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Synergistic-development of economy, resources, and environment in Guangdong-Hong Kong-Macao Greater Bay Area and its obstacles: a new sustainable framework

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In recent years, the swift expansion of urban agglomerations has given rise to a profusion of resource and environmental challenges, intensifying the prominent conflict between the imperatives of sustainable development and economic pursuits. This paper clarifies the intricate connection and synergistic dynamics among the economy, resources, and the environment, with the aim of determining their collective influence on the sustainable trajectory of urban agglomerations. Focusing on the exemplary case of Guangdong-Hong Kong-Macao Greater Bay Area, this paper utilizes panel data ranging from 2006 to 2020 to disentangle the spatial-temporal subtleties and obstacles hindering the harmonious development of its economy-resource-environment trinity. Firstly, it integrates the coupling coordination mechanism within the DPSR (Driving Force, Pressure, States, and Response) analytical framework to create a novel sustainable development paradigm. Secondly, it builds a comprehensive evaluation index system to measure the spatial-temporal evolution of the economic-resource-environmental matrix within Greater Bay Area. And thirdly, by employing an obstacle degree model, this paper identifies key obstacles that impede the coordinated progress of the economic-resource-environmental nexus in Greater Bay Area. Lastly, it highlights a continuous upward trajectory in the spatial-temporal evolution of Greater Bay Area, marked by decreasing variations in coupling degrees and enhanced inter-connectivity among the constituent elements. This paper not only provides insights into the complex dynamics shaping urban agglomerations, but also offers actionable intelligence to navigate the multifaceted challenges associated with sustainable development endeavors.

KEYWORDS

sustainable development framework, economic-resource-environment system, coupling coordination research, obstacle degree model, Guangdong-Hong Kong-Macao Greater Bay Area, Guangdong-Hong Kong-Macao Greater Bay Area (GBA)

1 Introduction

Presently, the global urbanization trajectory is gaining momentum, ushering in a new phase where cities take precedence in the spatial distribution structure of human economic and social activities (lmqvist et al., 2019; Hermanns and Li, 2018). With over half of the world's population already residing in urban areas, a statistic projected to surge to 70% by 2050 according to the 2023 Sustainable Development Goals report, cities served as pivotal hubs not only for livelihoods but also as catalysts for a nation's economic prosperity (Bai et al., 2014; Hidemichi et al., 2018). However, alongside the impetus for economic advancement that urbanization provides, cities were also saddled with the primary responsibility for addressing a gamut of challenges, including resource depletion and environmental degradation. From the 1950s–2000s, the urban expanse of the EU-25 burgeoned by 80%, exacting severe tolls on ecosystem structure and function, and precipitating myriad issues, strains on natural resources and the environment (EA. Urban Sprawl in Europe, 2006; Bai et al., 2016). These encompass urban metabolism, biodiversity depletion, dwindling carbon sinks, alterations in land use and cover, disruptions to biogeochemical cycles, and climate perturbations (Seto et al., 2024; Grimm et al., 2008; Angle et al,. 2011; Li et al., 2005; Andree et al., 2019; Xia and Li, 2022). In the context of China, the nation's unprecedented economic growth trajectory and sustained duration represented a historical anomaly, yielding remarkable accomplishments (Yang and Li, 2012). Nonetheless, the concomitant forces of industrialization, urban sprawl, and burgeoning resident demands had escalated the requisites for diverse resources, outstripping the capacity of domestic reservoirs to fully satiate the burgeoning material and cultural aspirations of the populace for an enhanced standard of living. The conventional paradigm of extensive economic development had precipitated escalating levels of environmental contamination and ecological degradation, imposing immense strains on the very ecosystems pivotal for human sustenance, thereby imperiling human welfare and health. During the period of rapid industrialization from the 2000s to the early 2010s, China experienced unprecedented economic growth, becoming the world's second-largest economy. However, this uncontrolled economic growth had profound negative effects on the environment. During this time, China's economic growth was largely driven by heavy industries such as steel, coal, fertilizer, and construction materials, which are major sources of air pollution. The increased burning of coal, factory emissions, and automobile exhaust led to severe air pollution, especially in large cities like Beijing, Shanghai, and Tianjin. In the 2010s, air pollution in Beijing reached hazardous levels, with PM2.5 concentrations far exceeding the safety standards set by the World Health Organization. Air pollution has caused millions of premature deaths and health problems each year. This prevailing weak sustainability doctrine, predicated solely on ensuring the maintenance of aggregate wealth irrespective of ecological thresholds, necessitates supplanted by a robust sustainability framework (Ariken et al., 2021). The discord within the economic, resource, environment nexus manifests in resource scarcities, sub-optimal energy utilization efficiencies, and exacerbated environmental predicaments. Consequently, the imperative of fostering synchronized progress across the economic, resource, and environmental domains emerges as the sole trajectory to underpin China's journey towards sustainable development and the realization of a contemporary socialist nation over protracted epochs (Xu and Chen, 2021).

China's economy has transited to a new steady growth phase, differing from the preceding period of rapid expansion. Nevertheless, the dilemma of resource scarcity and environmental degradation continues unabated. In urban settings, the complex interplay among the economy, resources, and the environment has a profound effect on shaping the trajectory of complex urban systems. Positive synergies between these factors promote overall progress, while negative tensions and dissonance somewhat hinder the sustainable evolution of cities. Thus, a shift in paradigm towards coordinated development is essential. This requires a comprehensive perspective where the economy, the environment, and resources are thoroughly integrated into a unified framework. Exploring the synergetic relationship among the economy, resources, and the environment within urban systems holds the key to facilitating sustainable urban development. The efforts not only aim to identify development deficiencies but also facilitate the cultivation of positive feedback loops among endogenous factors, concurrently enhance the developmental quality of the economy, resources, and the environment subsystems. This undertaking has significant practical implications for guiding China towards the achievement of high-quality development objectives.

The contributions of this paper are as following: first, a brand-new sustainable development framework has been constructed, which integrates the coupling and coordination theory, the DSPR framework, the sustainable development theory, and the relevant theories of economic geography, and builds an evaluation index system for the coupling and coordination of the economic-resource-environmental system, to carry out the calculation of the coupling and coordination degree of the urban agglomeration in Guangdong-Hong Kong-Macao Greater Bay Area, and at the same time it realizes the effective connection between the time line and the spatial line of the coupling and coordinated development, and comprehensively summarizes the evolution law of the spatiotemporal pattern of the sustainable development of the coupling and coordination of the urban agglomeration in Guangdong-Hong Kong-Macao Greater Bay Area; second, the obstacle factors affecting the sustainable development of the urban agglomeration have been identified. The conclusion of this paper shows that protecting the environmental sub-system and enhancing the guarantee ability of the resource sub-system are the key factors for Guangdong-Hong Kong-Macao Greater Bay Area to achieve sustainable development of the urban system in the future, and excessive emphasis on economic development is not sustainable in the long run.

2 Literature review

With the continuous, sustained, and stable development of the Chinese economy, the consumption of resources has also gradually increased, and the damage to the ecological environment has also been increasingly intensified. Resolving the contradiction between economic development, resources, and the environment has already become the fundamental orientation for the sustainable development of Chinese cities. Up to now, scholars have carried out many explorations on the coupled and coordinated development of the economy-resources-environment, and the focus of the research mainly focuses on three aspects.

Firstly, it is the expansion of the connotation of coupled and coordinated development. As one of the important contents of the sustainable development theory, through conducting the evaluation research on coupled and coordinated development, it can combine sustainable development with empirical research, and achieve the practical implementation of the sustainable development theory. System coupling itself is a concept in physics, which refers to the phenomenon that two or more systems achieve synergy through mutual movement and interaction, and ultimately influence each other (Song et al., 2018; Wang et al., 2022; Tian et al., 2019). A city is a complex system, and there are complex interrelationships and interactions between different aspects of development. The evaluation of the coupled and coordinated level can answer the question of the degree of interaction or influence between different aspects in urban development. Scholars have recognized that there usually exist complex nonlinear coupling relationships between urban subsystems, and sustainable development relies on the coordination of different aspects. Therefore, regarding the coordinated development of subsystems as a scientific approach to achieving urban sustainable development can provide an important practical background and scientific basis for the formulation of government policies and planning (Fan et al., 2019; Wang et al., 2019; Zhao et al., 2016). From the perspective of the expansion of the connotation of coupled and coordinated development, the process of coordination is essentially the process of the system evolving towards a higher-level ordered (Sun et al., 2018), so the coordination relationship study between urban subsystems can support further analysis of urban sustainable development issues.

Secondly, from the perspective of the research content, the earlier researchers mainly used relevant theories and methods of economics to separately discuss energy and environmental related issues (Liu et al., 2014). They relied on the classic hypothesis of the environmental Kuznets curve (EKC) proposed by the famous American environmentalists and economists Crossman and Krueger, established a binary system of economy-environment or economy-energy, and explored the mutual influence between them (Crossman and krueger., 1995; Panayoutou, 1993). For example, Dasgupta and Heal (1979) analyzed the optimal exploitation and utilization path of exhaustible resources. Since the middle and late 1980s, the endogenous growth models represented by Romer (1986), Lucas (1988), Grossman and Helpman (1991) emerged, and internalized factors such as human capital accumulation and technological progress. In this field of research, environmental pollution began to be regarded as a production factor, and environmental quality was included in the utility function, and the endogenous economic growth model was used to analyze and discuss sustainable development. Peng (2007), Xu et al. (2008), etc. introduced the energy element, Huang (2009), Li and Zhao (2008) introduced the environmental pollution element, while Zhang and Zuo (2007) simultaneously introduced both energy and the environment into the model. At present, as the theory of sustainable development matures, to achieve coordinated progress from all parties, it is necessary to start from multiple perspectives such as the economy, resources, and the environment. Therefore, the binary system is no longer sufficient to complete the accurate evaluation of the regional development mode, and the related research on coupling and coordination has also been transformed from the binary system such as the economy and resources or the economy and the environment to the ternary system of the economy, resources, and the environment. For example, Liu et al. (2021) conducted research on the energy-economy-ecosystem in the Yangtze River Economic Belt. Li and Yi (2020) evaluated the sustainability of nine central Chinese cities by analyzing the coordinated development level between the economic, social, and environmental subsystems. From the perspective of the research content, in recent years, the contradiction between the different steps in the development of China's population and economy and the resource and environmental system has become increasingly prominent. Scholars have begun to realize that studying the coordinated development among the economy, resources, and the environment can promote the synergy effect between the systems and have begun to focus on the coordinated development of the regional "economy-resource-environment" composite ecosystem.

And thirdly, from a methodological standpoint, the early exploration of the environment-economy nexus predominantly relied on the environmental Kuznets (EKC) model. Subsequently, a plethora of scholars delved into the interplay between economy and energy across diverse regions, employing methodologies such as the Granger causality test (Raft and Krafe, 1978; Lee, 2006), co-integration test (Lee, 2005), and error correction model (Aslan, 2013). In recent years, the coupled coordination degree model (CCDM) has emerged as a prevalent tool for assessing the level of coordination within urban systems (Yan et al., 2019; Peng et al., 2017; Huang et al., 2018). Economists have augmented this model by integrating efficiency calculations, leveraging techniques like productivity index decomposition, Data Envelopment Analysis (DEA), and derivative model analysis. This expanded approach facilitates discussions on the mechanisms influencing coupling coordination degree or production efficiency (Liu and An, 2012; Zhou and Zhang, 2019). Geographical researchers, meanwhile, utilize Geographic Information Systems (GIS) and other methodologies to analyze spatial and temporal patterns derived from coupling coordination degree calculations (Fu and Ma, 2015; Jiang et al., 2015; Liang et al., 2019). Despite the dominance of the CCDM, a few studies have pursued alternative methodologies, such as crafting a comprehensive coordinated evaluation index (Cui et al., 2019; Wang et al., 2020). In summary, the coupling coordination degree model stands as the linchpin in contemporary research on the interrelationship between China's economy, resources, and environment. Its fusion with other methodologies, particularly for interpreting regional coupling and coordination development patterns through spatial characteristics, is poised to be a focal point for future investigations.

In summary, although in recent years, there have been significant achievements in the research on the connotation interpretation, research content, and research methods of the coupled and coordinated development of the economy-resource-environment, there are still some shortcomings existed, such as the lack of innovation in the integration of the coupling and coordination mechanism and the sustainable development evaluation model within the research framework, which makes it difficult to implement a comprehensive evaluation of the coupled and coordinated development of the economic-resource-environment system, and it is necessary to further explore suitable indicator systems to clarify the stage at which the region is in terms of the coordinated development of the three. At the same time, the systematic factors that affect urban sustainable development have not yet been clearly defined.

Based on previous research in the field of urban systems, this study, guided by complex systems science, considers the comprehensiveness and integrity of complex urban systems. It comprehensively takes into account the economic subsystem, resource subsystem, and environmental subsystem within urban systems, proposing a "economy-resource-environment" integrated system as the research object for studying the coupling and coordination. The economic, resource, and environmental subsystems are independent yet interdependent, interacting with one another. The economic subsystem forms the foundation of the urban system, providing financial support for urban development, social construction, environmental protection, and resource development. The resource subsystem consists of natural resources endowed by nature, serving as the material source for the urban system. The environmental subsystem refers to the external space, conditions, and environment in which humans live, including atmospheric, water, and land environments. Unlike previous studies that often use natural resource indicators such as energy, water, land, and forests to represent the resource system, and pollution emissions and related governance indicators to represent the environmental system, this study integrates the DPSR framework with the coupling and coordination framework. A novel economic-resource-environment system coupling coordination evaluation indicator system is constructed. The DPSR model integrates the economic, resource, and environmental elements, clearly indicating the impact of socioeconomic development and human production activities on the ecological environment. It also reflects the influence of human social behaviors on environmental conditions, thereby showing the reciprocal impact on society and the economy. Therefore, the selection of indicators in this new framework better reflects the trade-offs among the three subsystems—economy, resources, and environment—within urban agglomerations.

Therefore, this paper first constructed a new sustainable framework to calculate the coupling and coordination index of Guangdong-Hong Kong-Macao Greater Bay Area to quantify the coordinated situation of the economic-resource-environment system in Greater Bay Area. Secondly, it analyzed the spatial-temporal evolution characteristics of the urban agglomeration in Greater Bay Area through the coupling and coordination index. Finally, the key factors affecting the coordination of the economic-resource-environment system were identified using the obstacle degree model. From the perspective of the sustainable development of urban agglomerations, the sustainable development of Guangdong-Hong Kong-Macao Greater Bay Area deserves more attention and research.

3 Research area and methodology

3.1 Research area

Guangdong-Hong Kong-Macao Greater Bay Area (GBA) is one of the most vibrant economic regions in China and even the world (Fang and Wang, 2022), including nine cities such as Guangzhou city, Shenzhen city, Zhuhai city, Zhongshan city, Foshan city, Huizhou city, Zhaoqing city, Dongguan city, and Jiangmen city, as well as two special administrative regions, Hong Kong and Macau. Since the industrial scale of Hong Kong and Macau is relatively small, the dominant industries are mainly concentrated in modern service industries such as tourism, finance, export processing, and gambling. The proportion of the secondary industry only accounts for about 3%, and the development mode has a relatively small impact on the environment. Overall, Macau and Hong Kong maintain a relatively high level of coordinated and balanced development in terms of socio-economic factors, resources, and ecological environment (Liu and Nie, 2023; Zhu et al., 2023). In contrast, the other nine cities are mainly dominated by manufacturing. In the past few decades, soil pollution and water pollution caused by the industrialization process cannot be ignored, which poses a serious threat to the sustainable development of Guangdong-Hong Kong-Macao Greater Bay Area. Therefore, the author only conducted a sample survey for these nine cities (in Figure 1).

3.2 Theoretical model construction

In order to examine the coupling and coordination situation of the economy, resources, and environment in Guangdong-Hong Kong-Macao Greater Bay Area, this paper introduces the DSPR framework. This framework comprehensively considers four basic constituent elements of driving force, pressure, states, and responses. By combining this framework with the coordination theory, the interaction mechanism among the economy, resources, and environment is analyzed. Based on this, this paper combined with the specific situation of Guangdong-Hong Kong-Macao Greater Bay Area, a theoretical model covering three dimensions of the economy, resources, and environment (refer to Figure 2) is constructed, and an index system is established. This paper conducts a quantitative analysis of the progress of the coupling and coordination relationship among the economy, resources, and environment in Guangdong-Hong Kong-Macao Greater Bay Area. This paper analyzes from both the temporal and spatial levels, and uses the obstacle degree model to explore the constraints received by the region. Finally, based on the empirical results, it puts forward policy recommendations to promote the sustainable development of Guangdong-Hong Kong-Macao Greater Bay Area.

3.3 Index system construction

The PSR model proposed by Atkins can neatly reveal the interactions between human activities and ecology, environment, and natural resources (Wei et al., 2019), while the concept model of DPSR adds the analysis of driving force to the basic framework of the PSR model. From the perspective of system analysis, taking the simplified internal causal relationship of the system as a more comprehensive way to assess the interactions between human activities and the ecological environment, the DPSR model integrates social, economic, resource, and environmental

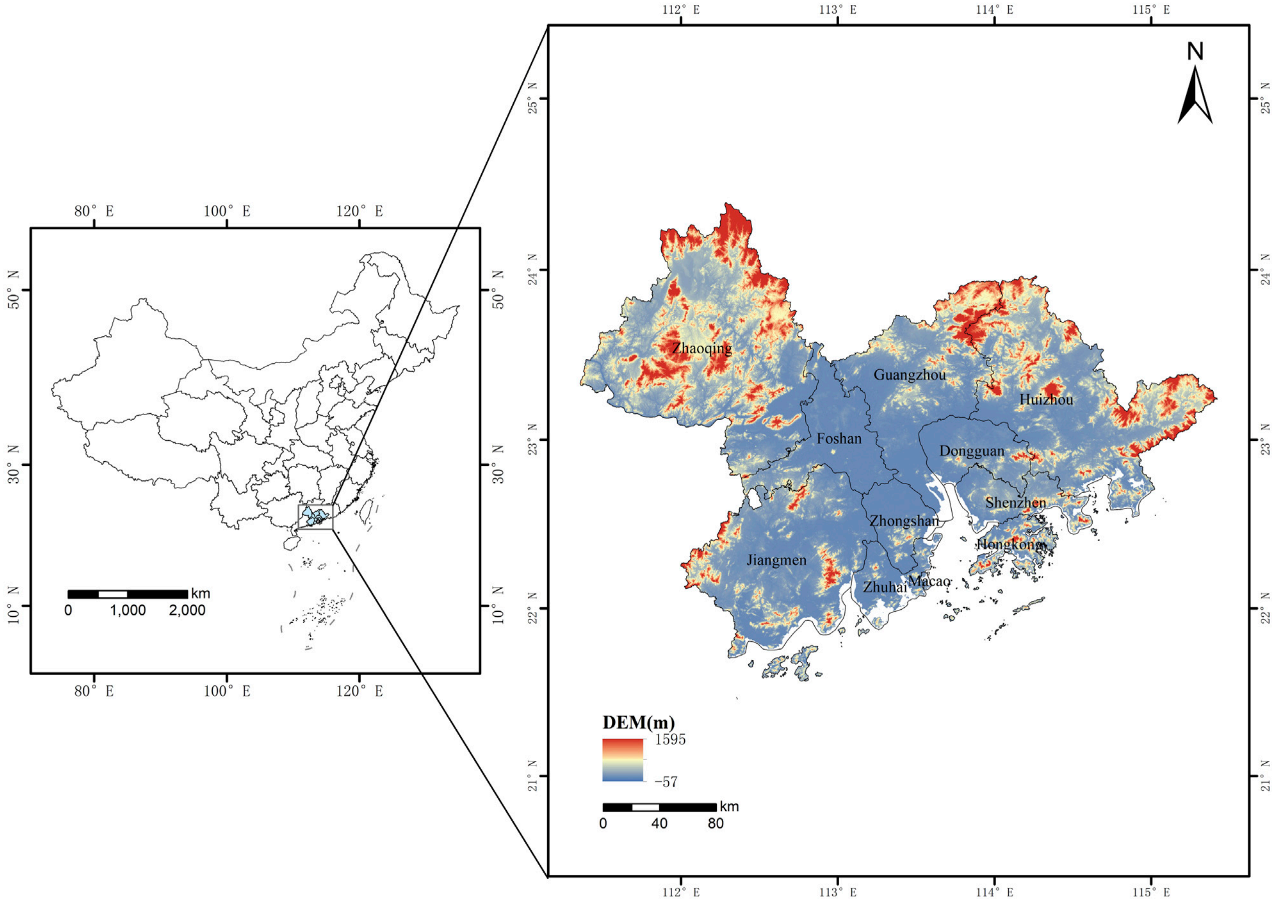

FIGURE 1
Geographical location map of Guangdong-Hong Kong-Macao Greater Bay Area.

elements, clearly indicating the impact of socio-economic development and human productive activities on the ecological environment. At the same time, it also reflects the impact of the changes in environmental conditions caused by the complex human social behaviors, thus reflecting the impact on society and the economy. In this paper, the regional energy system is taken as the research carrier, and the DPSR framework is adopted to comprehensively consider the driving force, pressure, States, response, and other key elements in order to explore the coupling and coordination mechanism between the system and the external economic system and ecological system as shown in Figure 3.

The DSPR is utilized to dissect and refine the interrelationship among the driving force, pressure, states, and responses in environmental issues. Here, the driving force refer to the root causes that give rise to environmental problems, while the pressure refers to the direct impact that the driving force have on the environment. The driving force can encompass factors such as population growth, economic development, and technological innovation; while the pressure is the environmental pressure induced by these driving force, such as resource utilization, energy consumption, and pollution emissions. The environmental States embody the quality and sustainability of the environment, such as air quality, the availability of water resources, and biodiversity. The increase in environmental pressure can lead to the deterioration of the environmental States, like air pollution caused by pollutant emissions and water shortage caused by excessive use of water resources. The environmental States will have an effect on the responses of the government, society, and individuals, and changes in the environmental States may trigger attention and actions towards environmental issues. Response measures will have an impact on the driving force, and the implementation of environmental protection measures and policies may potentially alter the underlying causes that drive environmental problems. For example, policy regulation, technological innovation, and the enhancement of environmental awareness may reduce environmental pressure and thereby have an impact on the factors driving environmental problems. This theoretical framework can not only cover the necessary elements required such as the economy, resources, and the environment, but also describe the complex causal relationships between the systems. The solid arrows within this framework are used to indicate the active effects between different types of factors, while the dashed arrows are used to represent the feedback and constraint effects after a certain type of factor has been influenced. The interaction, feedback, and constraints of the four main factors collectively

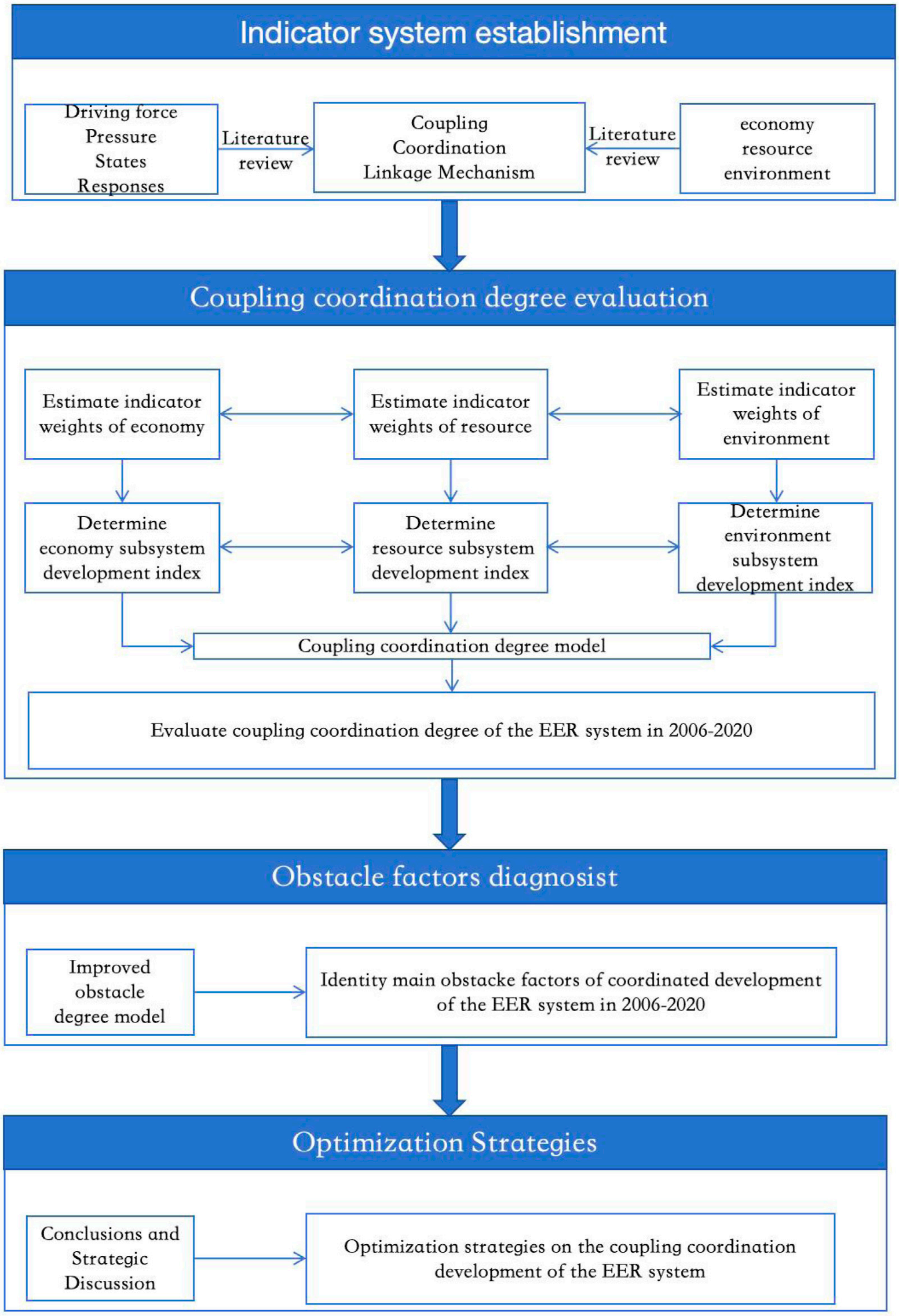

FIGURE 2
Process of regional economy-resources-environment system coupling coordinated development.

constitute the coupling and coordination mechanism of the economic-resource-environmental system.

Therefore, by combining the DPSR framework with coordination theory (refer to Figures 2, 3), this study deepens the understanding of the interaction mechanisms between the economy, resources, and environment, providing a more systematic perspective for analyzing the coupling and coordination relationships between the resource and environmental systems

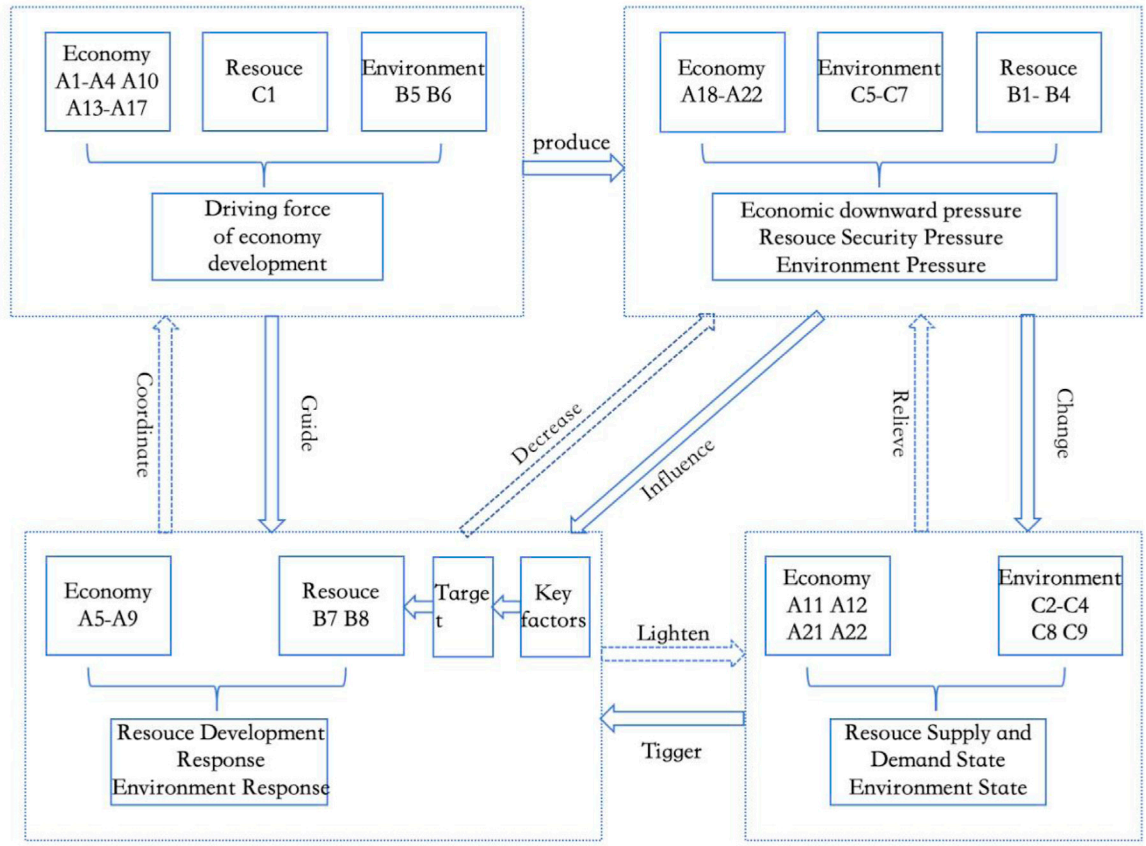

FIGURE 3
Coupling coordination mechanism of regional economy-resources-environment system.

and the external economic system. Based on this theoretical framework, this study has developed a new sustainable development evaluation framework and proposed a comprehensive set of evaluation indicators for the coupling and coordinated development of the economy, resource, and environmental systems. The indicator selection process integrates multidimensional factors related to Driving Force, Pressure, State, and Response, adhering to the principles of completeness, scientific rigor, and practicality to ensure their effectiveness and reliability in real-world applications, drawing on relevant literature from both domestic and international scholars (Xiao et al., 2016; Li, 2012; Hu et al., 2023; He et al., 2017; Fei et al., 2021; Luo et al., 2021) Through careful design, this evaluation system is capable of accurately capturing and elucidating the complex dynamic relationships between the economy, resources, and environment within the Guangdong-Hong Kong-Macao Greater Bay Area (refer to Table 1), providing systematic theoretical support for regional sustainable development.

In formulating the index system, this paper categorizes the influence direction of the indices on the target into three main attributes: positive, negative, and intermediary.

1. Positive attribute: It indices categorized as positive attributes denote that as their values increase, the realization of the goal or the positive effects represented by the goal also increase. In essence, a rise in the index value of a positive attribute signifies an enhancement or improvement of the goal. For instance, consider the urban green land rate index: an increase in its value signifies an enhancement in urban greening, thereby fostering improvements in environmental quality and residents' quality of life.
2. Negative attribute: Conversely, it indices categorized as negative attributes indicate that as their values increase, the realization of the goal or the negative effects represented by the goal also increase. Simply put, an escalation in the index value of a negative attribute signifies a deterioration or exacerbation of the goal. For example, take the traffic congestion index: an increase in its value signifies a worsening of traffic congestion, leading to adverse effects on urban traffic.
3. Intermediary attributes: It indices classified as intermediary attributes do not directly reflect improvements or deterioration of the goal but rather serve as connectors or regulators in achieving the goal. Although these indicators may be pertinent to the goal, their numerical variations do not directly dictate the attainment of the goal. Instead, they may influence other factors related to the goal. For instance, population density can serve as an intermediary index; its fluctuations may impact various aspects such as *per capita* green park area, subsequently influencing the overall level of social sustainable development.

TABLE 1 Evaluation index system of economy-resource-environment coupling coordinated development.

Target layer	System layer	Subsystem layer	Index level	Properties
Evaluation index system of economy-resource-environment coupling coordinated development	Economy	Economic aggregate	A1 R&DActive personnel (people)	Positive
			A2 R&DExpenditure as a percentage of GDP (%)	Positive
			A3 Foreign Direct Investment (US $10,000)	Positive
			A4 Total imports and exports (USD 100 million)	Positive
			A5 Investment in fixed assets (RMB 100 million)	Mediating
			A6 Research and experimental development expenditure (100 million yuan)	Positive
			A7 Investment in science and technology fixed assets (RMB 100 million)	Positive
			A8 Investment in transportation fixed assets (RMB 100 million)	Positive
			A9 Investment in education fixed assets (RMB 100 million)	Positive
			A10 Population density (people/km^2)	Mediating
		Economic proportion	A11 Secondary industry as a share of GDP (%)	Mediating
			A12 Share of tertiary industry in GDP (%)	Positive
		Economic benefits	A13 Per capita budget revenue of local public finance (Yuan)	Positive
			A14 Growth rate of government revenue (%)	Positive
			A15 Total industrial production value (100 million yuan)	Positive
			A16 Natural population growth rate (‰)	Negative
			A17 Engel coefficient (%)	Negative
			A18 Urbanization rate (%)	Positive
			A19 Urban registered unemployment rate (%)	Negative
			A20 CPI index	Positive
			A21 Per capita disposable income as a percentage of total income (%)	Positive
			A22 Number of patent applications granted (pieces)	Positive
	Resource	Resource consumption	B1 Total industrial electricity consumption (10,000 kW h)	Mediating
			B2 Daily *per capita* water consumption (L)	Negative
			B3 Total domestic electricity consumption (10,000 kW h)	Mediating
			B4Energy consumption per unit of GDP (tons of standard coal/10,000 yuan)	Negative
		Resource States	B5 Common cultivated land area (10,000 mu)	Positive
			B6Water resources *per capita* (m^3/person)	Mediating
			B7 Number of public transport vehicles per 10,000 people (vehicles)	Positive
			B8 Per capita urban road area (square meters)	Positive
	Environment	Environmental Quality	C1 Ambient air quality excellent rate (%)	Positive

(Continued on following page)

TABLE 1 (*Continued*) Evaluation index system of economy-resource-environment coupling coordinated development.

Target layer	System layer	Subsystem layer	Index level	Properties
			C2 Per capita green park area (square meters/ person)	Positive
			C3 Green area ratio (%)	Positive
			C4 Annual mean traffic noise (decibeLs)	Negative
		Environmental governance	C5 Total industrial smoke (dust) emissions (10,000 tons)	Negative
			C6 Industrial wastewater discharge (tons)	Negative
			C7 Industrial sulfur dioxide emissions (10,000 tons)	Negative
			C8 Harmless treatment rate of domestic waste (%)	Positive
			C9 Urban sewage treatment rate (%)	Positive

3.4 Data sources

All the data of this paper collected from the statistical yearbooks and statistical bulletins of each city in Guangdong-Hong Kong-Macao Greater Bay Area from 2006 to 2020. Including "Statistical Yearbook of China Urban Construction", "Guangdong Statistical Yearbook", etc. As well as the local statistical yearbooks of nine cities such as Guangzhou city, Dongguan city, Foshan city, Huizhou city, Jiangmen city, Shenzhen city, Zhaoqing city, Zhongshan city, and Zhuhai city. The missing data are supplemented by the interpolation method and the data are prepossessed to obtain the data that meets the statistical requirements.

At the beginning of 2020, novel corona-virus pneumonia (COVID-19) broke out in China, which had a significant impact on various aspects such as economic development and social life. This unexpected public health event led to abnormal statistics of China's economic and social indicators, which did not meet the normative requirements of statistical analysis. Using such abnormal data for analysis would severely distort the research results. To avoid the possible adverse effects brought about by using abnormal data, the end point of the research period in this paper is set as 2019. Future studies will focus on conducting targeted research using data after 2020. In summary, in order to ensure the consistency of the statistical data in this paper, and avoid the adverse effects of using a large amount of abnormal data on the research results, so the base period is set from 2005 to 2019.

3.5 Entropy weight method

The entropy weight method is an objective method for seeking weights, which is used to judge the degree of discretization of the indicators. Entropy is a measure of uncertainty, and it is generally believed that the greater the entropy value of the indicator, the greater the impact on the comprehensive evaluation; the smaller of the entropy value, the smaller of the difference of the indicator, and the smaller of the weight of the indicator. The use of the entropy value method can avoid subjective errors, effectively it reflects the role of the indicator in the evaluation object, and identifies the key factors affecting the sustainable development of the urban agglomeration (Joshi and Kumar, 2019), so it can provide a scientific basis for the coordinated improvement of the sustainable development level in Guangdong-Hong Kong-Macao Greater Bay Area. The specific steps are as follows:

Supposed $X = (x_{ij})_{m\times n}$, $X' = (x'_{ij})_{m\times n}$, X_{ij} is the index value before standardization, $x'_{ij}$is the index value after standardization, m is the evaluation year, and n is the number of evaluation indicators.

(1) The standardization of positive indicators

The higher of the positive index value, the better of the ecological environment quality. The standardized formula for the positive index is as follows (Equation 1):

$$x'_{ij}= \frac{x_{ij} - \min\limits_{1\leq i\leq m}\left(x_{ij}\right)}{\max\limits_{1\leq i\leq m}\left(x_{ij}\right) - \min\limits_{1\leq i\leq m}\left(x_{ij}\right)} \tag{1}$$

(2) Standardization of negative indicators

The greater of the negative index value, the worse of the ecological environment quality. The negative index standardization formula is as follows (Equation 2):

$$x'_{ij}= \frac{\min\limits_{1\leq i\leq m}\left(x_{ij}\right) - x_{ij}}{\max\limits_{1\leq i\leq m}\left(x_{ij}\right) - \min\limits_{1\leq i\leq m}\left(x_{ij}\right)} \tag{2}$$

(3) Standardization of medium index

The medium indicator refers to the indicator closer to a specified value, the better of the indicator. The standardized formula for the median index is as follows (Equation 3):

$$x'_{ij}= \begin{cases} 1 - \dfrac{x_{j0} - x_{ij}}{M}, x_{ij} < x_{j0} \\ 1 - \dfrac{x_{ij} - x_{j0}}{M}, x_{ij} > x_{j0} \\ 1, x_{ij} = x_{j0} \end{cases} \tag{3}$$

$M = max[x_{j0} - \max\limits_{1\leq i\leq m} x_{ij}, \max\limits_{1\leq i\leq m} x_{ij} - x_{j0}]$, x_{j0} is the ideal value of the j indicator.

(4) Determination of index weight

The methods for calculating weights include the Delphi method, Analytic Hierarchy Process (AHP), coefficient of variation method, and entropy weight method, among others. However, the Delphi method and AHP are subjective and may affect the objectivity of the evaluation results. Therefore, this paper selected the entropy weight method to calculate the weights of the indicators. The entropy weight method is a commonly used objective weighting method. Generally, the larger the information entropy value, the more balanced the system's structure, and the smaller the difference, the smaller the weight of the indicator, and *vice versa*. The steps for calculating weights using the entropy weight method are as follows.

Step 1: Numerical standardization, view Formula 1–3 for details;
Step 2: Determination of specific gravity is as Formula 4:

$$Y_{ij} = \frac{{x_{ij}}'}{\sum_{i=1}^{m} x_{ij}} \tag{4}$$

Step 3: Entropy calculation is as Formula 5:

$$e_j = -\frac{1}{ln^m}\sum_{i=1}^{m} Y_{ij}\, ln^{Y_{ij}} \tag{5}$$

Step 4: Calculation of coefficient of variation is as Formula 6:

$$\gamma_j = 1 - e_j \tag{6}$$

Step 5: The weight vector is as Formula 7:

$$v = \{v_1, v_2, \cdots, v_n\} \tag{7}$$

Step 6: Weight calculation is as Formula 8:

$$v_j = \frac{\gamma_j}{\sum_{j=1}^{n} \gamma_j} \tag{8}$$

3.6 Research model

3.6.1 Coupling coordination model

The coupling degree is a method used to assess the degree of interconnection between systems, which can reflect the degree of mutual influence between sustainable development and coordinated development. In this paper, the author has adjusted the coupling degree and established a coupling and coordination adaptation degree model to better assess the coupling and coordination adaptation degree between sustainability and coordinated development. The steps are as follows:

Step 1: Calculating the comprehensive sustainable development value F using the entropy method.

Utilizing the results of data processing from the entropy method, the comprehensive sustainable development values of nine cities are obtained, denoted as F.

After normalizing the tertiary indicators of the 9 cities, multiplying each indicator by its relative weight and then adding them up by weighting, the normalized data results of the secondary indicators can be obtained. Multiplying the normalized value of the secondary indicators by the corresponding weight of the secondary indicators and then adding them up by weighting can obtain the normalized result of the primary indicators. The normalized result of the primary indicators is the comprehensive sustainable development value of the 9 cities, which can be used as a comprehensive development evaluation index to measure the sustainable development situation of each city. The specific steps are as follows:

Let W_{ij} represent the absolute weights of 39 third-level indicators (directly computed through the entropy method), and W_{ij} represent the relative weights of the three second-level indicators. Here, i denotes the sequence of the *ith* second-level indicator, and j represents the sequence of the *jth* third-level indicator within the *ith* second-level indicator.

A represents the economic index, B represents the resource index, and C represents the environmental index. The normalization calculation method of the secondary index is as Formula 9–11:

$$A = \sum A_j \times W'_{ij} \tag{9}$$

$$B = \sum B_j \times W'_{ij} \tag{10}$$

$$C = \sum C_j \times W'_{ij} \tag{11}$$

Simultaneously, please note that W_i represents the corresponding weights for the second-level indicators, where W_1 stands for the weight of economic indicators, W_2 denotes the weight of resource indicators, W_3 signifies the weight of environment indicators, and F (Equation 12) represents the normalization result of the first-level indicators, which F is essentially the sustainable development value of each city.

$$F = A \times W_1 + B \times W_2 + C \times W_3 \tag{12}$$

Step 2: The measure of coupling coordination fitness can be determined by Equation 13.

$$C = \frac{n\sqrt{F_1 \times F_2 \times \cdots \times F_n}}{\left(\frac{F_1+F_2+\cdots+F_n}{n}\right)} \tag{13}$$

Since Formula 13 represents the degree of sustainable development balance of the economic development indicators of the total number of nine cities, the higher the degree, the higher the degree of coupling. That is, the C value tends to 0, indicating a large difference in development degree and a small coupling degree; The more C tends to 1, the smaller the difference in development degree and the higher the coupling degree.

Step 3: The comprehensive index T (Equation 14) of sustainable development level representing the total amount of the region:

$$T = U_1 \times F_1 + U_2 \times F_2 + \cdots + U_n \times F_n \tag{14}$$

Step 4: Calculate the coupling coordination fit D (Equation 15):

$$D = k\sqrt{C \times T} \tag{15}$$

Where C represents the degree of sustainable development imbalance, T is the comprehensive index of regional sustainable development level, and D is the coupling coordination fit. This model reflects the overall synergistic effect between cities. Among them, k is the regulating variable, which is related to the policies adopted by each region, the degree of economic development, and other factors.

3.6.2 Obstacle degree model

By introducing the degree of obstruction (Lei et al., 2016) for the diagnosis of obstruction factors, it can effectively quantify the impact of the economy - resources - environment on the coordinated development of Guangdong-Hong Kong-Macao Greater Bay Area.

$$I_i = \frac{w_i \times (1 - y_{ij})}{\sum_{i=1}^{m} w_i \times (1 - y_{ij})} \tag{16}$$

In the Equation 16, $(1 - y_{ij})$ represents the deviation degree between the standardized index value and its optimal value.

3.7 Declaration of academic ethics

All the relevant contents involved in this paper have obtained academic approval from Guangdong University of Finance and Economics, and it is carried out and implemented based on the local legislative provisions and institutional requirements.

4 Results

4.1 Comprehensive evaluation of economy, resources and environment

The findings of this paper indicate that the economic development of the nine cities generally presents an upward trend (refer to Figure 4), and the ranking of the economic development levels of each city in different stages changes relatively steadily. In 2020, Shenzhen city, Zhuhai city, and Foshan city performed most exceptionally in the economic system ranking. In the development process of the past 15 years, the development efficiency of these three cities has always been in a leading position. As one of the first batch of open economic special zones in China, Shenzhen city, in the early days, relied on its location advantage close to Hong Kong, and attracted a large number of investments and business orders from Hong Kong, which strongly promoted the rapid progress of Shenzhen's foreign trade, exports, and production and processing industries. Subsequently, Shenzhen city has gradually transited and developed towards the fields of science and technology and finance, and has achieved remarkable achievements in these fields by virtue of its open and free environmental atmosphere, becoming an economically prosperous city. Zhuhai city has the unique location conditions and has unique development elements. Since the construction of Hengqin Free Trade Zone started, Zhuhai city relies on the policy support of the national-level development zone and quickly enters the fast track of economic development. Foshan city, as a key node city in Guangdong-Hong Kong-Macao Greater Bay Area, the Guangfo-Zhao Economic Circle, and the Guangzhou Metropolitan Area, is closely related to the development of surrounding cities. When Guangzhou city develops rapidly, Foshan city has become one of the biggest beneficiaries of its industrial spillover effect, and the close regional connection has strongly promoted the sustained growth of Foshan's economy.

FIGURE 4
Changes in the development level of the economic system.

The development of the resource systems in the nine cities of GBA demonstrates an N-shaped trend, experiencing an initial rise followed by a decline. Some cities exhibit a rising development trend (refer to Figure 5). By 2010, all nine cities had reached peak of the upward trend. This was primarily due to vigorous efforts in the six major and the construction of eight major carriers in all nine cities, leading to the initial formation of a modern industrial system. Accelerated development high-end service industries, such as modern logistics, finance, exhibitions, technology services, and business services, has propelled the productivity of the service sector, while simultaneously emphasizing energy conservation, emission reduction, ecological construction, environmental protection, and land use efficiency In 2013, the urban agglomeration began to feel the impact of the global economic crisis, leading to a gradual decline in external demand. This was mainly due to the export industrial structure, which faced a downturn along with the weakness in export markets. To this challenge, the cities entered a difficult period of industrial transformation. Meanwhile, 2013 also marked the beginning of Guangdong Province comprehensive implementation of the important directives of the 18th National Congress of the Communist Party of China and the important instructions of General Secretary Jinping XI during his inspection of Guangdong. Throughout this process, infrastructure and manufacturing industries experienced rapid development but also led to a depletion of resources. By 2017, slight improvements in resource utilization were observed in Foshan city, Zhaoqing

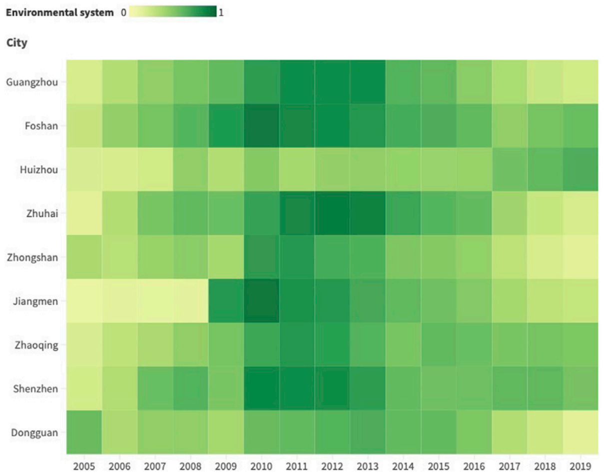

FIGURE 5
Changes of resource system development level.

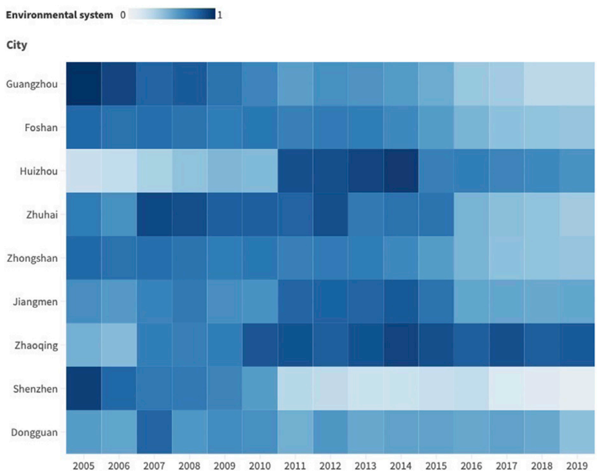

FIGURE 6
Change of environmental system development level.

city, Shenzhen city, and Huizhou city, leading to a more rational overall resource utilization. After a period of hardship, the urban agglomeration successfully achieved industrial transformation, laying a solid foundation for sustainable development in the future.

The research findings indicate significant disparities in the environmental quality development levels among 9 cities (refer to Figure 6). Among these, the cities of Guangzhou, Foshan, Zhongshan, and Shenzhen are experiencing a trend of declining environmental quality, predominantly attributed to their reliance on the manufacturing industry as the leading sector. The manufacturing process in these cities often emits a large amount of toxic substances, exacerbating environmental pollution issues such as air, water, and noise pollution. On the other hand, the environmental quality development in Huizhou city, Zhuhai city, and Jiangmen city has witnessed a trend of initial improvement followed by a subsequent decline. As for Zhaoqing city, it shows a clear upward trend in environmental quality, largely due to its geographical advantage of having the largest land area and richest ecological resources in Guangdong-Hong Kong-Macao Greater Bay Area. With over 1.06 million hectares of woodland, a forest coverage rate exceeding 70%, and river length accounting for about 20% of the Pearl River Delta region, these superior environmental resources have provided crucial support for its environmental quality enhancement. In general, the environmental quality and resource status in Greater Bay Area exhibit a certain downward trend, although some cities show signs of improvement in environmental quality, there are still cities where environmental quality continues to decline.

Based on the evolutionary trends of the comprehensive development levels of subsystems presented in Figure 7, the economic subsystem exhibits a remarkably upward trend, indicating a gradual convergence of the economic structure within Guangdong-Hong Kong-Macao Greater Bay Area. The region's economic activities continue to rise, primarily attributed to factors such as population growth, technological innovation, and market expansion. In contrast to the economic subsystem, the environmental subsystem shows an initial period of stability followed by a declining trend. This indicates that in the initial phase, with economic growth and increased resource utilization, there were no significant signs of environmental deterioration.

However, despite the environment being relatively stable initially, environmental quality eventually declined in 2014 due to excessive resource consumption. The resource subsystem demonstrates an evolutionary trend of initial rise, subsequent stability, and then decline. It shows that the resource availability or quality in Greater Bay Area initially improved with economic growth but reached a relatively stable level after 2010. While the availability of resources remained relatively stable, factors such as over exploitation, pollution, or others led to a decrease in the quantity or quality of resources.

In this scenario, the continual rise in the economic level curve may lead to increased pressure on resources and the environment. According to the strong sustainability theory, to achieve sustainable development, methods must be explored to decouple the linkage between economic growth and resource consumption in order to mitigate negative environmental impacts.

4.2 Time distribution characteristics of coupling coordination degree

The overall coordinated development of Guangdong-Hong Kong-Macao Greater Bay Area demonstrates a stable upward trend (refer to Figure 8). However, the development of Shenzhen exhibits recurrent fluctuations of both ascent and descent. The primary reason for this phenomenon lies in Shenzhen's imminent transition into the advanced stage of a developed economy, yet it lags to a certain extent in terms of environmental and resource utilization. Furthermore, although the proportion of the secondary industry has bottomed out and rebounded, the transformation and upgrading of the manufacturing industry face dual constraints from internal and external pressure. By 2005, various cities in Greater Bay Area had essentially achieved a

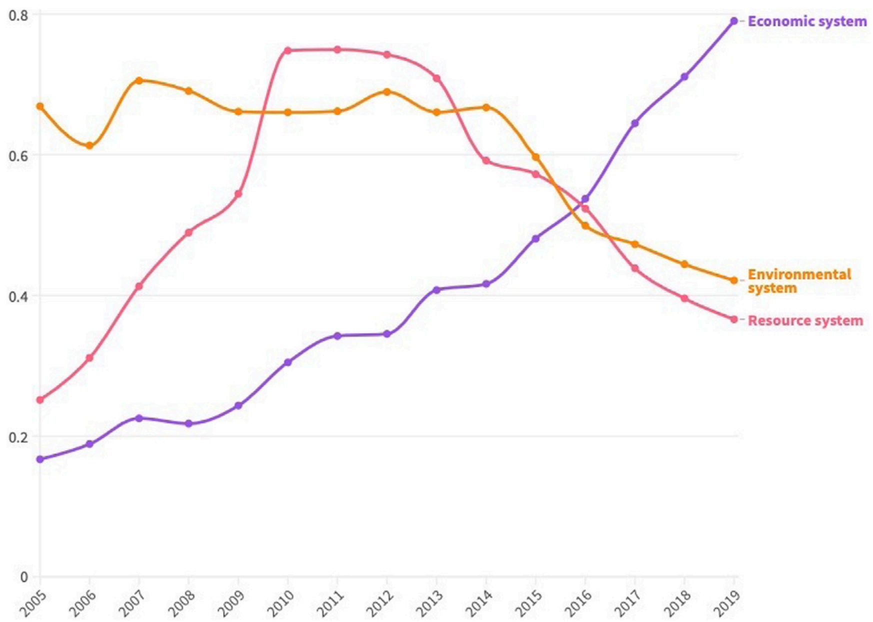

FIGURE 7
Comparison of the comprehensive development level of the economic system, resource system and environmental system in Guangdong-Hong Kong-Macao Greater Bay Area.

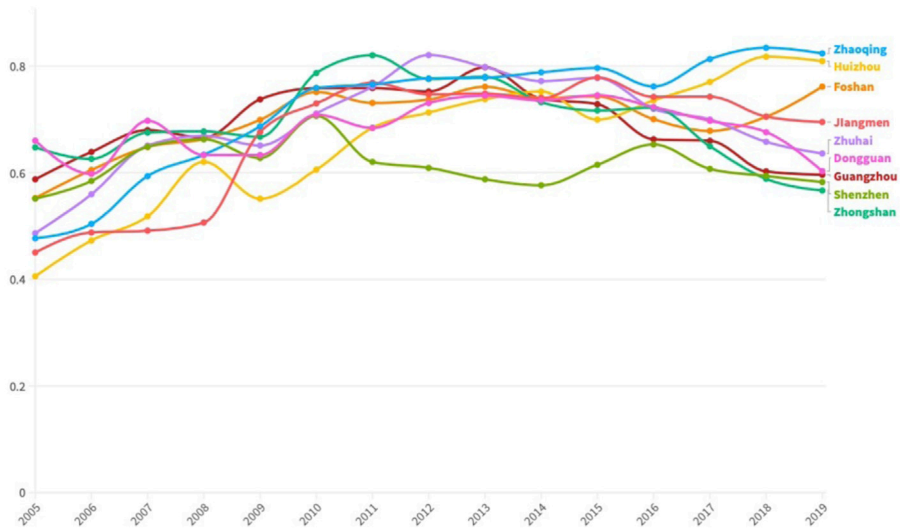

FIGURE 8
Coupling coordination degree of economy-resource-environment in Guangdong-Hong Kong-Macao Greater Bay Area.

state of coordinated development, with Dongguan city and Zhongshan city particularly standing out in their coordination. By 2011, all cities had reached a high level of coordination. In the future development process, the construction of an ecological civilization has become the core task of urban development. Guided by government policies, the interactions among the economic, environmental, and resource elements of Greater Bay Area continue to strengthen, highlighting the increasingly significant trend towards coordinated development.

4.3 Spatial distribution characteristics of coupling coordination degree

Figures 9–11 illustrate the dynamic changes in the spatial distribution of the coupling coordination degree of the economy, resources, and environment of various cities in Guangdong-Hong Kong-Macao Greater Bay Area from 2005 to 2019. The research findings indicate that the spatial coupling coordination degrees of the economy, resources, and environment in each city have all been

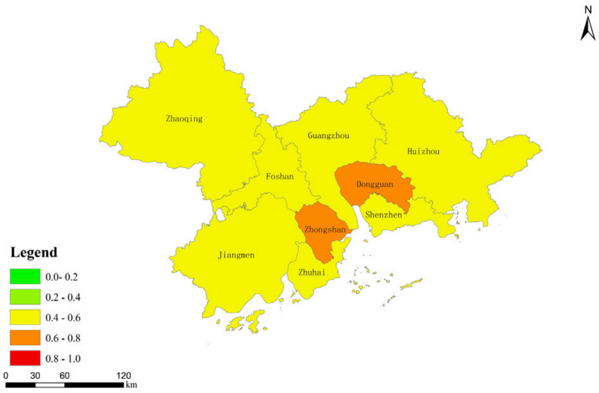

FIGURE 9
Spatial distribution characteristics of CCI values in Guangdong-Hong Kong-Macao Greater Bay Area in 2005.

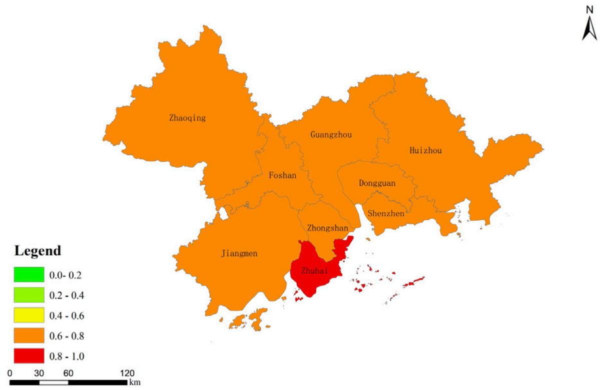

FIGURE 10
Spatial distribution characteristics of CCI values in Guangdong-Hong Kong-Macao Greater Bay Area in 2012.

improved to varying degrees, with the differences in spatial coupling coordination degrees between regions gradually narrowing. Of particular note is that Huizhou city and Zhaoqing city have exceeded a coupling coordination degree of 0.8, demonstrating a promising development trend, with these two cities exhibiting particularly remarkable growth rates. According to the regional planning of the Guangdong Provincial Government, the Guangfo-Zhaoqing, Shenzhen-Dongguan-Huizhou, and Zhuhai-Zhongshan-Jiangmen urban agglomerations have been clearly designated as key development areas. However, within these three regions, there still exist certain disparities in their coupling degrees. Therefore, it is imperative for the government to strengthen the construction of urban clusters and fully leverage the radiating driving force of core cities on surrounding areas. Furthermore, the government should expedite the reform process to achieve the grand goal of building a world-class bay area. Concurrently, it is essential to actively seize the opportunities presented by adjustments in the global political and economic landscape, striving to occupy a position in the mid-to-high end of the value chain, thereby realizing sustainable development of the bay area economy and enhancing its international competitiveness.

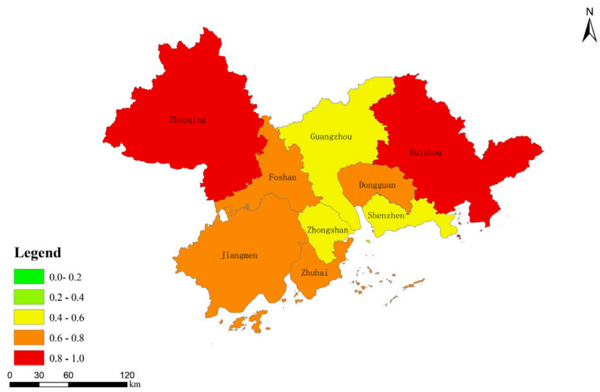

FIGURE 11
Spatial distribution characteristics of CCI values in Guangdong-Hong Kong-Macao Greater Bay Area in 2019.

4.4 Analysis of obstacle factors

In 2005, obstacles that significantly impeded the coupled and coordinated development of the 9 cities in Guangdong-Hong Kong-Macao Greater Bay Area primarily stemmed from economic factors (see Table 2). Among these, suboptimal levels of economic development and inefficiencies in economic productivity were the main contributing factors. The industries in these 9 cities predominantly revolve around industrial manufacturing and technological innovation, with investments in areas such as foreign direct investment, fixed asset investments in education, and fixed asset investments in technology playing a profoundly impactful role in the coupled and coordinated development of Greater Bay Area. With the rapid urbanization process in Greater Bay Area, the issue of uncoordinated resource and environmental management has gradually become more pronounced. The increase in urban population density has led to a continual reduction in available arable land, thereby affecting the coordinated development of the three major systems. Furthermore, the accelerated urbanization process has resulted in a growing demand for industrial and domestic electricity, leading to increased greenhouse gas emissions which exacerbate global climate change. The excessive use of electricity transforms into thermal energy, causing indoor temperatures to rise, subsequently increasing the usage of cooling devices such as air conditioners and fans, further escalating energy consumption and greenhouse gas emissions. Consequently, electricity wastage can trigger substantial energy wastage as well. Additionally, the emissions of industrial sulfur dioxide and industrial dust have profound effects on the coupled and coordinated development of the 9 cities in Guangdong-Hong Kong-Macao Greater Bay Area. Sulfur dioxide, as one of the primary pollutants in the atmosphere, not only contributes to the formation of acid rain but also damages the ozone layer, further exacerbating the greenhouse effect. Hence, reducing the emissions of industrial

TABLE 2 Indicators of the top three barriers in Guangdong-Hong Kong-Macao Greater Bay Area.

Year	Ranking	Guangzhou	Foshan	Huizhou	Shenzhen	Zhuhai
2005	1	A22	A7	A2	A6	A7
	2	A3	A9	B5	A9	A22
	3	A7	A3	A3	A7	A6
2012	1	A3	A7	A2	A6	A7
	2	A14	A9	B5	A9	A22
	3	A22	A3	A3	A4	A6
2019	1	A14	C7	A2	C7	B1
	2	A7	A8	B1	C5	B3
	3	B3	A14	B3	A3	C7
Year	**Ranking**	**Dongguan**	**Jiangmen**	**Zhaoqing**	**Zhongshan**	
2005	1	A6	A7	A22	C5	
	2	A22	A3	A4	A7	
	3	A1	B1	A5	A22	
2012	1	A6	A7	A22	A7	
	2	A22	A3	A4	A22	
	3	A14	A8	A5	A8	
2019	1	A14	A7	A5	C5	
	2	B3	B1	A3	A14	
	3	B1	B3	A14	B3	

pollutants is a crucial task in driving the coupled and coordinated development of the 9 cities in Guangdong-Hong Kong-Macao Greater Bay Area.

In 2005, the early and middle period of the 11th Five-Year Plan, China's economic and social development level was relatively backward. Heavy chemical industry with high pollution and high energy consumption was the main driving force for economic development, and the overall development mode of Guangdong-Hong Kong-Macao Greater Bay Area was extensive. At this time, the main factor affecting the coupling and coordinated development of the economy-resource-environment system was economic factors. After 15 years of development, the growth rate of economic development is obviously faster than the improvement process of resources, energy, and ecological environment. Due to the limited resource and energy endowment and ecological environment carrying capacity, the existing resources, energy, and ecological environment conditions will not be able to meet the needs of social and economic development. This is consistent with the fact that the principal contradiction in our society has changed, as stated in the report to the 19th National Congress. The development of the resource system and environmental system is stagnating or even regressing. The proportion of resource systems and environmental system affecting the coupling and coordinated development of the economy-resource-environment system is increasing year by year (refer to Figures 12, 13). The obstacle degree of the economic system decreases from 0.79 to 0.45, and the obstacle degree of the resource system increases from 0.17 to 0.35. The obstacle degree of the environmental system increased from 0.04 to 0.20. If the transformation of development mode and industrial upgrading cannot be completed within a limited time, the trend of increasing the level of coordinated development of the economy-resource-environment system will be fundamentally broken, and resource shortage and environmental deterioration will become a huge obstacle in the process of China's socialist modernization.

5 Discussion

Lin et al. (2022) conducted research indicating a positive trend in sustainable development within Guangdong-Hong Kong-Macao Greater Bay Area, though with notable variations among different cities. They also noted an overall improvement in the coupling coordination degree of the region. Similarly, Song and Wu (2022) found relative stability in the regional system and economic subsystem of the urban agglomeration, alongside widening regional disparities in coordinated development levels. These studies collectively suggest that Greater Bay Area's urban agglomeration is experiencing improved coordination and stable development.

However, existing literatures have not identified a slowdown in the coupling coordination degree of Greater Bay Area, as illustrated in Figure 14. Furthermore, influencing factors have shifted from primarily economic to environmental and resource-related issues. Factors such as over development and pollution have led to a decline

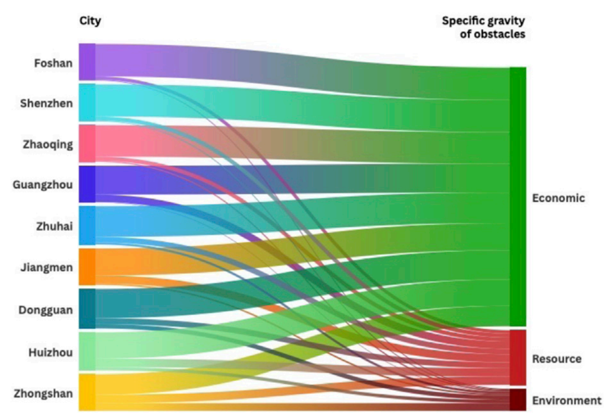

FIGURE 12
Proportion of barrier factor indicators in 2005.

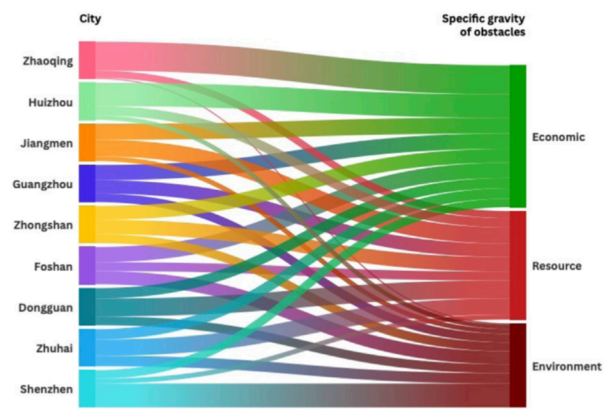

FIGURE 13
Proportion of obstacle factor indicators in 2019.

in both the quantity and quality of resources over time, escalating pressure on the environment. Sustainable development principles emphasize the necessity of decoupling economic growth from resource consumption to mitigate these adverse impacts. This paper proposes an innovative approach by integrating the coupling coordination mechanism with an urban sustainable development evaluation model. Constructing a novel sustainable development framework enables a more precise delineation of the current status and challenges pertaining to sustainable development within Greater Bay Area.

6 Conclusions, suggestions and limitations

6.1 Conclusions

In this paper, Guangdong-Hong Kong-Macao Greater Bay Area is selected as the research object, and a new sustainable development framework is built through the innovative integration of DSPR framework and coupling coordination mechanism. Based on this framework, the paper studies the spatial-temporal coupling characteristics of economy-resource-environment in the process of sustainable development of Guangdong-Hong Kong-Macao Greater Bay Area, and analyzes the obstacles to the coordinated development of the coupling. This paper clearly presents the coupling relationship between economy-resource-environment in Guangdong-Hong Kong-Macao Greater Bay Area, and ultimately aims to provide some references for other urban agglomerations to achieve urban sustainable development. The conclusions are as follows:

(1) There is a significant gap in the development levels among the economy, resource, and environmental systems. The economic system has a higher overall development level compared to the resource and environmental systems. The performance of the economic system continues to grow at a steady pace, while the resource and environmental systems lack stable growth and are currently showing a downward trend. In this context, the continued development of the economic system exacerbates the degradation of resources and the environment.
(2) The coupling and coordinated development within the Guangdong-Hong Kong-Macao Greater Bay Area (GBA) exhibits significant spatial and temporal variations. Overall, regional collaborative development shows a stable upward trend, and the spatial coupling and coordination gaps between cities are gradually narrowing. Between 2005 and 2012, cities with similar coupling coordination levels demonstrated a clustering effect, with cities like Dongguan and Zhaoqing, exhibiting higher coordination levels, showing spatial spillover effects. However, between 2012 and 2019, the coupling and coordination development of Guangzhou and Shenzhen declined. In general, the coupling and coordination development in the GBA is relatively positive, but it has not yet achieved long-term, synchronized development between economic growth, resource utilization, and ecological environment.
(3) The primary obstacle to the coupling and coordinated development in the GBA is economic factors. Although investments in research and development (R&D) and environmental protection can promote the development of the resource and environmental subsystems, they are still insufficient to offset the resource and environmental costs associated with economic growth. The influence of resource and environmental factors on coupling and coordinated development is gradually increasing. To achieve sustainable and coordinated development, it is necessary to prioritize economic development below the levels of resource energy and ecological environment, sacrificing a moderate pace of economic growth in exchange for better resource efficiency and environmental quality.

6.2 Suggestions

Based on the previous study, this paper proposes the following suggestions:

(1) Promoting the transformation and upgrading of the industrial structure of urban agglomeration The fundamental reason for the

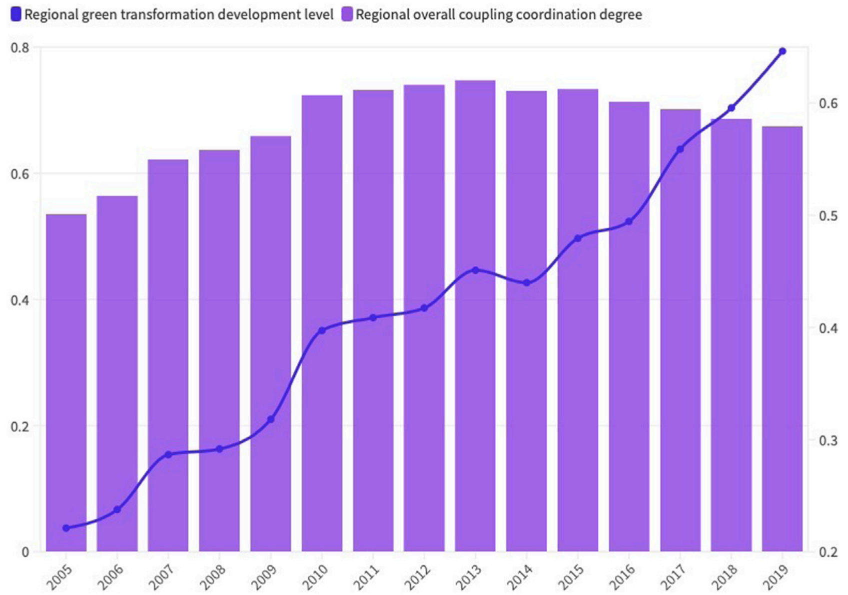

FIGURE 14
Comparison of regional sustainable development level and regional coupling coordination degree in Guangdong-Hong Kong-Macao Greater Bay Area.

low degree of coordinated development in the economic-resource-environment nexus lies in the traditional extensive development model. Achieving coordination and sustainable development in this nexus requires a correct understanding of the interrelationships among economic growth, the development and utilization of resources and energy, and environmental protection. Policies and measures related to economic development, resource conservation, and environmental protection should be coordinated. Relying solely on population and economic capital inputs cannot achieve coordination among these three aspects or sustainable development, nor is it conducive to the effective implementation of energy conservation and emission reduction measures. Only by increasing the proportion of technological progress contributing to economic growth and accelerating the pace of industrial transformation and upgrading can the production and lifestyle of the people be more inclined towards sustainable, low-carbon, and ecological trends, ultimately promoting the sustainable development of the socioeconomic.

(2) Optimizing the energy consumption structure and increase the proportion of clean energy The current energy consumption pattern in China, primarily dominated by coal consumption and largely concentrated in the secondary industry, has yet to be fundamentally reversed, with the adjustment of energy structure closely linked to the optimization of industrial structure. In the process of industrialization, it is imperative to rationally utilize conventional energy sources, actively explore renewable and clean energy sources as alternatives, continuously promote coal substitution and electrification, improve energy-saving technologies, constantly enhance energy utilization efficiency, emphasize the development and utilization of clean energy, and persistently strengthen and improve energy conservation and emissions reduction efforts. Leveraging the advantageous and pillar industries of Guangdong Province, efforts should be made to foster the growth of strategic emerging industries, expand the development scope of modern service industries, increase their proportion in the economy, actively develop ecological and sustainable industries, achieve integration between industrial development and resources, energy, and the environment, and promote the optimization of energy consumption structure alongside the adjustment of industrial structure.

(3) Fully demonstrating the effectiveness of the government's macro-control In the process of coupling coordination and sustainable development of the economic-resource-environment system, the government should fully leverage its macroeconomic regulation role based on relevant research and feedback information from the system itself, to formulate scientifically rational policies and guidelines. To accelerate the pace of transformation and upgrading, the government should strategically plan industrial development, energy development, and environmental protection at the top level. Targeting underdeveloped areas, it should implement a series of fiscal policies and macroeconomic regulation through monetary policies to narrow the development gap between regions as much as possible, and achieve China's common prosperity and socialist modernization construction at an early date.

6.3 Limitations

Although this paper has comprehensively analyzed the economic, resource, and environmental connections in Guangdong-Hong Kong-Macao Greater Bay Area, potential distortions may arise due to the complexity of the system under study and the use of linear interpolation to complete missing data, necessitating further refinement. The mechanisms of various elements in urban sustainable development are intricate, requiring heterogeneous analysis of system interactions and the intermediate and time-lag effects on outputs. Future research could establish consistent cross-regional indicators to better examine the sustainable development of multiple urban clusters.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

CY: Resources, Writing–review and editing. HZ: Data curation, Software, Writing–original draft. GG: Funding acquisition, Writing–review and editing.

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Conflict of interest

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

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