2019, this increase is significantly greater than the network size, and indicates that the degree of relevance of green development between cities in the GBA is growing. The average distance between nodes in the network fluctuates to a certain extent, but the overall decline is from 1.750 in 2015 to 1.622 in 2019, indicating that the degree of cooperation and exchange in green development between cities in the GBA has increased. The cohesion index, increases from 0.297 in 2015 to 0.595 in 2019, which shows that the cohesion of the green development spatial association network in the GBA continues to increase. The network density is 0.182 in 2015, which is relatively low. However, it increases to 0.400 in 2019 (an increase of 2.198 times), which indicates that the green development spatial association network in the GBA is tight. Overall, from 2015 to 2019, the total number of network connections, cohesion index, and network density increase significantly, and the average distance decreases to a certain extent. This indicates that the degree of interconnection between the green development of cities in the GBA has increased in addition to the tightness of the green development spatial association network.

4.2.2. Individual centrality analysis of the GBA's green development spatial association network

The calculation results of the degree centrality (DC), closeness centrality (CC), and betweenness centrality (BC) of the GBA's green development spatial association network from 2015 to 2019 are shown in Table 5.

Table 5. Centrality of the GBA's green development spatial association network

		Guangzhou	Shenzhen	Zhuhai	Foshan	Huizhou	Dongguan	Zhongshan	Jiangmen	Zhaoqing	Hong Kong	Macao
DC	2015	50	70	30	10	10	30	30	20	0	30	20
	2016	60	80	40	20	10	30	40	20	0	40	20
	2017	60	80	40	20	10	30	40	20	0	50	30
	2018	70	80	40	40	20	40	40	30	10	40	30
	2019	70	80	40	50	30	50	60	30	10	70	30
CC	2015	41.670	45.460	35.710	31.250	33.330	38.460	38.460	32.260	0	35.710	34.480
	2016	43.480	47.620	40	37.040	34.480	38.460	40	34.480	0	40	35.710
	2017	43.480	47.620	40	37.040	34.480	38.460	40	34.480	0	41.670	37.040
	2018	76.920	83.330	58.820	62.500	50	62.500	62.500	52.630	45.460	62.500	52.630
	2019	76.920	83.330	58.820	66.67	52.630	66.670	71.430	52.630	45.460	76.920	52.630
BC	2015	27.040	47.040	1.110	0	0	2.960	5.190	0	0	1.110	0
	2016	14.820	37.410	3.700	0	0	0	6.670	0	0	1.850	0
	2017	15.190	33.700	2.410	0	0	0	6.300	0	0	4.630	0
	2018	30.670	33.410	2.300	3.190	0	4.220	5.780	0.740	0	4.150	0
	2019	25.770	19.100	1.110	3.410	0	3.780	8.970	0	0	13.410	0

The degree centrality of all cities increases from 2015 to 2019, indicating that the connection degree of green development between cities has increased. It further shows that the internal connection within the GBA's green development spatial association network continuously increases. Regarding the comparison of various cities, Shenzhen and Guangzhou rank in first and second place for the degree centrality of the network, respectively, and are at the core position of the network. The degree centrality of Hong Kong fluctuates, but the overall trend is rising, which is the same as Guangzhou in 2019. The degree centrality of Macao, Jiangmen, Huizhou, and Zhaoqing are lower than the GBA's average value from 2015 to 2019. This shows that these cities have few green development connections with other cities and are in the subordinate position of the GBA's green development spatial association network.

The closeness centrality of all cities increases from 2015 to 2019, with a significant increase between 2017–2018, indicating that the cities in the GBA can connect with other cities for green development using a shorter network distance, and the overall network connectivity and smoothness have improved. From the comparison of various cities, the closeness centrality of Shenzhen and Guangzhou rank in first and second place, while the closeness centrality of Hong Kong rapidly increases from 2017, which is the same as Guangzhou in 2019. These three cities have the shortest distances from other cities in the green development spatial association network, and play the leading role of the "central actor" in the network. Conversely, the closeness centrality of Huizhou, Jiangmen, and Zhaoqing is lower than the average value in the network. Due to low green development performance or geographical limitations, these cities play the role of the "edge actor" in the network.

Regarding betweenness centrality, the GBA's green development connection from 2015 to 2019 is mainly realized through Shenzhen and Guangzhou. These two cities are important hubs in the spatial association network, play a powerful role as a bridge to link the transmission of elements and resources of green development, and have strong resource control capabilities. However, Shenzhen's betweenness centrality sharply declines from 2015 to 2019, and is lower than Guangzhou in 2019. This may be due to the strengthening of the network's internal connections, and its dependence by other cities has decreased, thus the ability to control resources is weakened. The betweenness centrality of Hong Kong increases significantly from 2018 to 2019, but there remains a certain gap with Shenzhen and Guangzhou. Although Zhongshan has a lower betweenness centrality than Shenzhen and Guangzhou, it is in a leading position compared with other cities, and plays a certain "bridge" role in the network. The centrality of all other cities is almost lower than the average, indicating that they are highly dependent on green development and are dominated and influenced by the core cities in the network.

Overall, from 2015 to 2019, the centrality index trend of each city improves. Guangzhou and Shenzhen are at the core of the GBA's green development spatial association network. They have more connections with the surrounding cities and play an important role in the GBA's green development. Simultaneously, Hong Kong's centrality index significantly improves, and gradually enters the ranks of the core cities, which promotes the green development of other cities. However, Huizhou, Jiangmen, Zhaoqing, and Macao are at the edge of the network due to their lagging centrality. Thus, the green development connections with other cities must be further strengthened.

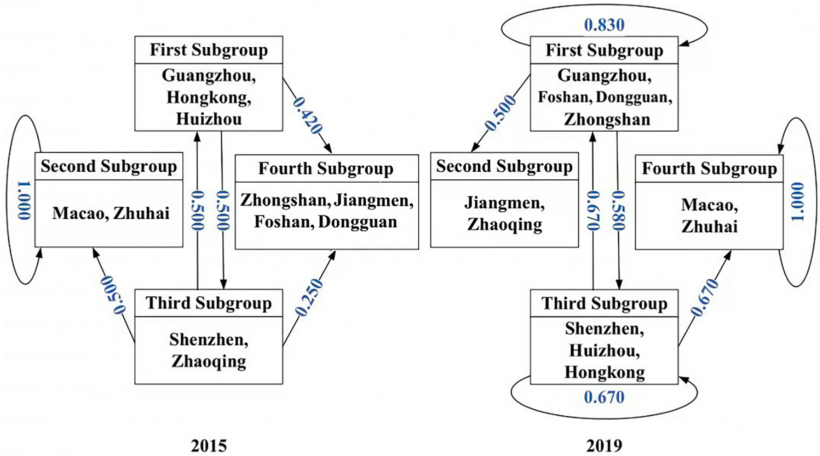
4.2.3. Analysis of the cohesive subgroups of the GBA's green development spatial association network

To explore whether there is a "small group" in the GBA's green development spatial association network, this study uses the CONCOR method in the UCINET 6.0 software to divide the spatial association network into sections, with a maximum segmentation depth of 2 and a concentration of 0.2. The results are shown in Table 6. On this basis, the density matrix and image matrix between the subgroups is measured (see Appendix), and the connection density between the subgroups is visualized (see Figure 2) to more intuitively reflect the spillover effect of green development.

Table 6 shows the GBA's green development spatial association network divided into four subgroups from 2015 to 2019. Over time, the composition of the subgroups gradually stabilizes. The first subgroup is mainly composed of "Guangzhou-Foshan-Dongguan"; the second subgroup is mainly composed of "Jiangmen-Zhaoqing"; the third subgroup is mainly composed of "Shenzhen-Huizhou"; and the fourth subgroup is mainly composed of Macao. Further analysis of Figure 2 shows that, compared to 2015, the first subgroup establishes a strong mutual spillover relationship with the third subgroup in 2019, with contact densities of 0.580 and 0.670, respectively. This shows that the "Guangzhou-Foshan-Dongguan-Shenzhen-Huizhou" green development corridor in the eastern part of the GBA has taken shape. The composition and connection of the second and fourth subgroups have also undergone major changes. Particularly, the second subgroup, which accepts the spillover relationship with the first subgroup in 2019, has low contact density, and is at the edge of the network. Jiangmen and Zhaoqing in the second subgroup are also likely to remain in the marginal subgroup for a long time due to the lack of radiation from other cities. In addition, in the green development spatial association network, a multilevel delivery mechanism has started to take shape. The third subgroup acts as a "bridge" in the network. The first subgroup transfers the green development resources to the third subgroup, and the third subgroup further transfers it to the fourth subgroup. This transfer mechanism reflects that the gradient characteristics that

Table 6. Division of cohesive subgroups of the GBA's green development spatial association network

Subgroups	2015	2016	2017	2018	2019
First	Guangzhou, Hong Kong, Huizhou	Guangzhou, Foshan, Dongguan, Shenzhen, Jiangmen	Guangzhou, Zhaoqing	Guangzhou, Foshan, Dongguan	Guangzhou, Foshan, Dongguan, Zhongshan
Second	Macao, Zhuhai	Zhaoqing	Hong Kong, Zhuhai, Shenzhen, Macao	Jiangmen, Zhaoqing	Jiangmen, Zhaoqing
Third	Shenzhen, Zhaoqing	Huizhou, Zhuhai	Huizhou, Foshan, Dongguan	Shenzhen, Huizhou, Zhuhai	Shenzhen, Huizhou, Hong Kong
Fourth	Zhongshan, Jiangmen, Foshan, Dongguan	Zhongshan, Macao, Hong Kong	Zhongshan, Jiangmen	Zhongshan, Macao, Hong Kong	Macao, Zhuhai



Note: The arrow values represent the connection density between subgroups.

Figure 2. Association between the cohesive subgroups of the GBA's green development spatial association network in 2015 and 2019

exist between the subgroups of the GBA's green development spatial association network have gradually become prominent. Overall, although the composition of the cohesive subgroups of the network has undergone major changes from 2015 to 2019, the composition and connections of the subgroups have gradually stabilized to show a "multicenter, multilevel, and multi-node" network structure.

4.3. Influencing factors of the GBA's green development spatial association network

The Statnet package in the R software is used to construct the ERGM of the GBA's green development spatial association network. The network endogenous structural variables, node attribute variables, and network covariates determined above are incorporated into the model to explore the influencing factors of the green development spatial association network in the GBA. The results are shown in Table 7.

Regarding the endogenous structural variables, the Edges parameter estimation passes the 1% significance level test from 2015 to 2019, and the coefficient is negative. This indicates that the density of the GBA's green development spatial association network is relatively low, and the real observation network exhibits the typical characteristics of a sparse effect. In addition, the Mutual parameter estimation passes the 1% significance level test from 2015 to 2019, and the coefficient is positive, which indicates a reciprocal effect in the GBA's green development spatial association network. This effect can further promote the formation of the green development spatial association network. It also means that the flow of green development elements and resources between cities is mutual and becomes increasingly obvious over time.

Regarding the node attribute variables, except for the Econ parameter estimation in 2017 which is not significant, the coefficients of Econ in the remaining years are all significantly negative, and the significance gradually increases over time. This shows a negative impact on the formation of the GBA's green development spatial association network. That is, when the economic development level of a city continues to increase, the probability of its relationship with another city's green development will continue to decrease. This result further shows that when promoting urban development, one should not blindly pursue economic benefits and ignore other aspects of development because doing so will inhibit the formation of the GBA's green development spatial association network. The Urban parameter is estimated to pass the 1% significance level test, and the coefficient is positive from 2015 to 2019, which shows that the improvement of the urbanization level can promote the formation of the GBA's green development spatial association network. For example, the Urban coefficient in 2019 is 0.123 ($p < 0.001$) (exp (0.123) = 1.131), which means that for every percentage point increase in the urbanization level of cities in the network, the probability of establishing a new set of relationships increases by 13.1%. However, the Urban coefficient fluctuates during the inspection period, and has a relatively obvious decline, which indicates that the impact of the urbanization level on the formation of the green development spatial association network has been weakened to a certain extent. In addition, the Ecol parameter is estimated to pass the 1% significance level test from 2015 to 2019, and the coefficient is positive. This shows that the better the ecological environment of a city, the more it can promote the formation of a new relationship between the green development space of the GBA. For example, the Ecol coefficient in 2019 is 0.299 ($p < 0.001$) (exp (0.299) = 1.348), which means that for every percentage point increase in the ecological environment endowment of cities in the network, a new set of relationships will increase in the probability of establishment by 34.8%. Simultaneously, since 2015, the Ecol coefficient has been increasing, which shows that it has become increasingly obvious in promoting the formation of the green development spatial association network in the GBA. Therefore, to further promote the formation of this network, it is necessary to increase the importance of the joint protection and governance of the regional ecological environment (Xu et al., 2019).

Regarding the network covariates, the GP parameter is estimated to be significant at the 1% level, and the coefficient is negative, which shows that geographical distance has significantly inhibited the formation of green development relationships within the GBA from 2015 to 2019. However, from the perspective of magnitude of the coefficient, GP has a relatively limited impact on the green development spatial association network in the GBA, and there is a certain weakening, indicating that with the continuous improvement of transportation facilities, communication facilities, and so on, the influence of geographical distance on the flow of elements and resources for green development between cities has gradually weakened. The InP parameter is estimated to be significant at the 1% level, and the coefficient is negative, except for in 2016, which indicates that the institutional difference between cities mainly inhibit the formation of green development relations between cities. In short, the more similar the institutional systems are between cities, the higher the probability of forming a spatial association of green development. Since 2017, the IdP parameter passes the 1% significance level test, and the coefficient is positive, which indicates that appropriate industrial difference has a promoting effect on the formation of green development relations between cities. In short, if the industries between cities are too similar, it will be detrimental to the formation of the green development spatial association network in the GBA. Therefore, cities in the GBA should maintain a certain industrial gap, build a hierarchical and differentiated industrial structure in the GBA, and jointly promote the formation of a green development network. TP only passed the 5% significance level test in 2018, and the coefficient is negative, which means that only in 2018 is the formation of the green development spatial association network suppressed due to the technological gap between cities, and the technological gap in the remaining years did not have a significant impact on the network's formation. This indicates that it had a limited impact on the green development association network. In addition, EP does not pass the significance test from 2015 to 2019, which shows that the economic gap does not have a significant impact on the formation of the GBA's green development spatial association network.

Through our findings, which explain our observations and are partly in accordance with the research results of some empirical studies about China (Chen et al., 2022; Jia et al., 2021; Zhang & Wu, 2021), Although the specific methods, the research object (research area) are not the same. The same conclusion as the existing research is that the geographical distance and institutional difference between cities have inhibitory effects on the formation of the green development spatial association network. In other words, the geographic distance between cities has a negative effect on the green development spatial association network in the GBA. The increase in geographic distance increases the cost of element flow and the difficulty of element space transfer, thereby affecting the spatial spillover effect of urban green development. Location proximity is more conducive to the spatial transfer of various elements between cities, which in turn promotes the generation of "polarization effect" and "trickle drop effect" between cities, forming a stable spatial association network. Institutional difference is an important factor affecting green development cooperation and exchanges between cities. The green development of the GBA is a practical innovation under the principle of "one country, two systems". However, due to the different stages of economic and social development and environmental demands in the three places, the different regulatory systems and institutional environments, and the differences in governance models and con-

Table 7. Parameter estimation results of the ERGM

	variables	2015	2016	2017	2018	2019
Structural configurations	Edges	–26.670***	–22.420***	–31.360***	–26.310***	–27.840***
	Mutual	0.701***	2.331***	1.373***	2.947***	3.401***
City-related attributes (nodecov)	Econ	–0.075*	–0.067**	–0.050	–0.103***	–0.117***
	Urban	0.244***	0.223***	0.300***	0.279***	0.123***
	Ecol	0.199***	0.123***	0.170***	0.167***	0.299***
City network covariates (edgecov)	GP	–0.070***	–0.041***	–0.036***	–0.053***	–0.041***
	EP	0.000	0.000	–0.000	–0.000	0.000
	TP	0.282	0.078	–0.034	–0.176**	–0.014
	IdP	0.213	–0.029	0.404***	0.339***	0.150***
	InP	–0.525***	0.155***	–0.894***	–0.631***	–0.351***
AIC		66.880	84.460	81.380	76.440	79.260
BIC		93.880	111.500	108.400	103.400	106.300

Note: ***, ** or * denotes significance at the 1%, 5%, or 10% level, respectively.

tent, green coordinated governance and development facing difficulties (Wu et al., 2021; Xu & Ma, 2020). Therefore, institutional difference has an inhibitory effect on the formation of the green development spatial association network in the GBA.

The difference from the existing research conclusions is: we find that industrial difference has a significant positive impact on the formation of the green development spatial association network in the GBA. Existing research generally believes that similar industrial structures have a significant impact on the formation of China's inter-provincial green development spatial association network. The possible explanation is that the research object selected in this study is the GBA, which is one of the urban agglomerations with the strongest economic vitality, the most concentrated scientific and technological innovation resources, and the most active development of emerging industries in China. Industrial division of labor and collaboration is the core concept of the construction of the GBA. In recent years, the GBA has optimized the industrial structure through industrial differentiation, promoted the formation of a reasonable industrial division of labor between cities, improved the quality and efficiency of the industrial structure, and provided support for the regional green coordinated development. The GBA has a relatively good level of industrial division of labor and has huge room and potential for industrial cooperation. Most cities in the GBA have relatively high industrial complementarities: Hong Kong's main industries are financial services, tourism, trade, logistics, and professional services, and Macao's main industries are gambling tourism, construction and real estate, and financial services. Mainly, the 9 cities in the Pearl River Delta have formed an industrial system dominated by manufacturing with distinctive characteristics (Liu et al., 2020). The "heterogeneous type" of complementary and cooperative relations established between cities in the GBA due to differences in industrial structure is conducive to the formation of green development spatial association network.

Conclusions and policy recommendations

Based on duality theory, this study evaluates the GBA's green development performance from 2015 to 2019, uses an improved gravity model to identify the spatial association of the green development, and constructs a spatial association network. Then, it uses SNA to analyze the structural characteristics and evolution of its spatial association network regarding the overall network structure characteristics, individual centrality, and cohesive subgroups, and uses an ERGM to reveal the influencing factors of the spatial association network formation. The conclusions are as follows:

1. The overall green development of the GBA shows a steady trend, and the spatial association network tends to be tight during the sample period. Specifically, the green development performance steadily improves from 2015 to 2019, and the green development between cities starts to show complex association relationships. The tightness of the green development spatial association network increases in addition to the network cohesion.
2. The individual centrality of different cities is quite distinct. Specifically, Guangzhou, Shenzhen, and Hong Kong take the core position in the GBA's green development spatial association network. They are also important hubs for the spatial association

network, and assume the transmission role of a "bridge". Simultaneously, Hong Kong gradually enters the ranks of the core cities, and an increasing number of cities are affected by the spillover of Hong Kong's green development. However, the centrality of Huizhou, Jiangmen, Zhaoqing, and Macao lag behind. They are at the edge of the network and have weak interoperability with other cities.

3. There are four cohesive subgroups in the GBA from 2015 to 2019, and the internal composition of each subgroup changes greatly in different years. With the general strengthening of the green development connections between cities in the GBA, the gradient characteristics between the subgroups become more obvious, and the multilevel transmission mechanism of the GBA's green development spatial association network gradually forms.
4. The ERGM's empirical analysis results show that: in the formation of the GBA's green development spatial association network, among the node attribute variables of the network, the impact of a city's Econ level is significantly negative, while the impacts of a city's Urban level and Ecol level are significantly positive. Regarding the network covariates, the impacts of GP and InP are significantly negative and the impact of IdP is significantly positive; that is, the geographical distance and institutional difference between cities have an inhibitory effect on the formation of the green development spatial association network in the GBA, while an appropriate industrial gap between cities has a promoting effect on the formation of the network.

Based on the above conclusions, this study proposes the following policy recommendations:

1. Establish a green development concept of spatial integration to build a green development community in the GBA. Scientifically plan the green development of the GBA, actively explore effective ways to promote the spatial connection of green development, break down the barriers between Guangdong, Hong Kong and Macao, and explore the establishment of relevant departments as green development cooperative institutions. By increasing the intensity of spatial association and improving the closeness between cities to promote the formation of the GBA's green development spatial association network.
2. Promote the transition from green development in the GBA to a networked spatial development model. Specifically, by enhancing the spatial radiation effect of network core cities such as Guangzhou, Shenzhen, and Hong Kong, encouraging them to continue to explore new ways of green development, and finding new ways to promote the spatial association of green development. Cities with relatively low levels of green development and relatively scarce green development resources must actively accept and use the spillover effects of green development from other cities to strengthen their spatial relationships in the network. While improving the city's own conditions such as urbanization and green development, it is also necessary to strengthen the interactive exchanges and fair development of the key elements of green development between cities, form a green development pattern with reasonable division of labor and mutual promotion, and share the technology and agglomeration spillovers of core cities.
3. Promote green development exchange and cooperation among the subgroups in the spatial association network. On the one hand, promote the formation of subgroup cit-

ies in the region, promote the formation of stable green development exchanges and cooperation connections between cities within subgroups, and at the same time avoid the hindrance of subgroup connections on the overall regional connections. On the other hand, by building a green development alliance between the subgroups, using the multilevel transmission mechanism of the green development spatial association network, adjusting measures to local conditions, rationally allocating various levels of green development elements and resources, and jointly promoting the improvement of the overall level of green development in the GBA.

4. Strengthen the flow of green development elements and resources from various aspects, and break the green development barriers within the GBA. Specifically by improving the overall strategy, institutional arrangements, and coordinated development mechanisms for green development in the GBA; eliminating the barriers to green development in the GBA from such factors as geographic distance and institutional difference; promoting the formation of appropriate industrial differentiation between cities; increasing the cross-city flow of green development element resources; and promoting the generation of spatial association effects of green development.

This study also has the limitation. This study is still in the exploratory stage of the research on the influencing factors of the formation of the GBA's green development spatial association network. There may be many node attribute variables and network covariates that affect the formation of the spatial association network. In future research, these issues will be further explored, and the related issues of the green development spatial association network will be studied more in-depth.

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Author contributions

Zhijun Feng and Zaoli Yang conceived the study and were responsible for the design and development of the data analysis. Zhijun Feng, Zinan Chen and Hechang Cai were responsible for data collection and analysis. Zhijun Feng and Zaoli Yang were responsible for data interpretation. Zinan Chen wrote the first draft of the article.

Disclosure statement

The authors report no conflict of interest.

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APPENDIX

Table A1. Density matrix and image matrix table of the GBA's green development spatial association network

		Density matrix				Image matrix			
2015	Subgroups	First	Second	Third	Fourth	First	Second	Third	Fourth
	First	0	0.170	0.500	0.420	0	0	1	1
	Second	0	1	0	0	0	1	0	0
	Third	0.500	0.500	0	0.250	1	1	0	1
	Fourth	0.080	0	0	0.080	0	0	0	0
2016	Subgroups	First	Second	Third	Fourth	First	Second	Third	Fourth
	First	0.400	0	0.200	0.270	1	0	0	1
	Second	0	0	0	0	0	0	0	0
	Third	0.200	0	0	0.330	0	0	0	1
	Fourth	0.400	0	0.500	0	1	0	1	0
2017	Subgroups	First	Second	Third	Fourth	First	Second	Third	Fourth
	First	0	0.250	0.330	0.500	0	1	1	1
	Second	0.250	0.830	0.330	0.250	1	1	1	1
	Third	0.170	0	0	0.330	0	0	0	1
	Fourth	0	0	0	0.500	0	0	0	1
2018	Subgroups	First	Second	Third	Fourth	First	Second	Third	Fourth
	First	1	0.500	0.220	0.220	1	1	0	0
	Second	0	0	0	0	0	0	0	0
	Third	0.440	0	0.670	0.670	1	0	1	1
	Fourth	0.220	0.170	0.560	0.170	0	0	1	0
2019	Subgroups	First	Second	Third	Fourth	First	Second	Third	Fourth
	First	0.830	0.500	0.580	0.130	1	1	1	0
	Second	0	0	0	0	0	0	0	0
	Third	0.670	0	0.830	0.670	1	0	1	1
	Fourth	0.130	0	0.330	1	0	0	0	1

Note: If the subgroup density is greater than the overall network density of the year, the corresponding value in the image matrix is 1; otherwise, it is 0.