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The Evaluation of the Sustainable Development Capacity of Bay Cities in China: Under the Background of Blue Bay Remediation Action

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Abstract: In response to the urgent need for sustainable development of the marine environment, the Chinese government initiated the Blue Bay Remediation Action (BBRA) in 2016, piloting efforts in 16 bay cities. Recognizing that these areas function as integrated ecosystems, it is clear that solely addressing issues within the bays will not completely resolve the ecological challenges. Guided by the principles of comprehensive treatment and sustainable development inherent in the BBRA policy, this paper incorporates ecological indicators of bays and the surrounding sea into a sustainable development framework for 52 bay cities. To identify a balanced approach for the development of the economy, ecology and society, a three-component evaluation system with 39 indicators is established to assess the sustainable development levels of bay cities from 2015 to 2019 in China. According to the result of the principal component and coupling coordination degree analysis, it indicates that after BBRA, the change of sustainable development levels of the pilot bay cities is not obvious. Significant disparities exist in the levels of sustainable development among the majority of pilot cities, with imbalances observed across economic, ecological, and social dimensions. Consequently, in researching the balanced sustainable development of bay cities, it is essential to consider the unique development characteristics of each city during the implementation process of the BBRA.

Keywords: Blue Bay Regulation Action; bay cities; marine sustainable development; Principal Component Analysis; Coupling Coordination Degree Method

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1. Introduction

The Intergovernmental Oceanographic Commission of United Nations Educational, Scientific and Cultural Organization (UNESCO) launched the United Nations Decade of Ocean Science for Sustainable Development in 2021 to enhance global and sustainable ocean governance [1-3]. Maritime environmental and economic issues have become increasingly important since 2010 given the intersection of ocean and land environments, the sustainable development of coastal cities has garnered considerable interest from researchers [4-7]. Bay cities play a vital role in fostering innovation and economic clustering due to their open economic structure, efficient resource allocation capabilities, significant agglomeration and advanced functions. These cities serve as critical growth hubs that drive global socioeconomic development and lead advancements in technology. For instance, San Francisco has experienced remarkable growth due to industrial development along the coast, alongside the appeal of Silicon Valley, which has attracted an increasing population and resource allocation [8-10]. New York serves as a prominent hub for finance, international trade, media, fashion, education, and manufacturing. Its development is supported by a network of cities, each with its distinct characteristics: New York is recognized as the financial and trading center; Washington, D.C. acts as the political center; Philadelphia is known for its industrial and transportation significance; and Boston is identified as the center for technology and education [11]. Additionally, the geographic proximity of the New York Bay area to numerous universities has greatly contributed to its development [11]. Tokyo, on the other hand, was established with a growth strategy centered on manufacturing, shaped by government policies and regulations. The technological upgrades within its industrial economy have allowed the Tokyo Bay Area to implement a robust development strategy focused on advanced manufacturing and a knowledge-intensive economy, particularly emphasizing high-end services in information and communication technology [12]. However, despite the rapid economic development of these bay cities, the lack of coordination of social and ecological development poses significant risks to their sustainability [10]. The swift progress, often pursued without adequate consideration of environmental implications, has negatively impacted environmental quality and ecological balance [13]. Furthermore, the neglect of pressing social issues, such as high living costs, traffic congestion, and public health concerns, has deterred sustainable development of these bay cities [10, 14].

In China, bay cities have developed and experienced a sharp economic expansion due to their inherently advantaged position and the natural resources supplied by oceans [4, 5]. However, because of the intense human activities and the sea-land combinative geographic features, the ecosystem of sea, oceans and bay cities are more vulnerable to suffering from severe damage such as the decrease of mud flats and natural shoreline, marine pollution and biodiversity loss [4]. Bay cities are different from the normal inland cities as they are often the hub of marine transport and the location of ocean industries, tourist resorts and home of marine organism [6]. They are strategically positioned in the national economic and social development, considering the established precedents related to the development of the renowned bay cities mentioned above, it is of great importance to prioritize sustainable development of bay cities [1, 6]. The non-point source pollution from cities needs be controlled, and the ecosystem-based management should be promoted to maintain ecosystem health and sustainable development in cities, bays and oceans [4, 15, 16]. It is key priority to carry out integrated marine and land development planning of bay cities, and a comprehensive development evaluation an important initial starting point [7, 16].

In 2016, the Chinese Government introduced the Blue Bay Remediation Action (BBRA) project as a response to the urgent requirements for sustainable development pertaining to the marine environment. The Ministry of Finance and the Oceanic Administration of China determined that the central government would offer support for the remediation of blue bays in coastal cities, with the aim of enhancing the ecological functions of coastlines, marine areas and islands, while also safeguarding marine ecological security [17]. According to the unique characteristics of each bay, local governments have initiated measures to manage land-based pollution, prevent offshore eutrophication, oversee marine ecological challenges, and restore coastal wetlands.

Seas, bays, and cities are included in a complex but interconnected system, and solely implementing remediation actions on bays will not fully achieve sustainable development [18-20]. Firstly, the marine ecology, encompasses both seas and bays, serves as an important asset for bay cities by providing essential areas for shipping, industry, recreation, and tourism, which can drive economic growth [4, 15]. Marine life in both the sea and bays support commercial fisheries and aquaculture, enhances local tourism with picturesque harbor views, and may also contain mining and energy resources that contribute substantial income. Furthermore, approximately 17% of the Chinese population resides in bay cities, which constitute only about 4.6% of China's land area [21]. The marine environment and bays play a crucial role in shaping the cultures, customs, and traditions of local communities [22-24]. Additionally, the oceans and coasts offer invaluable ecosystem services, such as carbon dioxide absorption, nutrient cycling, and urban pollution purification [6, 24]. Secondly, urban waste is a primary contributor to pollution in seas and bays [5, 25]. The combination of high population density and robust industrial activities in coastal cities generates large quanities of sewage and industrial wastewater that are often discharged directly into rivers, bays, and oceans. Additionally, inshore aquaculture, maritime traffic, and oil spills can introduce harmful chemicals into these waters [25, 26]. Furthermore, tourism can lead to substantial solid waste, such as plastic bags and bottles, accumulating on beaches, which may be washed into the sea by waves, posing a threat to marine life. Moreover, there is an increasing rate of urbanization which is resulting in a greater area of impervious surfaces, such as rooftops and roads [4, 5]. During storms, stormwater can flow over these surfaces, transporting debris, chemicals, sediments, trash, and other pollutants to streams and rivers, ultimately degrading the ecology of our bays and oceans [20]. Thirdly, the ecological degradation of bays and seas significantly impacts the urban economic development of bay cities. The livelihoods of fisheries can be jeopardized by challenges such as overfishing and poor water quality, including issues such as eutrophication, which can lead to fish mortality. Additionally, compromised ecological environments can result in decreased tourism and may pose health risks to local residents [24, 27].

Since the United Nations Conference on Environment and Development (UNCED) in 1992, there has been an increasing focus among researchers on evaluation methods for sustainable development. Index system evaluation methods typically integrate economic, ecological and social indicators to assess and forecast the level of sustainable development [4, 15, 18]. These methods represent one of the main approaches to evaluating sustainability. There are about 5 framework patterns of the sustainable development index system: the pressure-state-response (PSR) model, economics-based model, three-component or theme model, linked human-ecosystem well-being model, and multiple capital model [4, 16, 28, 29]. The three-component or theme model usually includes economy, ecology, and society as the three thematic indicators. It is commonly applied in specific regional sustainability assessments [4, 29].

However, for seas, bays, and bay cities, only a limited number of studies have developed index systems and considered them as a whole system for their analysis. Zhou et al. (2017) propose a novel conceptual index system utilizing systems science, the entropy weight method, a triangular model, and a coupling coordination degree model for assessing Land Use Management Framework (LUMF), as well as analyzing the relationships among various land use sub-functions [30]. This framework was applied to six cities within the urban agglomeration surrounding Hangzhou Bay (UAHB) in eastern China's Zhejiang Province, employing twenty-two indicators related to production, living, and ecology analysis during the period from 2004 to 2013. Fries et al. (2019) employed an ecosystem health report card to assess and monitor the ecological status of Guanabara Bay in Brazil [31]. Various measures were implemented to address the significant environmental challenges faced by the bay. The findings indicated that despite numerous interventions, the ecosystem of Guanabara continues to deteriorate due to ongoing urbanization, and poverty in certain areas along the river persists as a source of pollution affecting the bay's ecological restoration efforts. This situation is akin to the results reported by Evans (2018), which outlined that in Australia, the State of the Environment (SoE) framework, along with 123 indicators for coastal ecological remediation, emphasizes the importance of considering the cumulative effects of activities across different sectors, including atmosphere, built environment, heritage, biodiversity, land, inland water, coasts, marine environment, and the Antarctic environment, in ecological remediation efforts [32]. Sun et al. (2016) and Sun et al. (2018) utilized the pressure-state-response (PSR) model to evaluate the health levels of wetland ecosystems in the Hangzhou Bay, China [33, 34]. The weights of the indicators and components of the PSR model, as well as the normalized wetland health score, were determined and calculated using the analytic hierarchy process (AHP) method. In the AHP method, expert scoring plays a significant role in forming the weight coefficients, which can introduce a level of subjectivity. To enhance the objectivity of our analysis, this paper employs the principal component analysis (PCA) method. Given the unique geographical combination of sea and land in this region, the assessment of sustainable development in bay cities is inherently complex, and research in this area continues to evolve.

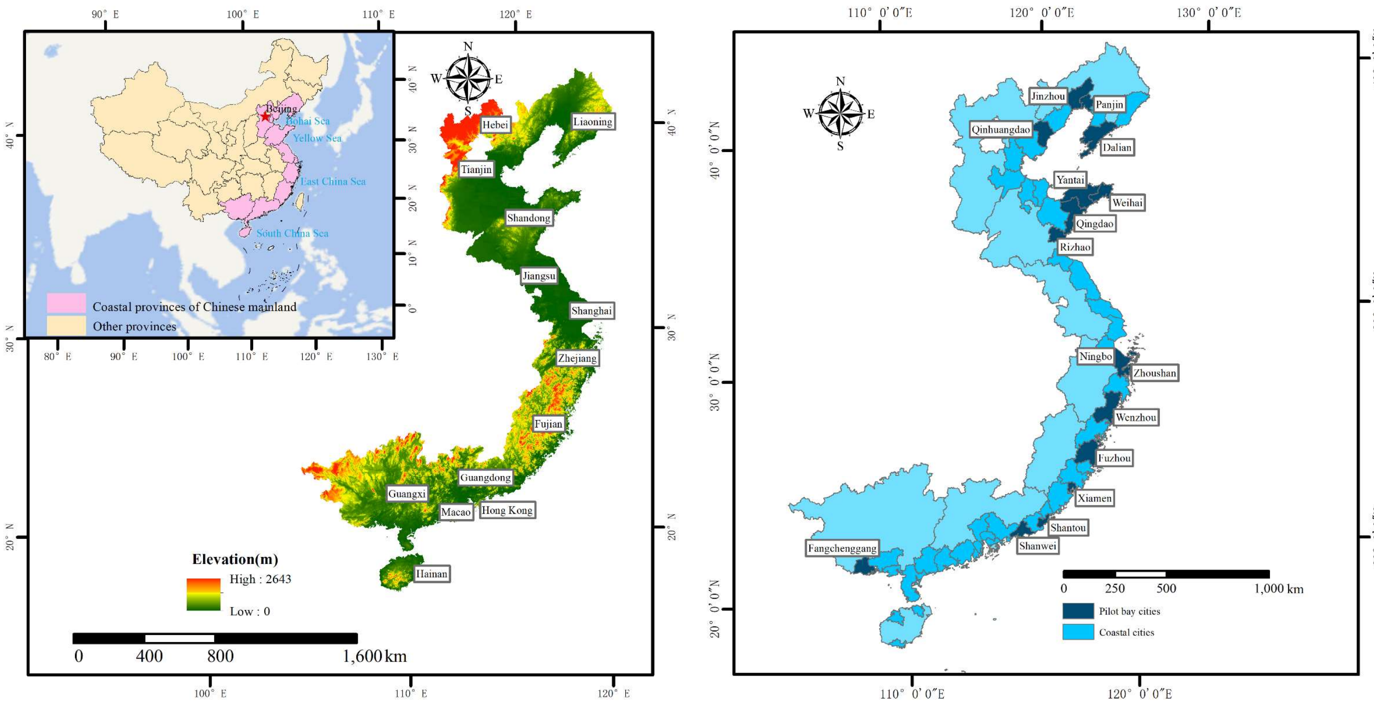
This study establishes an analytical framework informed by systems theory and sustainable development theory to explore the sustainable development of bay cities [35]. Systems theory highlights that the development of bay cities operates as a complex system, incorporating the interactions among economic, ecological, and social factors [36]. Sustainable development theory emphasizes the importance of balancing economic growth, ecological protection, and social well-being, advocating that development must address not only the ecological needs of the bay but also the economic and social requirements of its cities [35, 36]. Practically, systems theory offers a structured approach to analyzing the development of bay cities, while sustainable development theory outlines a pathway for achieving equilibrium among economic, ecological, and social dimensions throughout the development process, ultimately offering policy recommendations for sustainable development in bay cities. Drawing on these two theories, a three-component evaluation system for the sustainable development of bay cities has been created.

In summary, seas, bays, and cities exist within the same economy-ecology-society system; therefore, addressing only bay remediation will not fulfill the goals of sustainable development. Consequently, this paper employs 39 appropriate indicators to consider the interconnection of seas, bays, and cities as a unified system, aiming to promote the balanced sustainable development of pilot bay cities and to identify key issues that require attention during the implementation of BBRA.

2. Materials and Methods

2.1 Study Area

China is situated in the eastern region of the Eurasian continent, with its eastern coastal area facing the expansive Pacific Ocean. The coastal provinces of the Chinese mainland include Liaoning, Hebei, Shandong, Jiangsu, Zhejiang, Fujian, Shanghai, Guangdong, Hainan, Guangxi, as well as the special administrative regions of Hong Kong and Macao, as shown in Figure 1(a). The four main maritime areas bordering China, from north to south, are the Bohai Sea, Yellow Sea, East China Sea, and South China Sea. According to the Chinese Marine Economic Statistics Yearbook of 2022, there are a total of 53 coastal cities in mainland China, however, due to data limitations, Sansha is not included in this article. As per BBRA, in 2016, 16 bay cities were selected as the initial group of pilots for this policy. These cities, listed from north to south, include Dalian, Panjin, Jinzhou, Qinhuangdao, Yantai, Weihai, Qingdao, Rizhao, Zhoushan, Ningbo, Wenzhou, Fuzhou, Xiamen, Shantou, Shanwei, and Fangchenggang, as shown in Figure 1(b). Of the first 16 pilot bay cities, Dalian, Jinzhou, Panjin, and Qinhuangdao are located in the Bohai and Bohai Bay Area; Yantai, Weihai, Qingdao, and Rizhao are part of the Yellow Sea and the Yellow Sea Bay Area; while Shantou, Shanwei, and Fangchenggang belong to the South Sea and South Sea Bay Area.



(**a**) (**b**)

Figure 1. Geographical overview of Chinese mainland coastal provinces, cities and BBRA pilot cities. Note: The maps are based on the standard map authorized by the Ministry of Natural Resources of the People's Republic of China (Approval Number: GS (2019) 1823). The map approval number (GS (2019)1823) can be found at http://bzdt.ch.mnr.gov.cn/ for verification (accessed on 15 November 2024). Note 2: The data regarding the coastal provinces and cities is sourced from the China Marine Economic Statistics Yearbook (2022). Inset in Figure 1. Distribution of Chinese mainland coastal cities and BBRA pilot cities

2.2 Data collection

The data concerning GDP, GDP per capita, the proportion of the tertiary industry, FDI per capita, wholesale and retail trade sales per capita, the number of industrial enterprises above designated size, as well as water and road passenger traffic volume, water and road freight volume, water supply, land area, annual electricity consumption, local general public budget expenditure, green coverage of built-up areas, industrial wastewater discharge, industrial sulfur dioxide emissions, industrial soot emissions, industrial nitrogen oxide emissions, comprehensive utilization rate of industrial solid wastes, harmless disposal rate of household garbage, centralized treatment rate of sewage treatment plants, urban population density, labor force quantity, average wage of employed workers, education expenditure, science and technology spending, the number of buses per ten thousand people, urban road area per capita, public library book collections per ten thousand people, and the number of hospital beds per ten thousand people, are sourced from the Chinese City Statistics Yearbook (2015-2019). The data regarding wharf length, number of 10,000-ton berths, diversity indices of phytoplankton, macro zooplankton, and benthic organisms, as well as the frequency of red tides (greater than or equal to 100 square kilometers), is obtained from the China Marine Economic Statistics Yearbook (2015-2019). The mean indicator of ecological environment quality data is sourced from the Chinese National Earth System Science Data Center (https://www.geodata.cn/main/). Additionally, the Baidu Index for Sustainability, Global Warming, Clean Energy, and

Recycling is available from the Baidu website (http://index.baidu.com). All the data of indicators and references of them can be seen in Table 1.

Table 1 Three-component evaluation indicators of bay cities' sustainable development level

Target Layer	Rule Layer	Index Layer	Unit	Ref.
Economic Sustainable Development	Comprehensive economic strength	GDP	Billion yuan (CNY)	[4,10]
	Economic effectiveness	GDP per capita	Yuan (CNY)	[10,37]
	Level of economic development	The third industry proportion	%	[4,10]
	Level of economic openness	FDI per capita	U.S. dollar	[4]
	Economic prosperity	Wholesale and retail trade sales per capita	Yuan (CNY)	[10]
		Number of industrial enterprises above designated size	Piece	[10]
	Maritime economic power	Water and road passenger traffic volume	Million people	[38]
		Water and road freight volume	Million ton	[38]
	Maritime economic potential	Wharf Length	m	[10]
		Number of 10,000 tons berths	Piece	[10]
	Basic resources support for economic development	Water supply	Billion m³	[37,38]
		Land area	Hm²	[10]
		Annual electricity consumption	Million kilowatt-hours	[15,38]
		Local general public budget expenditure	Billion yuan (CNY)	[4]
	Economic green construction	Green coverage of built-up area	%	[6]
Ecological Sustainable Development	Comprehensive ecological level	Mean indicator of ecological environment quality		[39]
	Pollutant discharge	Industrial wastewater discharger	Million ton	[4]
		Industrial Sulphur dioxide emissions	Million ton	[15]
		Industrial soot emissions	Million ton	[15]
		Industrial nitrogen oxide emissions	Million ton	[15]
	Environment control	Comprehensive utilization rate of industrial solid wastes	%	[15]
		Harmless disposal rate of household garbage	%	[15]
		Centralized treatment rate of sewage treatment plants	%	[15]
	Offshore biodiversity indices	Phytoplankton		[4,15]
		Macro zooplankton		[4,15]
		Benthic organisms		[4,15]
	Marine biological disasters	Times of Red tide (more than 100 square kilometers)	Time	[4,15]
Social Sustainable Development	Index of population and labor force	Urban population density	People/hm²	[10,37]
		Quantity of labor force	Million people	[10]
		Average wage of employed workers	Yuan (CNY)	[10]
	The level of infrastructure development	Education expenditure	Billion yuan	[10]
		Science and technology spending	Billion yuan	[10]
		Urban road area	Hm²	[6]
		Public collection of books	Thousand pieces	[10]
		Number of beds in hospital	Pieces	[7,10]
	Public awareness of sustainability development	Baidu Index of Sustainability		[4]
		Baidu Index of global warming		[4]
		Baidu Index of clean energy		[4]
		Baidu Index of recycling		[4]

2.2.1. Economic sustainable development indicators

The sustainable development of the economy in coastal cities is evaluated based on 10 dimensions: comprehensive economic strength, economic effectiveness, level of economic development, level of economic openness, economic prosperity, maritime economic power, maritime economic potential, basic resources support for economic development, and economic green construction. Comprehensive economic strength is assessed through GDP, which serves as a synthesized and representative indicator [4,10]. Economic effectiveness is evaluated by GDP per capita, reflecting the economic efficiency of population [10,37]. The level of economic development is measured by the proportion of the tertiary industry, with a higher proportion signifying a more advanced economic development level [1,10]. The degree of economic openness is indicated by FDI per capita, while economic prosperity can be gauged through wholesale and retail trade sales per capita, as well as the number of industrial enterprises of a designated size [4,10]. Given the available data, the assessment of maritime economic power is based on the passenger and freight volume of water and road traffic in coastal cities, which can reflect the maritime economic income of these regions [38]. Additionally, wharf length and the number of 10,000-ton berths are considered to gauge maritime economic potential [10]. Basic resources and financial support for economic development are represented by metrics such as water supply, land area, annual electricity consumption, and local general public budget expenditure [10,37,38]. Finally, the green coverage of urban areas is utilized to reflect the degree of greening in urban construction [6].

2.2.2 Ecological sustainable development indicators

The ecological sustainable development of bay cities was evaluated across five dimensions: comprehensive ecological level, pollutant discharge, environmental management, offshore biodiversity indices, and marine biological disasters. The comprehensive ecological level is represented by a mean ecological index derived from the average indicators of ecological environment quality [39]. The metrics chosen to represent pollutant discharge in bay cities include the volumes of industrial wastewater, emissions of industrial sulfur dioxide, emissions of industrial soot, and emissions of industrial nitrogen oxides [4,15]. The comprehensive utilization rate of industrial solid waste, the rate of harmless disposal of household waste, and the centralized treatment rate of sewage treatment facilities were utilized to indicate environmental management in bay cities [15]. Offshore biodiversity indices are assessed through the measurement of phytoplankton, macro zooplankton, and benthic organisms [4,15]. The frequency of red tides (spanning more than 100 square kilometers) is used as an indicator of marine biological disasters [4,15].

2.2.3 Social Sustainable development indicators

Social indicators, such as population density and the construction of municipal infrastructure in urban areas, can significantly influence bay pollution [24]. The assessment of sustainable social development in bay cities is derived from five dimensions: the population and labor force index, investments in education and science, infrastructure development, and public awareness of sustainability. To represent the population and labor force index, criteria such as urban population density, the size of the labor force, and average wages of employed individuals are utilized [10,37]. The level of infrastructure development is indicated by metrics education expenditure, spending on research and technology, urban road area per capita, public library resources per ten thousand residents, and the availability of hospital beds per ten thousand residents [7,10]. Public awareness of sustainability is assessed using the Baidu Index for topics such as sustainability, global warming, clean energy, and recycling [4].

2.3 Methods

The Principal Component Analysis (PCA) method is employed across various disciplines to evaluate sustainable development [40-44], while the Coupling Coordination Degree Method (CCDM) is primarily used to demonstrate the interactions and influences among two or more systems [45, 46]. This article utilizes PCA to evaluate the sustainable development levels—comprising economic, ecological, and social components—of 16 polit cities within the BBRA framework. Furthermore, the Coupling Coordination Degree Model (CCDM) is employed to assess the interdependence of sustainable development across these three domains. The methodological and technological framework supporting this study is presented in Figure 2.

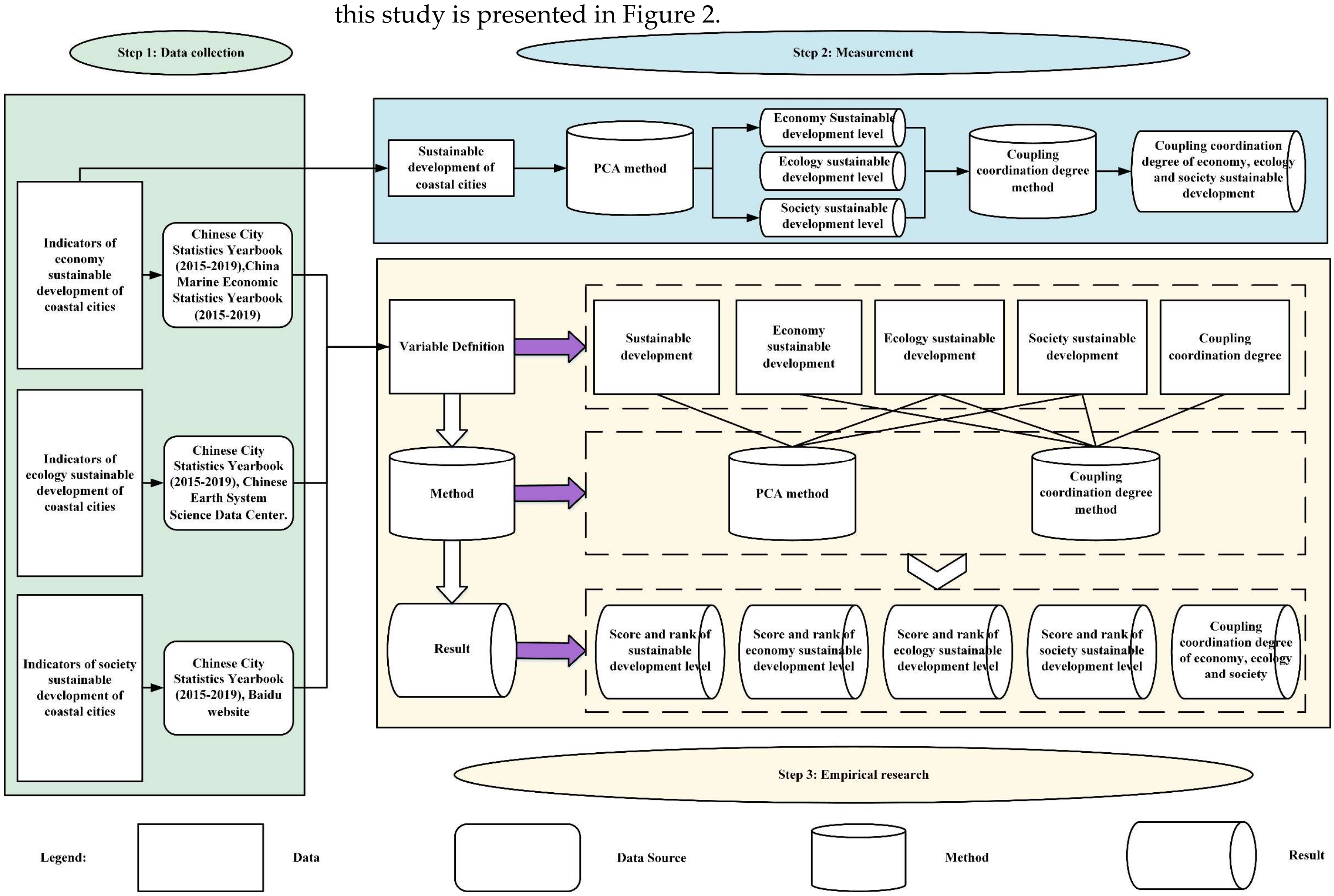


Figure 2. Methodological and technological framework.

Based on systems theory and sustainable development theory, this article utilizes data from Chinese City Statistics Yearbook (2015-2019), China Marine Economic Statistics Yearbook (2015-2019), Chinese National Earth System Science Data Center (https://www.geodata.cn/main/) and Baidu website (http://index.baidu.com), establishing a three-component evaluation system with 39 indicators. Through the application of Principal Component Analysis (PCA) and coupling coordination degree methods, the study gets scores and ranks of comprehensive sustainable development level, economy, ecology and society sustainable development level as well as coupling coordination degree among them to assess the sustainable development levels of bay cities from 2015 to 2019 in China.

2.3.1 Principal Component Analysis Method

Principal Component Analysis (PCA) is a statistical technique that reduces the dimensionality of data by transforming the original correlated indicators into a new set of mutually independent comprehensive indicators. This transformation allows for the selection of principal components that capture the majority of the information contained in the original variables [37,47]. Rather than simply eliminating variables, PCA are derived through linear combinations of the indicator variables, enabling a comprehensive evaluation of the research subject while preserving as much original information as possible [47].

There are n samples and p indicators (variables) $x_1, x_2, \ldots, x_p$ to compose the original data array:

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1p} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{np} \end{bmatrix} = \begin{bmatrix} X_1 \\ \vdots \\ X_n \end{bmatrix} \quad (1)$$

$$x_i = (x_{1i}, x_{2i}, \ldots, x_{ni})^T, \quad i = 1,2,\ldots,p \quad (2)$$

By using p indicator vectors of the data matrix X, a linear combination is established:

$$F_i = a_{1i} x_1 + a_{2i} x_2 + \cdots + a_{pi} x_p, i = 1,2,\ldots,p \quad (3)$$

The above equation requires:

$$a_{1i}^2 + a_{2i}^2 + \cdots + a_{pi}^2 = 1, i = 1,2,\ldots,p \quad (4)$$

And the coefficient a_{pi} is determined by the following principles:

(1) F_i is not related to F_j $(i \neq j,\ i, j = 1, \ldots, p)$;

(2) F_1 is the linear combinations of $x_1, x_2, \ldots, x_p$ with the largest variance; F_2 is the linear combinations of $x_1, x_2, \ldots, x_p$ with the largest variance, which is unrelated to F_1. By analogy, F_p is the linear combinations of $x_1, x_2, \ldots, x_p$ with the largest variance which is not related to $F_1, F_2, \ldots, F_{p-1}$.

With n sample units and p indicators, the original data array X can be obtained.

To standardize the original data array x_{ij} denote the jth indicator of sample i:

$$z_{ij} = x_{ij} - \bar{x}_j / s_j, \ i = 1,2,\ldots,n;\ j = 1,2,\ldots,p \quad (5)$$

where x_{ij} represents the initial value of the i^{th} sample's j^{th} indicator. The sample mean and sample standard deviation of the j^{th} indicator are denoted by $\bar{x}_j$ and s_j, respectively.

To obtain the correlation coefficient matrix of the indicator data

$$R = (r_{ij}) p \times p, i = 1,2 \ldots, p;\ j = 1,2,\ldots,p \quad (6)$$

Where r_{ij} is the correlation coefficient between indicator i and indicator j.

$$r_{ij} = \frac{1}{n-1} \sum_{i=1}^{n} [(x_{ij} - \bar{x}_i)/s_i][(x_{ij} - \bar{x}_j)/s_j], i = 1,2,\ldots,p;\ j = 1,2,\ldots,p \quad (7)$$

Finding the eigenvalues $\lambda_1, \lambda_2, \ldots, \lambda_p$ of R and the corresponding unit eigenvectors, and $\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_p \geq 0$.

There,

$$\partial_1 = (a_{11}, a_{21}, \ldots, a_{p1})^T$$

$$\partial_2 = (a_{12}, a_{22}, \ldots, a_{p2})^T$$

$$\ldots$$

$$\partial_p = (a_{1p}, a_{2p}, \ldots, a_{pp})^T \quad (8)$$

Writing the principal component and find the principal component score from the normalized raw data array:

$$F_i = a_{1i} x_1 + a_{2i} x_2 + \cdots + a_{pi} x_p, i = 1,2,\ldots,p \quad (9)$$

When solving the actual problem, we generally do not take p principal components. If the contribution rate of the first k principal components has reached 85%, it means that the first k principal components basically contain the information of all the measurement indicators. This method can reduce the number of variables and make it easy to analyze the actual problems. Because of

$$Var(F_i) = \lambda_i / \sum_{i=1}^{p} \lambda_i \quad (10)$$

And the first principal component contribution rate is $\lambda_1 / \sum_{i=1}^{p} \lambda_i$, so

$$\lambda_1 / \sum_{i=1}^{p} \lambda_i = Var(F_1) / \sum_{i=1}^{p} Var(F_i) \quad (11)$$

Therefore, the contribution rate of the first principal component is the ratio of the variance of the first principal component to the total variance $\sum_{i=1}^{p} \lambda_i$. The larger the value, the stronger the ability of the first principal component can contain more information of $x_1, x_2, \ldots, x_p$. The cumulative contribution rate of first k principal components is defined as

$$\sum_{i=1}^{k}\lambda_i/\sum_{i=1}^{p}\lambda_i \quad (12)$$

2.3.2 Coupling Coordination Degree Method

The Coupling Coordination Degree Method (CCDM) can not only evaluate the extent of coupling intensity among systems but also reflect the strength of coordination levels between them. To more effectively assess the degree of interaction or complementarity among the subsystems of sustainable development in bay cities, the degree of coupling coordination is calculated using the following specific formulas:

$$C_j = \frac{\sqrt[3]{Y_{1j}Y_{2j}Y_{3j}}}{(Y_{1j}+Y_{2j}+Y_{3j})/3} \quad (13)$$

$$T_j = \alpha Y_{1j} + \beta Y_{2j} + \gamma Y_{3j} \quad (14)$$

$$D_j = \sqrt{C_j T_j} \quad (15)$$

In these formulas, *C* denotes the coupling degree of r systems. Y_1, Y_2 and Y_3 represent the sustainable development of the economy, ecology and society, respectively. The variable *j* refers to different years, and *T* is a composite indicator of system development. Generally, the three systems are considered equally important when their respective contributions to the overall system's growth are not significantly different, leading to values of α, β and γ being set at 1/3. The value of *D* reflects the degree of coupling coordination, with a higher *D* indicating a greater degree of coupling coordination. According to the existing literature [48-50], this paper utilizes a wide range of quadratic methods, and categorize the stages of coupling coordination into four categories: low coupling coordination ($0 < D \leq 0.2$), moderate coupling coordination ($0.2 < D \leq 0.5$), benign coordinated coupling ($0.5 < D \leq 0.8$), and coordinated coupling ($0.8 < D \leq 1$).

3. Results

3.1. The result of descriptive statistics of the 39 indicators of sustainable development system

In order to find out the basic characteristics of the data, descriptive statistics of the 39 indicators of sustainable development system are conducted. The results are shown in Table 2.

Table 2 Descriptive statistics of the 39 indicators of sustainable development system

Index	Mean	SD	Kurt	Skew	Min	Max
GDP	492.52	599.45	8.45	2.74	23.17	3815.60
GDP per capita	102764.23	89886.29	8.51	2.60	21200	544300
The third industry proportion	47.64	9.50	1.31	1.04	30.65	79.23
FDI per capita	344.37	509.42	6.64	2.49	0.00	2975.45
Wholesale and retail trade sales per capita	40042.04	29651.95	3.58	1.79	7215.32	173849.01
Number of industrial enterprises above designated size	2282.07	2256.05	1.41	1.37	18	10658
Water and road passenger traffic volume	58.37	99.4	57.21	7.11	4.4	916.08
Water and road freight volume	205.6	209.9	10.17	2.9	2.13	1329.23
Wharf Length	15077.13	18387.77	5.14	2.08	0	95772
Number of 10,000 tons berths	35.82	42.73	2.32	1.58	0	190
Water supply	5.48	5.76	7.26	2.11	0.19	38.43
Land area	816161.54	445809.35	-1.23	0.05	145500	1693100

Annual electricity consumption	2889630.39	3088966.65	3.96	1.96	96335.00	15685775.00
Local general public budget expenditure	75.48	120.93	18.93	4.11	5.7	835.15
Green coverage of built-up area	41.04	4.1	2.8	-0.75	23.24	57.94
Mean indicator of ecological environment quality	0.48	0.11	-1.24	0.26	0.31	0.71
Industrial wastewater discharger	86.7	109.95	28.7	4.28	0.07	965.01
Industrial Sulphur dioxide emissions	1071.95	2204.54	24.08	4.23	0.75	18877.35
Industrial soot emissions	293.84	1240.42	185.56	12.87	0.48	18598.66
Industrial nitrogen oxide emissions	265.52	310.77	11.37	2.95	0	2147.23
Comprehensive utilization rate of industrial solid wastes	87.23	18.04	10.73	-3.04	0	105.8
Harmless disposal rate of household garbage	97.29	10.57	55.83	-6.82	0	100
Centralized treatment rate of sewage treatment plants	86.05	22.08	9.13	-3.1	0	100
Phytoplankton	2.27	0.59	-0.17	0.57	0.9	3.7
Macro zooplankton	2.38	0.69	0.27	0.49	0.9	4
Benthic organisms	1.76	0.84	-0.92	0.02	0.2	3.54
Times of Red tide (more than 100 square kilometers)	0.19	0.66	46.61	5.79	0	7
Urban population density	6.8	4.87	5.82	2.32	1.52	26.34
Quantity of labor force	0.88	1.12	9.85	2.98	0.03	6.82
Average wage of employed workers	70674.89	17977.4	3.31	1.33	35790	160256
Education expenditure	12.21	15.01	13.15	3.37	1.39	99.57
Science and technology spending	3.19	7.99	21.19	4.45	0.01	55.5
Urban road area	3428.99	3793.02	5.75	2.3	261	24473
Public collection of books	6752.45	12413.03	19.72	4.18	110	80150
Number of beds in hospital	24000.98	21218.77	9.41	2.65	2361	136682
Baidu Index of Sustainability	1.61	5.45	50.75	6.56	0	54.92
Baidu Index of global warming	18.73	25.22	5.11	2.33	0	119.37
Baidu Index of clean energy	27.5	33.58	3.17	1.89	0	158.52
Baidu Index of recycling	28.44	33.2	2.63	1.77	0	145.27

These 52 China's bay cities exhibit considerable economic disparities. The average GDP stands at 492.52 billion CNY; however, the high standard deviation of 599.45 billion CNY and the extensive range from 23.17 billion to 3,815.6 billion CNY indicate inequality. The average per capita GDP is 102,764 CNY, yet there are considerable income gaps ranging from 21,200 to 544,300 CNY. The tertiary sector contributes an average of 47.64% to the economy, but this figure varies significantly from 30.65% to 79.23%, suggesting uneven economic diversification. Additionally, foreign direct investment (FDI) and industrial activity vary greatly among cities, with some attracting substantial FDI and experiencing robust industrial growth, while others lag in these areas.

Environmental challenges are a great concern in these 52 bay cities. Industrial emissions, including sulfur dioxide (86.70 million tons) and particulate matter (1045.06 million tons), vary considerably, resulting in some cities experiencing severe air quality issues. The average wastewater discharge is 0.48 million tons, although certain cities encounter higher levels of discharge. While the utilization of solid waste is generally high at 87.23%, and garbage disposal rates are at 97.29%, there are notable disparities among different regions. The average green coverage is 75.48%, but this figure varies widely between 5.70% and 835.15%, indicating inconsistent urban greening initiatives. Additionally, coastal cities are facing challenges related to marine pollution, including incidents of red tide in specific areas.

Social indicators illustrate disparities in development in these 52 bay cities. The average urban population density is 6.80 persons per hectare; however, this distribution is not uniform across regions. The labor force comprises approximately 0.88 billion individuals, and income levels average 70,674.89 CNY, revealing significant economic inequality. The allocation of public services, such as education, which receives 12.21 billion CNY, and healthcare, represented by 24,000 hospital beds, is inconsistent, with certain cities experiencing a lack of adequate resources. Public awareness regarding sustainability, clean energy, and recycling varies significantly, as indicated by Baidu Index scores, which reflect differing levels of environmental consciousness among the population in different cities.

3.2. KMO (Kaiser-Meyer-Olkin) and Bartlett's Test result

Before PCA, KMO and Bartlett's Test is conducted to indicate the suitability of the data in applying PCA, the result is shown in Table 3.

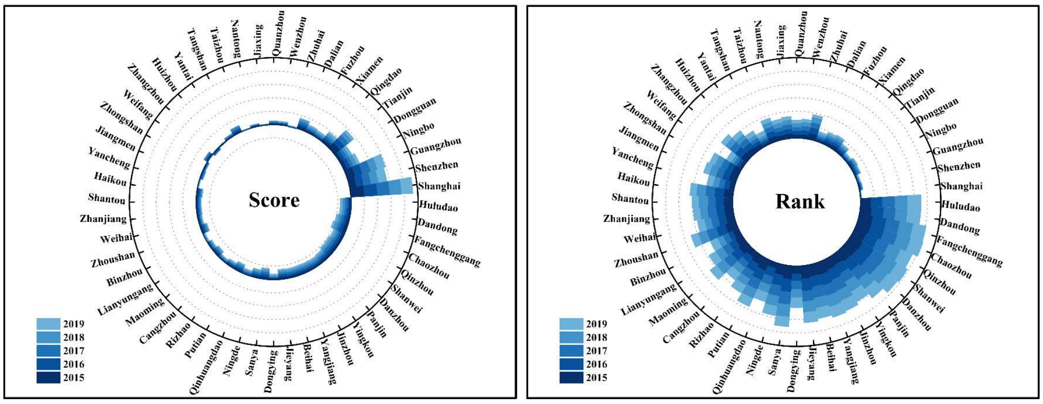
Table 3 Results of KMO and Bartlett's Test

Test	Value
KMO Measure of Sampling Adequacy	0.721
Bartlett's Test of Sphericity	P < 0.000

The results of the KMO and Bartlett's tests indicate that the data is suitable for PCA. The KMO value of 0.721 suggests that the sampling adequacy is acceptable. The Bartlett's Test of Sphericity is significant ($p < 0.001$), confirming that the correlation matrix is not an identity matrix and that the variables are sufficiently correlated for factor analysis.

3.3. The sustainable development ranking of 52 bay cities of from 2015 to 2019

Based on the 39 indicators outlined above, a principal component model is developed to assess the sustainable development of 52 bay cities, considering economic, ecological, and social indices. The scores and ranks for these cities from 2015 to 2019 are presented in Figure 3. To present these results in a more visual format in geography, ArcGIS is utilized to illustrate the distribution and dynamic changes in the scores of bay cities, as shown in Figure 4.



(**a**) (**b**)

Figure 3. The dynamic changes of the scores and ranks of sustainable development level of the 52 coastal cities. The data used in the figure are the composite scores and ranks derived from the PCA model. Note: (a) The changes of sustainable development scores of the 52 coastal cities from 2015 to 2019. (b) The changes of sustainable development ranks of the 52 coastal cities from 2015 to 2019.

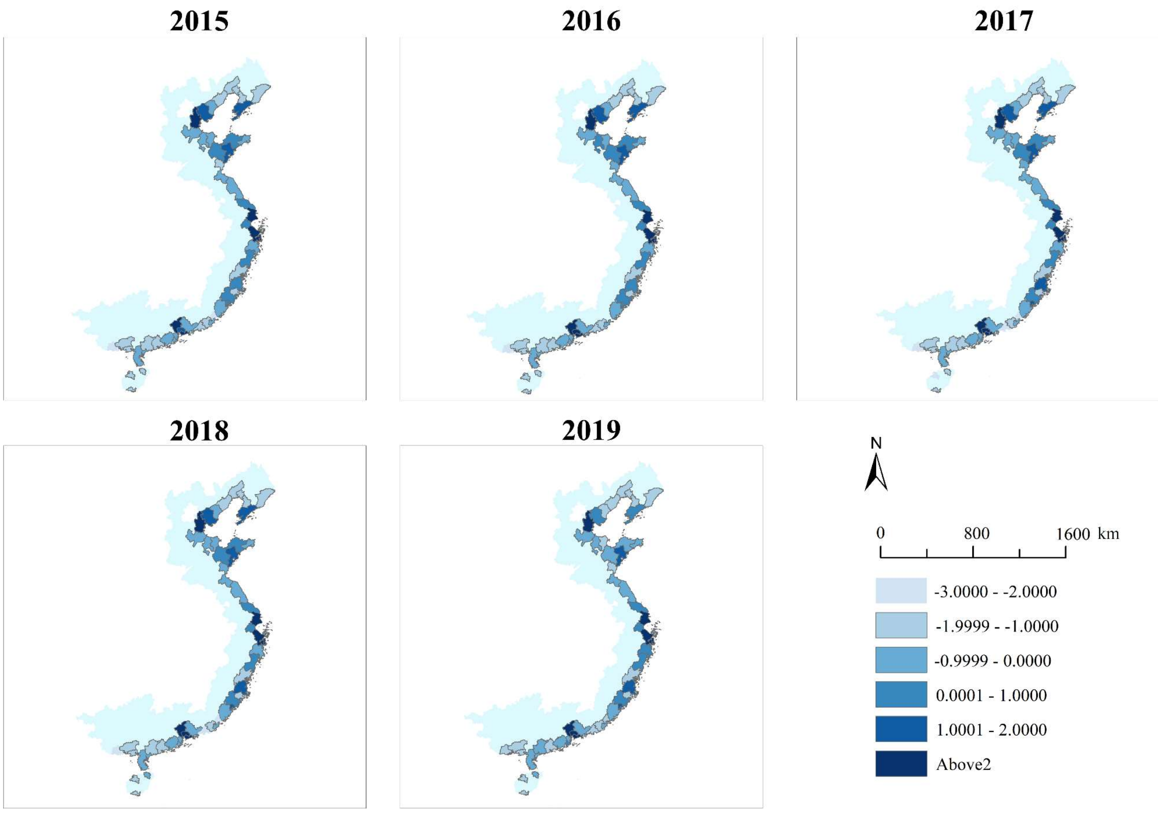


Figure 4 The distribution and dynamic changes of the sustainable development scores of coastal cities from 2015 to 2019. The background image is sourced from the administrative area planning map in the Environmental and Resource Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/), and the data of scores are derived from the PCA model.

As illustrated in Figure 3 (a), the scores for Shanghai, Shenzhen, Guangzhou, Ningbo, Dongguan, Tianjin, Qingdao, Xiamen, Fuzhou, Wenzhou, Quanzhou, Jiaxing, Nantong, Dalian, and Tangshan consistently remained above average from 2015 to 2019. In 2019, the scores for Zhuhai and Taizhou shifted from below average to above average, whereas Yantai and Weifang experienced a decline, moving from above average to below average. Except these cities, the scores of others remained below average from 2015 to 2019.

As depicted in Figure 3 (b), the ranks for Shanghai, Shenzhen, Guangzhou, Ningbo, Dongguan, Tianjin, Qingdao, Xiamen, Fuzhou, Dalian,Wenzhou, Quanzhou, Jiaxing, Nantong, Taizhou, Tangshan and Yantai consistently maintained rankings within the top 20 from 2015 to 2019. While the ranks for Cangzhou, Zhongshan, Jiangmen, Lianyungang, Dongying, Weihai, Zhanjiang, Shantou, Rizhao, Haikou, Maoming, Ningde, and Zhoushan ranked from 21 to 40. Furthermore, the cities of Dandong, Panjin, Yangjiang, Qinzhou, Danzhou, Shanwei, Fangchenggang and Chaozhou ranked between 41 and 52. Others are experiencing fluctuations across different stages.

As demonstrated in Figure 4, the intensity of the color indicates the score level, with deeper colors representing higher scores. When some coastal cities have scores below 0, indicating that their sustainability performance falls below the average level. In 2019, the coastal cities represented in the darkest blue (with scores above 2) include Shanghai, Shenzhen, Guangzhou, Ningbo, Dongguan and Tianjin. The most notable change observed in this figure is the elimination of the score between -3 and -2 (indicated in the lightest blue) in the year 2019. However, from 2015 to 2019, the variations in scores and rankings for the majority of coastal cities were not prominent. Additionally, it is clear that cities with positive scores demonstrate a clustering trend.

3.4 The sustainable development level of the pilot cities of BBRA

As illustrated in Figure 4, among the 16 pilot cities of BBRA, Ningbo was identified as the city with the highest score. The scores for Ningbo, Qingdao, Xiamen, Fuzhou, Dalian, Wenzhou, and Yantai consistently exceed the average, whereas the scores for others tend to fall below the average. The rankings of these 16 pilot cities can be categorized into three distinct stages. Ningbo, Qingdao, Xiamen, Fuzhou, Dalian, Wenzhou, and Yantai consistently rank within the top 20. In contrast, Shantou, Weihai, Zhoushan, Rizhao, and Qinhuangdao occupy positions between 21 and 40, while Jinzhou, Panjin, Shanwei and Fangchenggang are positioned from 41 to 52. By 2019, compared to 2015, the rankings of Ningbo, Qingdao, Fuzhou, Fangchenggang, Wenzhou, Weihai, Shanwei, Xiamen, Shantou, and Zhoushan have improved. Conversely, Rizhao, Panjin, Yantai, Dalian, Jinzhou, and Qinhuangdao have experienced declines. Notably, Zhoushan has shown the most considerable improvement, advancing 11 places, while Qinhuangdao has encountered the largest decline, dropping 16 places. The rankings of Wenzhou, Weihai, Ningbo, Qingdao, Fuzhou, Fangchenggang, Rizhao, Panjin, and Yantai have remained relatively stable, with fluctuations confined to within 2 rankings. According to the calculation process and results of PCA in SPSS, the contribution of each indicator can be linearly calculated into three principal components: economy, ecology, and society. To investigate the causes of the fluctuations, the scores of the economic, ecological and societal components of these pilot bay cities from 2015 to 2019 were analyzed, with the results presented in Figure 5, 6 and 7, respectively. The dynamic changes of the ranks are presented in Figure 8.

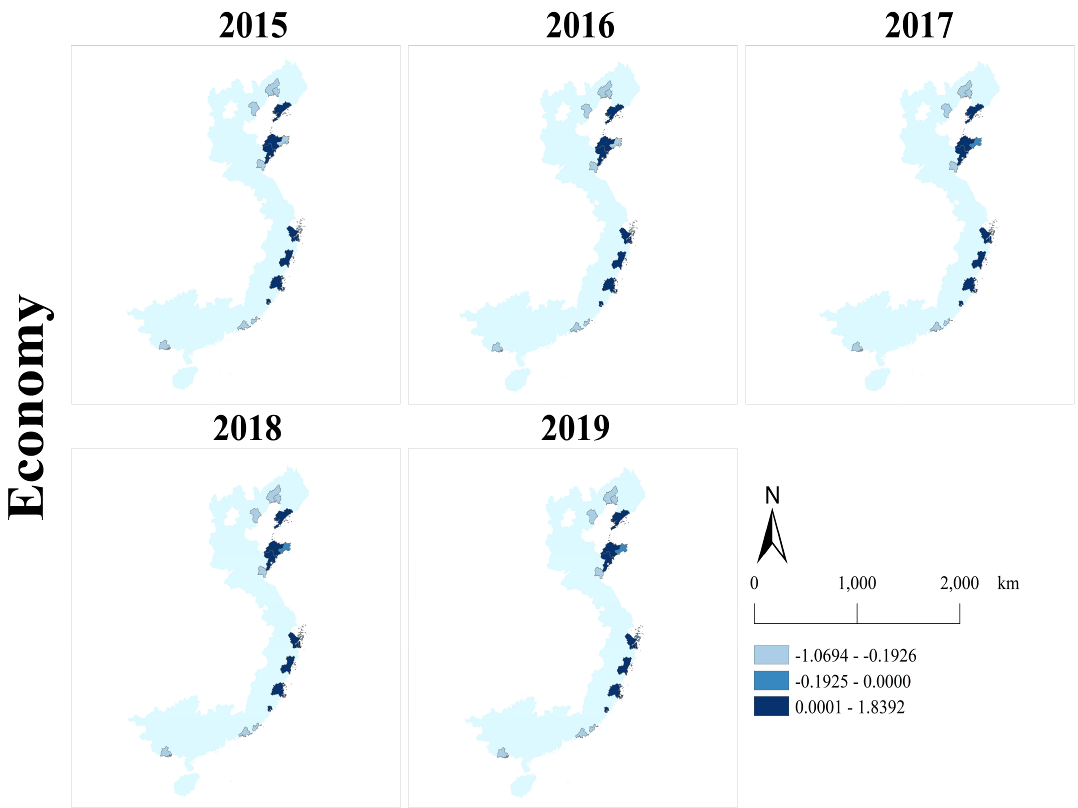


Figure 5. The dynamic changes of the economy scores of sustainable development level of the 16 polit bay cities from 2015 to 2019. The background image is sourced from the administrative area planning map in the Environmental and Resource Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/), and the data used for the three dimensions in the diagram are all scores derived from the PAC model.

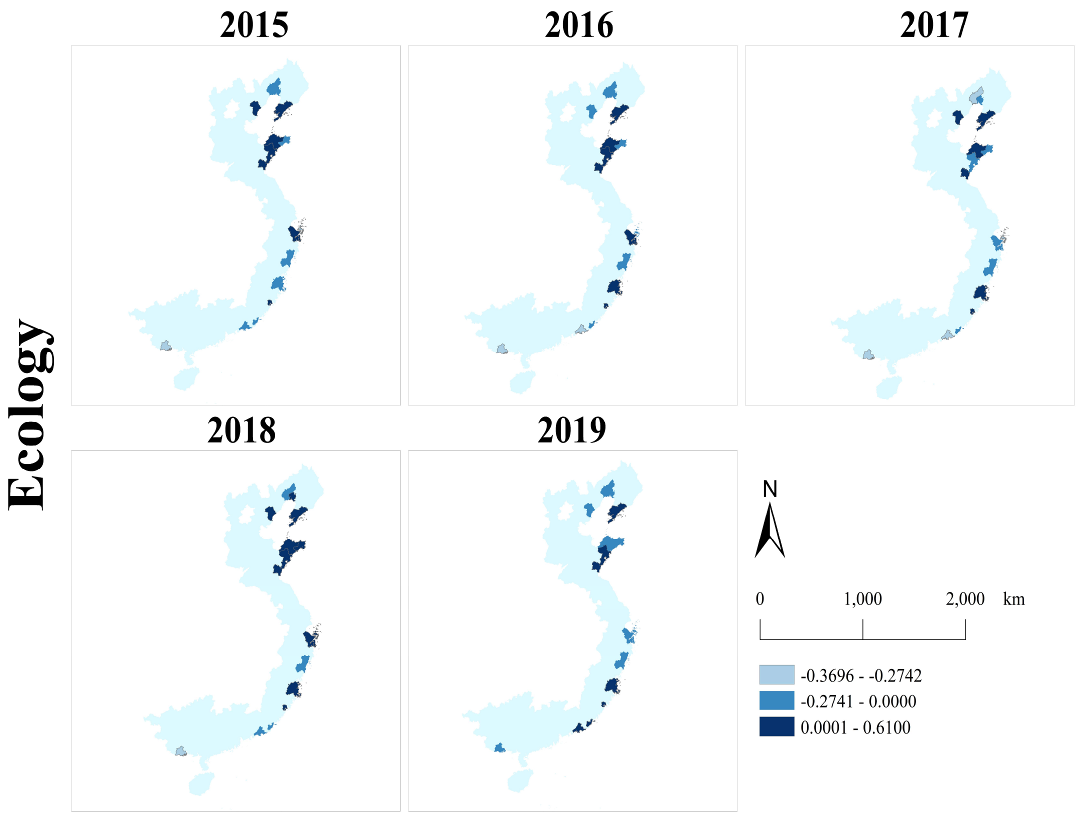


Figure 6. The dynamic changes of the ecology scores of sustainable development level of the 16 polit bay cities from 2015 to 2019. The background image is sourced from the administrative area planning map in the Environmental and Resource Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/), and the data used for the three dimensions in the diagram are all scores derived from the PAC model.

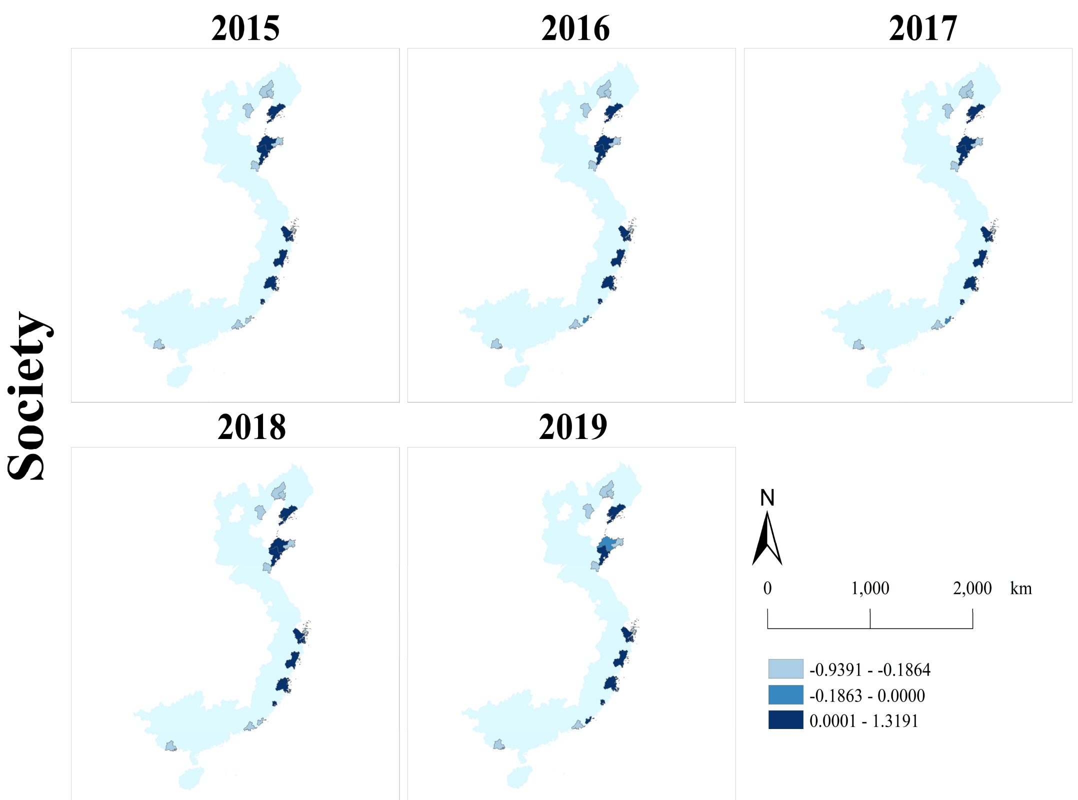
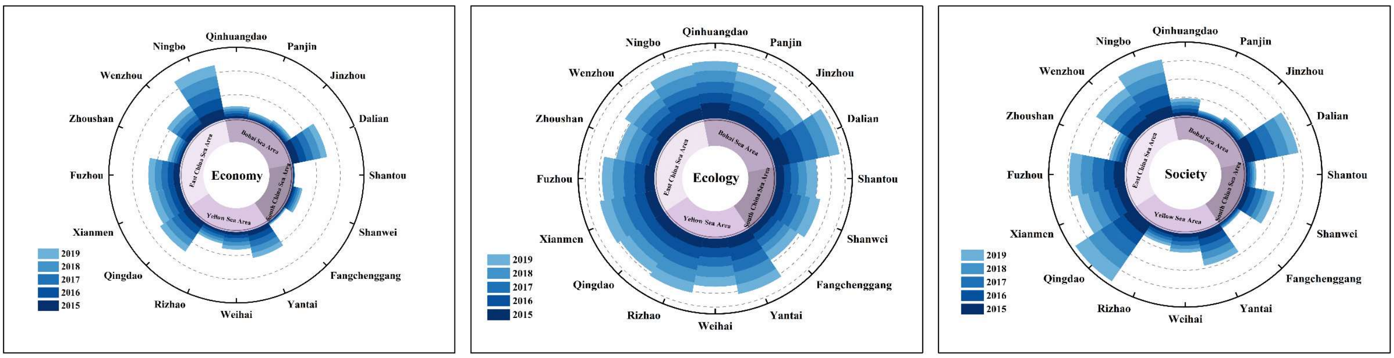


Figure 7. The dynamic changes of the society scores of sustainable development level of the 16 polit bay cities from 2015 to 2019. The background image is sourced from the administrative area planning map in the Environmental and Resource Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/), and the data used for the three dimensions in the diagram are all scores derived from the PAC model.



(**a**) (**b**) (c)

Figure 8. The dynamic changes of the ranks of sustainable development level of the 16 polit bay cities from 2015 to 2019 across three dimensions, which include economy, ecology and society. The data used for the ranks in the diagram are derived from the PAC model.

In Figure 5, a score below 0 indicates that the performance is below the average level. Therefore, among the 16 pilot cities, the economic sustainability development level of Panjin, Jinzhou, Qinhuangdao, Weihai, Rizhao, Zhoushan, Shantou, Shanwei, and Fangchenggang is rated below average. In terms of ecological sustainability in Figure 6, Panjin, Jinzhou, Qinhuangdao, Yantai, Weihai, Zhoushan, Ningbo, and Fangchenggang also fall below the average. Additionally, based on Figure 7, the social sustainability of Panjin, Jinzhou, Qinhuangdao, Yantai, Weihai, Rizhao, Zhoushan, Shanwei, and Fangchenggang is rated below average as well. Among the 16 pilot cities of BBRA, Dalian, Qingdao, Wenzhou, Fuzhou, and Xiamen achieve scores above the average for all three components, while Panjin, Jinzhou, Qinhuangdao, Weihai, Zhoushan, and Fangchenggang are noted to have below-average scores across all three components. From Figure 8, it also can be seen that the levels of sustainable development in the economy, ecology, and society in adjacent sea areas tend to exhibit a degree of consistency.

3.5 The coupling coordination degree of the pilot cities of BBRA

The dynamic changes of coupling coordination degree for economy, ecology and society sustainable development of the 16 BBRA pilot cities from 2015 to 2019 are shown in Figure 9.

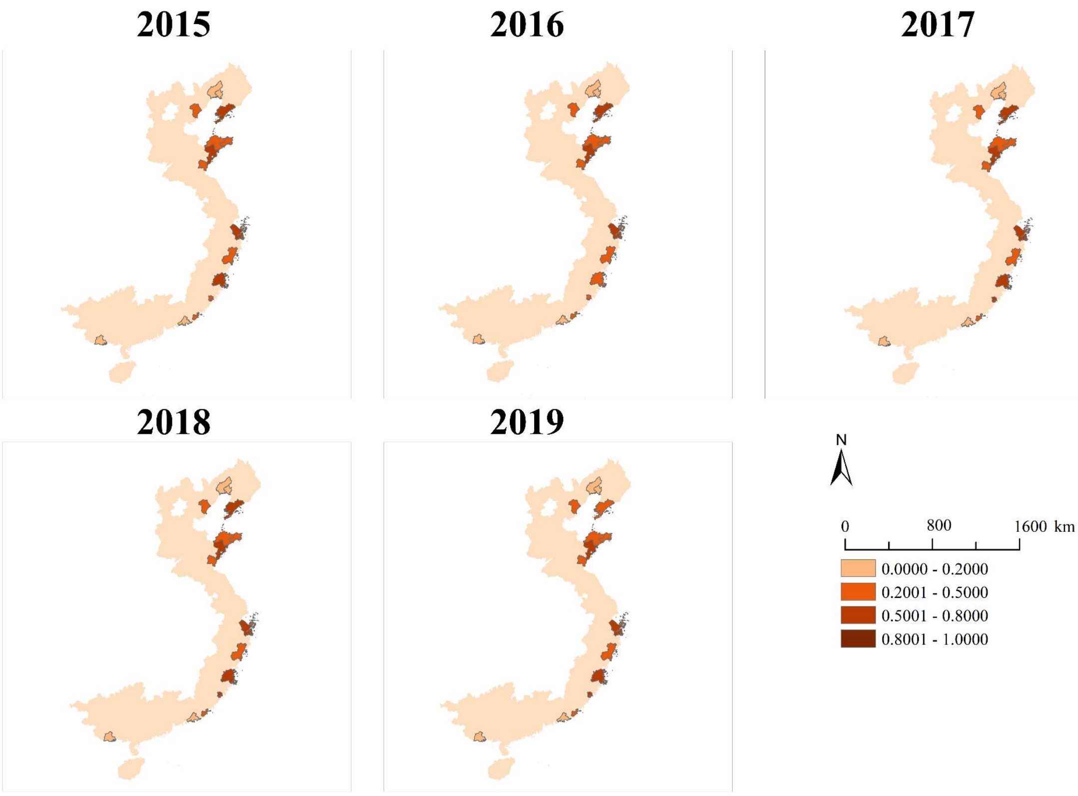


Figure 9. The dynamic changes of coupling coordination degree of the 16 polit bay cities from 2015 to 2019 across three dimensions, which include economy, ecology and society. The background image is sourced from the administrative area planning map in the Environmental and Resource Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/), and the coupling coordination degree in the diagram are from the coupling coordination degree model.

According to Figure 9, from 2015 to 2019, the coupling coordination degree of Panjin, Jinzhou, Shanwei, and Fangchenggang was categorized as low coupling coordination ($0 < D \leq 0.2$). In contrast, the coupling coordination degree of Qinhuangdao, Yantai, Weihai, Rizhao, Wenzhou, Fuzhou, Xiamen, and Shantou were the moderate coupling coordination category ($0.2 < D \leq 0.5$). During the same period, Ningbo exhibited a benign coordinated coupling ($0.5 < D \leq 0.8$). Dalian experienced a shift from benign coordinated coupling to moderate coupling coordination in 2019, while Qingdao transitioned to moderate coupling coordination in 2016 and then reverted to benign coordinated coupling in 2017 and kept it until 2019. Additionally, Zhoushan's coupling coordination degree fluctuated, displaying low coupling coordination in 2015 and 2017, and moderate coupling coordination in 2016, 2018, and 2019.

4. Discussion

According to Figure 5 ,6 and 7, which illustrates the dynamic changes in the rankings of economic, ecological, and societal sustainable development levels of the 16 pilot cities from 2015 to 2019, the reasons for fluctuations in sustainable development levels vary among the cities. By 2019, compared to 2015, Ningbo's improvement in sustainable development can be attributed to advancements in both economic and societal sustainability scores. Wenzhou's progress was primarily due to enhancements in economic sustainability. Qingdao's advancement stemmed from improvements in societal sustainability. The improvements seen in Zhoushan, Weihai, and Fangchenggang resulted from gains in both economic and ecological sustainability. Shanwei's enhancement was linked to advancements in ecological and societal sustainability scores. Fuzhou, Xiamen, and Shantou experienced comprehensive improvements across economic, ecological, and societal sustainability. In contrast, Dalian, Qinhuangdao, and Yantai have faced declines due to simultaneous decreases in economic, ecological, and societal sustainability scores. Jinzhou and Panjin both experienced declines primarily attributable to reductions in societal sustainability scores, while Rizhao's decline was due to reductions in both economic and societal sustainability scores.

The integrated development of the economic, ecological, and social aspects of the bay city is essential for the sustainable advancement of our coastal, bay, and ocean. According to Figure 10, which illustrates the rankings of economic, ecological, and societal sustainable development levels of the 16 pilot cities of 2019, the reasons obstacle coordinated development of 16 polit bay cities vary. The coupling coordination degree of Shantou and Shanwei was mainly influenced by relatively poor economy development. The coupling coordination degree of Dalian, Qinhuangdao, Yantai, Weihai, Qingdao, Zhoushan, Ningbo, Wenzhou, Fuzhou, was mainly influenced by backward ecology development. The coupling coordination degree of Panjin, Jinzhou, Rizhao, Xiamen and Fangchenggang was mainly influenced by relatively backward social development.

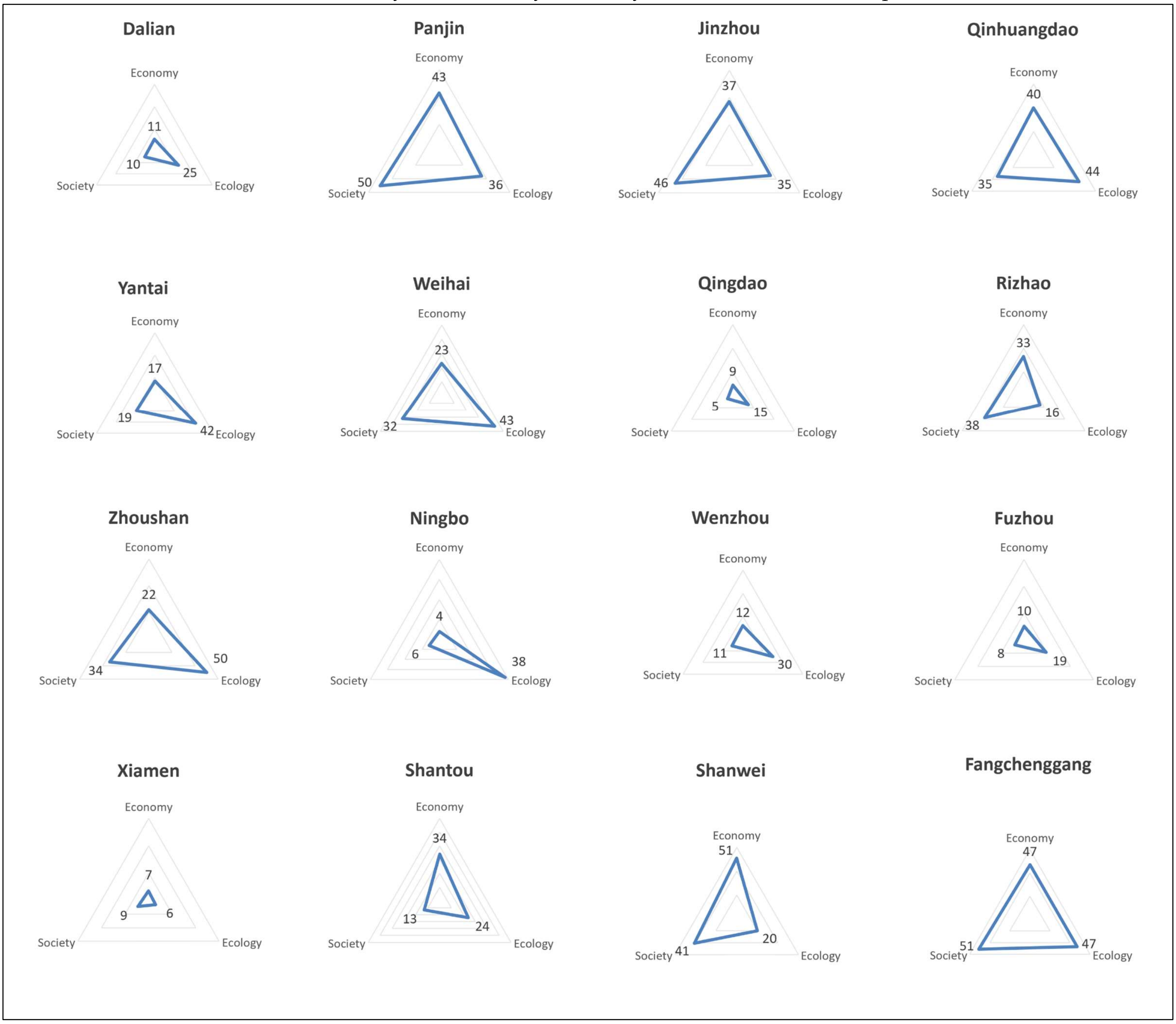


Figure 10. The radar map of ranks of the 16 polit bay cities of 2019 across three dimensions, which include economy, ecology and society. The data used for the ranks in the diagram are derived from the PAC model.

Among the 16 pilot cities of BBRA, Dalian has the highest ranking in the societal component, whereas its lowest ranking is in the ecological category. This trend is similarly observed in Qinhuangdao, Qingdao, Wenzhou, and Fuzhou. Conversely, for Panjin, Jinzhou, Rizhao, and Xiamen, the highest ranking is in the ecological component, while the societal component ranks the lowest. In Yantai, Weihai, Zhoushan, and Ningbo, the economic component holds the highest ranking, with the ecological component being the lowest. In Shantou, the societal component ranks the highest, whereas the economic component ranks the lowest. For Shanwei, the ecological component ranks highest, while the economic component ranks lowest. For Fangchenggang, all three components are ranked lower than the others.

Dalian, Jinzhou, and Panjin are all part of Liaoning Province. Unlike Jinzhou and Panjin, Dalian is situated at the convergence of the Bohai Sea and the Yellow Sea, exhibiting relatively higher scores in the economic, ecological, and social components. Dalian boasts robust economic growth and strong social infrastructure [51]. However, its primary development challenge lies in ecological concerns. To achieve balanced development, Dalian should focus more on sustainable ecological practices, particularly addressing issues related to ecological integrity and pollution emissions [52-54].

Qinhuangdao is located in Hebei Province. Along with Jinzhou and Panjin, Qinhuangdao is part of the Bohai and Bohai Bay Area. These three coastal cities share similar sustainable development challenges, as their economic, ecological, and social sustainability levels are all below the national average. In these three cities, the industrial structure is unreasonable, the pollutants that are emitted into the sea triggers environment problems such as red tide disasters as well as employment and medical care also restrict the sustainable development of their society [55-58]. The inefficient industrial framework results in a reliance on resource consumption that is neither sustainable nor beneficial, and it contributes to ongoing ecological degradation. There is a large number of land-based pollutants entering the sea, which has led to an increase in red tide incidents and a decline in coastal biodiversity. Furthermore, with the rapid pace of urbanization, these cities are grappling with social challenges, including population migration, employment, education, and healthcare access.

Yantai, Weihai, Qingdao, and Rizhao are all situated in the Yellow Sea and the Yellow Sea Bay Area, and they are part of Shandong Province. Among these cities, Qingdao demonstrates relatively higher performance in economic, ecological, and social domains. As a significant port city, Qingdao benefits from a robust industrial base and abundant tourism resources, which have catalyzed its sustainable economic development [59, 60]. Following the BBRA, Qingdao has initiated a series of ecological protection and ecological restoration projects, yielding remarkable outcomes in reducing pollutant emissions and safeguarding the ecological environment [59]. Qingdao also boasts a well-developed public service system, having made substantial improvements in education, healthcare, and other public services through enhanced infrastructure development [60,61]. In contrast, Yantai and Weihai exhibit below-average levels of ecological sustainable development, primarily due to higher pollution emissions and lower ecological quality [61]. Yantai's has subpar social sustainable development is largely attributed to a labour force shortage and limited public awareness regarding sustainable practices. For both Rizhao and Weihai, the low levels of social sustainable development stem not only from labour force shortages and inadequate public awareness but also from deficiencies in education, healthcare, and infrastructure. Rizhao's economic development is hindered by a lack of strength, effectiveness, and openness in its economic initiatives, while Weihai's lower economic performance is mainly due to a scarcity of developmental resources.

Zhoushan, Ningbo, Wenzhou, Fuzhou, and Xiamen are located in the East Sea and Bay Area of China. Zhoushan, Ningbo, and Wenzhou are part of Zhejiang Province, while Fuzhou and Xiamen belong to Fujian Province. Zhoushan is an archipelago, and its levels of economic, ecological, and social sustainable development are all below the average. The lower economic development level in Zhoushan is primarily due to a shortage of development resources. Key factors contributing to the lower level of ecological sustainable development include a significant number of land-based pollutants, reduced ecological quality, diminished coastal biological diversity, and an increased number of high tides. Furthermore, Zhoushan faces social challenges such as inadequate technological support, education, healthcare, and public awareness of sustainable development, all of which hinder its social sustainable development progress. In contrast, for Ningbo, Wenzhou, Fuzhou, and Xiamen, all components are above the average level, except for the ecological component of Ningbo, which is affected by a large number of land-based pollutants and a higher number of high tides.

Shantou, Shanwei, and Fangchenggang are situated in the South China Sea and Bay Area. Shantou and Shanwei are part of Guangdong Province, while Fangchenggang is located in Guangxi Province. The relatively lower level of economic development in Shantou, Shanwei, and Fangchenggang can be attributed to various factors, including weaker economic strength, efficiency, and openness, as well as a lack of development resources. In the cases of Shanwei and Fangchenggang, limited social sustainable development is primarily due to a shortage of labor force, public awareness, and deficiencies in education, healthcare, and infrastructure. Additionally, Fangchenggang faces ecological sustainability challenges, primarily due to pollution emissions, particularly the low sewage treatment rate.

Chinese bay cities are currently experiencing fast paced industrialization and urbanization, primarily driven by sectors such as manufacturing, trade, and port logistics. These cities benefit from advantageous geographic locations, a considerable labor force, and robust policy support. However, they also encounter challenges including environmental pollution, limited resources, and disparities in social development. Dalian, Qingdao, and Xiamen have accomplished relatively high ranking and balanced sustainable development after BBRA, largely attributable to their strategic development policies, well-defined planning initiatives, and effective urban management practices [4, 6, 53]. These cities have established clear objectives and measures for marine environmental protection through the utilization of national special funds of BBRA and local dedicated plans, including Dalian's "Marine Ecological Environment Protection Regulations," Qingdao's Jiaozhou Bay Management Special Plan, and Xiamen's Yuandang Lake Comprehensive Remediation Plan [16, 54, 60]. Furthermore, they emphasize the integration of ecological restoration with economic development, fostering green industries such as marine ranch construction and ecotourism [4, 16, 54]. This approach facilitates a mutually beneficial relationship between ecological conservation and economic advancement. Additionally, the adoption of technological innovations and ecological compensation mechanisms has enhanced governance efficiency and increased social engagement [60]. The collective impact of these policies, strategies, and initiatives has established a robust foundation for the sustainable development of these cities.

In comparison, global bay cities like San Francisco, New York, and Tokyo have progressed into post-industrial economies characterized by finance, technology, and high-end services [62,63]. These cities are recognized for their innovation, sustainability, and overall quality of life, yet they face challenges such as high living costs, restricted space for expansion, and social inequalities.

As of now, BBRA has been in effect for eight years. During this period, various pilot cities have implemented a series of rectification measures, including the renovation and repair of coastal areas, the protection of natural shorelines, the planting and restoration of coastal wetland vegetation, pollution control, the enhancement of bay water quality, marine ecological monitoring, and the promotion of sustainable development within the marine economy [17, 30, 61, 62]. However, after eight years, the development levels among the 16 pilot cities vary significantly. The sustainable development of these bay cities has been constrained by various factors.

In the future, Chinese bay cities should prioritize economic diversification by transitioning from heavy industry to high-tech and service-oriented sectors. Investment in innovation and the establishment of robust research and development ecosystems, along with the cultivation of global partnerships to attract talent and technology, are essential. Moreover, sustainable development initiatives should be emphasized through the implementation of stricter environmental regulations, advancements in green technologies, and enhanced waste management practices to tackle pollution and resource limitations. Enhancing infrastructure, promoting social equity, and fostering global integration should be prime objectives for Chinese bay cities. Key areas of focus include upgrading transportation and digital networks, addressing income inequality, and improving access to education and healthcare. By positioning themselves as global hubs for business and innovation, these cities can achieve balanced and high-quality growth while drawing lessons from the successes and challenges of leading bay cities around the world. In the future, local governments should address these shortcomings to achieve sustainable development.

5. Conclusions

It is vital to recognize that bay area's function as integrated ecosystems, by extracting insights from the successes and challenges of leading bay cities globally, it is evident that addressing issues solely within the bays will not fully resolve the ecological challenges. Following the implementation of the BBRA, the sustainable development levels of 16 coastal cities have not changed very much and certain cities continue to face challenges related to uneven development of economy, ecology and society. In particular, Ningbo requires enhancements in its ecological sustainable development level, while Yantai needs to focus on improvements in both ecological and social sustainability. Rizhao and Shanwei should work on strengthening their economic and ecological sustainable development levels. Additionally, Shantou must enhance its ecological sustainability. The situations in Panjin, Jinzhou, Qinghuangdao, Weihai, Zhoushan, and Fangchenggang are more concerning, as their sustainable development levels across economic, ecological, and societal dimensions are below average. To promote balanced sustainable development among these bay cities, governments should consider the unique developmental characteristics (shortcomings of economy, ecology or society) of each city during the implementation of the BBRA.

Furthermore, in future research, it is meaningful to explore the dynamic changes in sustainable development level within bay cities, particularly in light of the ongoing implementation of the BBRA. It is essential to investigate the factors that contribute to significant changes over time and across different regions. In this regard, the SPM-DID method [64, 65] for evaluating policy impacts may be an appropriate approach.

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References

1. Costa, C.M.; Santos, A.T. Building multiscalar sustainable ocean governance: How do global perspectives interact with the Portuguese national approach? *Heliyon* 2024, *10*(7), e28233. DOI: 10.1016/j.heliyon.2024.e28233.
2. Fasoulis, I. Governing the oceans: A study into Norway's ocean governance regime in the wake of United Nations Sustainable Development Goals. *Reg. Stud. Mar. Sci.* 2021, *48*, 101983. DOI: 10.1016/j.rsma.2021.101983.
3. Mao, Z.; Zhang, Z. Taking the "UN Decade of Ocean Science for Sustainable Development" as an opportunity to help build a "Community with a Shared Future between China and Pacific Island Countries". *Mar. Policy* 2024, *159*, 105943. DOI: 10.1016/j.marpol.2023.105943.
4. Wan, L.; Wang, X.H.; Wu, W. Assessment of coastal eco-environmental sustainable development under multiple pressures: A case study of Jiaozhou Bay, China. *J. Environ. Manag.* 2024, *363*, 121230. DOI: 10.1016/j.jenvman.2024.121230.
5. Chen, C.; Yao, Z.; Wen, Z.; Sheng, N. Impact of city characteristics on its phosphorus metabolism in the bay area: A comparative analysis of cities in the Greater Bay Area of China. *J. Clean. Prod.* 2021, *286*, 124925. DOI: 10.1016/j.jclepro.2020.124925.
6. Chen, P.; Chen, H.; Chen, K.; Ke, H.; Cai, M. Quantitative assessment of the response of seawater environmental quality to marine protection policies under regional economic development—A case study of Xiamen Bay, China. *Mar. Environ. Res.* 2023, *186*, 105934. DOI: 10.1016/j.marenvres.2023.105934.
7. Li, Q.; Wu, J.; Su, Y.; Zhang, C.; Wu, X.; Wen, X.; Huang, G.; Deng, Y.; Lafortezza, R.; Chen, X. Estimating ecological sustainability in the Guangdong-Hong Kong-Macao Greater Bay Area, China: Retrospective analysis and prospective trajectories. *J. Environ. Manag.* 2022, *303*, 114167. DOI: 10.1016/j.jenvman.2021.114167.
8. Scott, M. The San Francisco Bay Area: A Metropolis in Perspective. *Univ. Calif. Press* 1985, *Berkeley, CA*, 1–384. DOI: 10.1525/9780520323933.
9. Walker, R.; Schafran, A. The strange case of the Bay Area. *Environ. Plan. A* 2015, *47*, 10–29. DOI: 10.1068/a.46277.
10. Tian, Z.; Zhou, B. Sustainable future: A systematic review of city-region development in bay areas. *Front. Sustain. Cities* 2023, *5*, 1052568. DOI: 10.3389/frsc.2023.1052568.
11. Toz, A.C.; Koseoglu, B.; Sakar, C. Numerical modelling of oil spill in New York Bay. *Arch. Environ. Prot.* 2016, *42*(4), 19–32. DOI: 10.1515/aep-2016-0037.
12. Rose, S. Tokyo: Globalization and the postmodern experience. *J. Glob. Media Stud.* 2017, *21*, 33–39.

13. Zhang, X.; Ramos, B.A.; Cladera, J.R. Research on key influencing factors of ecological environment quality in Barcelona Metropolitan Region based on remote sensing. *Remote Sens.* 2024, *16*(24), 4735.
14. Couto, E.D.A.; Gregorio, L.T.D.; Valle, G.; Haddad, A.N.; Soares, C.A.P. ISO 37120 sustainable development indicators: Rio de Janeiro and the Latin American scenario. *Ambiente Soc.* 2023, *26*, e01322.
15. Wan, L.; Wang, X.H.; Gao, G.D.; Wu, W. Evaluation of the coordinated development level in the coastal eco-environmental complex system: A case study of Jiaozhou Bay, China. *Mar. Environ. Res.* 2024, *198*, 106515. DOI: 10.1016/j.marenvres.2024.106515.
16. Qian, L.; Wang, F.; Cao, W.; Ding, S.; Cao, W. Ecological health assessment and sustainability prediction in coastal area: A case study in Xiamen Bay, China. *Ecol. Indic.* 2023, *148*, 110047. DOI: 10.1016/j.ecolind.2023.110047.
17. Wang, M.; Wang, X.H. Introduction to the national blue bay remediation action plan in China. *Aust. J. Marit. Ocean Aff.* 2018, *10*(4), 256–262. DOI: 10.1080/18366503.2018.1534522.
18. Guo, T.; Fang, Q.; Jiang, X.; Zacarias, W.B.M.; Ioris, A.A.R. Evaluation of China's marine sustainable development based on PSR and SDG14: Synergy-tradeoff analysis and scenario simulation. *Environ. Impact Assess. Rev.* 2025, *111*, 107753. DOI: 10.1016/j.eiar.2024.107753.
19. Hua, T.; He, L.; Jiang, Q.; Chou, L.-M.; Xu, Z.; Yao, Y.; Ye, G. Spatio-temporal coupling analysis and tipping points detection of China's coastal integrated land-human activity-ocean system. *Sci. Total Environ.* 2024, *914*, 169981. DOI: 10.1016/j.scitotenv.2024.169981.
20. Wang, W.; Huo, Y.; Lin, C.; Lian, Z.; Wang, L.; Liu, Y.; Sun, X.; Chen, J.; Lin, H. Occurrence, accumulation, ecological risk, and source identification of potentially toxic elements in multimedia in a subtropical bay, Southeast China. *J. Hazard. Mater.* 2024, *476*, 135110. DOI: 10.1016/j.jhazmat.2024.135110.
21. Shepard, W. Ghost cities of China: The story of cities without people in the world's most populated country; *Bloomsbury Publishing*, 2015; pp. 15–19.
22. Delgado, L.E.; Sandoval, C.; Quintanilla, P.; Quiñones-Guerrero, D.; Marín, I.A.; Marín, V.H. Including traditional knowledge in coastal policymaking: Yaldad bay (Chiloé, southern Chile) as a case study. *Mar. Policy* 2022, *143*, 105181. DOI: 10.1016/j.marpol.2022.105181.
23. Sinfuego, K.S.; Buot, I.E. Mangrove zonation and utilization by the local people in Ajuy and Pedada Bays, Panay Island, Philippines. *J. Mar. Isl. Cult.* 2014, *3*(1), 1–8. DOI: 10.1016/j.imic.2013.11.002.
24. Piwowarczyk, J.; Wróbel, B. Determinants of legitimate governance of marine Natura 2000 sites in a post-transition European Union country: A case study of Puck Bay, Poland. *Mar. Policy* 2016, *71*, 310–317. DOI: 10.1016/j.marpol.2016.01.019.
25. Qin, X.; Sun, C.; Zou, W. Quantitative models for assessing the human-ocean system's sustainable development in coastal cities: The perspective of metabolic-recycling in the Bohai Sea Ring Area, China. *Ocean Coast. Manag.* 2015, *107*, 46–58. DOI: 10.1016/j.ocecoaman.2015.02.003.
26. Yao, Y.; Zhang, S.; Gao, S.; Lu, J.; Fu, G. Release capacity of Portunus trituberculatus enhancement in coastal waters: A case study in the marine ranching area of Haizhou bay. *Estuar. Coast. Shelf Sci.* 2024, *299*, 108684. DOI: 10.1016/j.ecss.2024.108684.
27. Zhong, J.; Wu, X.; Wu, S.; Wang, Y.; Peng, S. Regional patterns and factors analysis of the sustainable development of benefits in China's national-level marine ranching: Based on shellfish and algae. *J. Clean. Prod.* 2024, *467*, 142994. DOI: 10.1016/j.jclepro.2024.142994.
28. Bank, W. Monitoring environmental progress: A report on work in progress; *The World Bank*, 1995.
29. Guijt, I.; Moiseev, A. Resource kit for sustainability assessment. *IUCN*, Gland, Switzerland and Cambridge, UK, 2001.
30. Zhou, D.; Xu, J.C.; Lin, Z.L. Conflict or coordination? Assessing land use multi-functionalization using production-living-ecology analysis. *Sci. Total Environ.* 2017, *577*, 136–147. DOI: 10.1016/j.scitotenv.2016.10.143.
31. Fries, A.S.; Coimbra, J.P.; Nemazie, D.A.; Summers, R.M.; Azevedo, J.P.S.; Filoso, S.; Newton, M.; Gelli, G.; de Oliveira, R.C.; Pessoa, M.A.R.; et al. Guanabara Bay ecosystem health report card: Science, management, and governance implications. *Reg. Stud. Mar. Sci.* 2019, *25*, 100474. DOI: 10.1016/j.rsma.2018.100474.
32. Evans, K.; Bax, N.J.; Smith, D.C. Enhancing the robustness of a national assessment of the marine environment. *Mar. Policy* 2018, *98*, 133–145. DOI: 10.1016/j.marpol.2018.08.011.
33. Sun, T.; Lin, W.; Chen, G.; Guo, P.; Zeng, Y. Wetland ecosystem health assessment through integrating remote sensing and inventory data with an assessment model for the Hangzhou Bay, China. *Sci. Total Environ.* 2016, *566*, 627–640. DOI: 10.1016/j.scitotenv.2016.05.028.
34. Sun, B.; Lei, Y.; Cui, L.; Li, W.; Kang, X.; Zhang, M. Addressing the modelling precision in evaluating the ecosystem services of coastal wetlands. *Sustainability* 2018, *10*(4), 1136. DOI: 10.3390/su10041136.

35. Shi, L.; Han, L.; Yang, F.; Gao, L. The evolution of sustainable development theory: Types, goals, and research prospects. *Sustainability* **2019**, *11*, 7158. DOI: 10.3390/su11247158.
36. Ma, L.; Wang, Q.; Zhu, Y.; Liu, Z. The impact and mechanism of new-type urbanization on high-quality forestry development: A case study of the Yellow River Basin in China. *Diversity* **2025**, *17*, 7.DOI: 10.3390/d17010007.
37. Chen, J.; Tang, X. Towards sustainable cities: Studying evaluation index of water environment carrying capacity. *Water Resour. Manage.* **2023**, *37*, 5919–5938. DOI: 10.1007/s11269-023-03635-5.
38. Santos, T.; de Assis Cabral, J.; dos Santos Lima, P. V.; de Andrade Santos, M. Rio de Janeiro's ocean economy as a key vector for sustainable development in Brazil. *Marine Policy* **2024**, *159*, 105876. 10.1016/j.marpol.2023.105876.
39. Xu, D.; Yang, F.; Yu, L.; et al. Quantification of the coupling mechanism between eco-environmental quality and urbanization from multisource remote sensing data. *J. Clean. Prod.* **2021**, *128948*. DOI: 10.1016/j.jclepro.2021.128948.
40. Lamichhane, S.; Eğilmez, G.; Gedik, R.; Bhutta, M.K.S.; Erenay, B. Benchmarking OECD countries' sustainable development performance: A goal-specific principal component analysis approach. *J. Clean. Prod.* 2021, *287*, 125040. DOI: 10.1016/j.jclepro.2020.125040.
41. Tan, F.; Lu, Z. Assessing regional sustainable development through an integration of nonlinear principal component analysis and Gram Schmidt orthogonalization. *Ecol. Indic.* 2016, *63*, 71–81. DOI: 10.1016/j.ecolind.2015.11.018.
42. Palit, T.; Bari, A.B.M.M.; Karmaker, C.L. An integrated principal component analysis and interpretive structural modeling approach for electric vehicle adoption decisions in sustainable transportation systems. *Decis. Anal. J.* 2022, *4*, 100119. DOI: 10.1016/j.dajour.2022.100119.
43. Martins, M.S.; Kalil, R.M.L.; Rosa, F.D. Sustainable neighbourhoods: Applicable indicators through principal component analysis. *Proc. Inst. Civ. Eng. - Urban Des. Plan.* 2021, *174*(1), 25–36. DOI: 10.1680/jurdp.20.00058.
44. Wang, C.; Wang, L.; Zhai, J.; Feng, T.; Lei, Y.; Li, S.; Liu, Y.; Liu, Y.; Hu, Z.; Zhu, K.; et al. Assessing progress toward China's subnational sustainable development by Region Sustainable Development Index. *Sustain. Horiz.* 2024, *11*, 100099. DOI: 10.1016/j.horiz.2024.100099.
45. Zheng, Y.; Wu, J.; Du, S.; Sun, W.; He, L. Unrevealing the coupling coordination degree between atmospheric CO2 concentration and human activities from geospatial and temporal perspectives. *Sci. Total Environ.* 2024, *942*, 173691. DOI: 10.1016/j.scitotenv.2024.173691.
46. Yuan, D.; Du, M.; Yan, C.; Wang, J.; Wang, C.; Zhu, Y.; Wang, H.; Kou, Y. Coupling coordination degree analysis and spatiotemporal heterogeneity between water ecosystem service value and water system in Yellow River Basin cities. *Ecol. Inform.* 2024, *79*, 102440. DOI: 10.1016/j.ecoinf.2023.102440.
47. Salem, N.; Hussein, S. Data dimensional reduction and principal components analysis. *Procedia Comput. Sci.* **2019**, *163*, 292–299. DOI:10.1016/j.procs.2019.12.111.
48. Han, X.; Wang, Y.; Yu, W.; Xia, X. Coupling and coordination between green finance and agricultural green development: Evidence from China. *Financ. Res. Lett.* 2023, *58*, 104221. DOI: 10.1016/j.frl.2023.104221.
49. Hu, Z.; Kumar, J.; Qin, Q.; Kannan, S. Assessing the coupling coordination degree between all-for-one tourism and ecological civilization: Case of Guizhou, China. *Environ. Sustain. Indic.* 2023, *19*, 100272. DOI: 10.1016/j.indic.2023.100272.
50. Li, Y.; Zhou, B. Coupling coordination degree measurement and spatial characteristics analysis of green finance and technological innovation - Empirical analysis based on China. *Heliyon* 2024, *10*(13), e33486. DOI: 10.1016/j.heliyon.2024.e33486.
51. Liu, J.; Cheng, Z.; Yi, P.; Li, W.; Wang, L. Predictive evaluation of city sustainability based on benchmarking method: A case study of 34 cities in northeastern China. *Sustain. Cities Soc.* 2024, *112*, 105627. DOI: 10.1016/j.scs.2024.105627.
52. Han, G.; He, M.; Du, Z.; Wei, N.; Luo, H. Characterization and source apportionment of water-soluble ion pollution in PM10 of typical cities in northern China. *iScience* 2024, *27*(10), 110891. DOI: 10.1016/j.isci.2024.110891.
53. Zhang, X.; Li, X.; Liu, H.; Song, Y.; Gao, M. Research on urban thermal environment differentiation based on functional zones: Take four districts of Dalian as an example. *Urban Clim.* 2024, *58*, 102152. DOI: 10.1016/j.uclim.2024.102152.
54. Lyu, L.; Sho, K.; Zhao, H.; Song, Y.; Uchiyama, Y.; Kim, J.; Sakai, T. Construction, assessment, and protection of green infrastructure networks from a dynamic perspective: A case study of Dalian City, Liaoning Province, China. *Urban For. Urban Green.* 2024, *101*, 128545. DOI: 10.1016/j.ufug.2024.128545.
55. Gu, R.; Xu, Y.; Li, Z.; Jian, S.; Tu, J.; He, S.; Sun, J. PSR-FCCLP model based total maximum allocated loads optimization of TN and TP in Bohai Bay. *Mar. Pollut. Bull.* 2022, *185*, 114249. DOI: 10.1016/j.marpolbul.2022.114249.
56. Zhang, L.; Li, G.; Ding, D.; Qiao, L.; Wang, J.; Li, M.; Xing, L.; Liu, S.; Sun, J.; Liu, M. Coastline eco-efficiency and sustainable development of Bohai Rim cities. *Ocean Coast. Manag.* 2023, *243*, 106769. DOI: 10.1016/j.ocecoaman.2023.106769.

57. Zhang, T.; Niu, X. Analysis on the utilization and carrying capacity of coastal tidal flat in bays around the Bohai Sea. *Ocean Coast. Manag.* 2021, *203*, 105449. DOI: 10.1016/j.ocecoaman.2020.105449. 861 862
58. Wu, J.; Li, B.; Zhang, L.; Qu, Y. Spatio-temporal evolution and adaptive cycle of marine economy resilience in Bohai Rim Region. *Reg. Stud. Mar. Sci.* 2024, *80*, 103893. DOI: 10.1016/j.rsma.2024.103893. 863 864
59. Fang, X.; Shi, X.; Phillips, T.K.; Du, P.; Gao, W. The Coupling Coordinated Development of Urban Environment Towards Sustainable Urbanization: An Empirical Study of Shandong Peninsula, China. *Ecol. Indic.* 2021, *129*, 107864. DOI: 10.1016/j.ecolind.2021.107864. 865 866 867
60. Ge, Y.; Jia, W.; Zhao, H.; Xiang, P. A framework for urban resilience measurement and enhancement strategies: A case study in Qingdao, China. *J. Environ. Manag.* 2024, *367*, 122047. DOI: 10.1016/j.jenvman.2024.122047. 868 869
61. Wang, M.; Wang, X.H.; Zhou, R.; Zhang, Z. An indicator framework to evaluate the Blue Bay Remediation Project in China. *Reg. Stud. Mar. Sci.* 2020, *38*, 101349. DOI: 10.1016/j.rsma.2020.101349. 870 871
62. Pinto, P. J.; Kondolf, G. M.; Wong, P. L. R. Adapting to sea level rise: Emerging governance issues in the San Francisco Bay Region. *Environmental Science & Policy* **2018**, *90*, 28-37. DOI: https://doi.org/10.1016/j.envsci.2018.09.015. 872 873
63. Zhang, Q.; Guan, Y.; Wu, X.; Zhang, J.; Li, R.; Lin, K.; Wang, Y. Revealing the dynamic effects of land cover change on land surface temperature in global major bay areas. *Building and Environment* **2025**, *267*, 112266. DOI: https://doi.org/10.1016/j.buildenv.2024.112266. 874 875 876
64. Luo, C.; Qiang, W.; Lee, H. F. Does the low-carbon city pilot policy work in China? A company-level analysis based on the PSM-DID model. *J. Environ. Manage.* **2023**, *337*, 117725. DOI: 10.1016/j.jenvman.2023.117725. 877 878
65. Duan, Z.; Lee, S.; Lee, G. Evaluation of the effect of a low-carbon green city policy on carbon abatement in South Korea: A city-level analysis based on PSM-DID and LSA models. *Ecol. Indic.* **2024**, *158*, 111369. DOI: 10.1016/j.ecolind.2023.111369. 879 880