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Monitoring and Evaluation of Coastal Ecological Carrying Capacity in the Context of Sustainable Development: A Case Study of Shandong Province

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Abstract: The research on coastal ecological carrying capacity holds great significance for the sustainable development of coastal areas and is a focal point of the United Nations Sustainable Development Goals (SDGs). This study coupled multi-source data and ecological analysis models to construct a multi-level evaluation system and analysis method for the coastal ecological carrying capacity of Shandong Province so as to realize the dynamic monitoring and evaluation of the coastal ecological carrying capacity of Shandong Province from 2010 to 2020. The results indicated: (1) The ecological carrying capacity of the coastal zone in Shandong Province showed a "U"-shaped development trend, with 2016 being a turning point. (2) The economic development–social support system gradually became the main force driving the overall improvement of coastal ecological carrying capacity. (3) The system coupling coordination degree of ecological carrying capacity in the coastal areas of Shandong Province showed a trend of first decreasing and then increasing, with a high level of internal coupling coordination of carrying capacity. (4) Per capita GDP, environmental protection investment, per capita water resources, and other indicators were the main factors driving the changes in the ecological carrying capacity of the coastal zone. This study aims to provide methodological reference and data support for coastal ecosystem monitoring, assessment, and climate change response.

Keywords: coastal zone; ecological carrying capacity; monitoring and evaluation; contribution degree; coupling coordination degree; sustainable development

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1. Introduction

The coastal zone, as a transitional zone between land and sea, possesses both marine and terrestrial environmental characteristics, serving as a frontier for achieving integrated sustainable development of land and sea [1–4]. The coastal zone is also considered to be an important focus for the study of sustainable development [5–8]. The coastal zone of Shandong Province plays an important role in China's economic development and ecological protection. However, the dual effects of human activities and climate change make the natural resources and ecological environment of the Shandong coastal zone face great challenges [9,10]. In terms of human activities, the acceleration of industrialization and urbanization has led to the deterioration of marine water quality, the fragmentation of the coastal landscape, and the loss of coastal biodiversity [11]. At the same time, sea level rise, marine disasters, and climate warming lead to frequent phenomena such as coastal erosion, soil salinization, and groundwater pollution, thus damaging the carrying capacity of coastal ecosystems and seriously hindering sustainable development [12,13]. Therefore, ensuring the stability of the coastal zone's ecological environment while supporting sustainable socio-economic development has become a pressing issue for scholars, government agencies, and other stakeholders [14,15].

Human understanding of "carrying capacity" has evolved over several centuries, with the widely accepted definition of carrying capacity being the maximum biomass or number of individuals that an ecosystem can support under specific environmental conditions [16,17]. In the mid-20th century and beyond, the subjects of carrying capacity have become increasingly diverse, leading to concepts such as population carrying capacity, land comprehensive carrying capacity, resource–environment carrying capacity, and urban comprehensive carrying capacity. For instance, population carrying capacity is defined as the maximum population that a natural system in a certain region can sustain while maintaining natural, social, and economic stability [18,19]. Diansheng [20] defined resource–environment carrying capacity as the capacity of the resource–environment to support a certain population size and corresponding social–economic total amount within different scale regions under the premise of ensuring the benign circulation of natural resources such as atmospheric resources, water resources, and marine biological resources. Cui et al. [21] defined land comprehensive carrying capacity as the threshold of the maximum human activities that an ecological–economic–social coupled system, with land as the carrier, can withstand under certain conditions. Ecological carrying capacity is a derivative of this concept. For example, Wu and Hu [22] defined comprehensive ecological carrying capacity as the ability of ecosystems to provide resources and environments for social and economic development. Wu et al. [23] defined ecological carrying capacity as the ability of the regional ecological environment to support sustainable social development while ensuring the coordinated development of the ecological environment and the social–economic system. In summary, coastal zone ecological carrying capacity (CECC) manifests as the maximum capacity of the ecological environment to support or provide for sustainable social development, serving as a crucial link between regional development and environmental protection.

However, due to the complex environmental characteristics of coastal zones, dynamic monitoring and evaluation of CECC coupled with multi-source data and ecological analysis models has become a major difficulty [24]. In terms of CECC monitoring, quantitative methods for assessing ecological carrying capacity include the Ecological Footprint method [25,26], the "Pressure–State–Response (PSR)" framework model [27], the State Space model [28], and multidimensional evaluation indicator systems [29]. Among them, the combination of a multidimensional evaluation index system and state–space model can make full use of multi-source data to achieve efficient monitoring of CECC [30], which is also the quantitative method of CECC in this study. In terms of CECC evaluation, CECC evaluation research focuses on judging the load state or maximum carrying capacity of coastal ecosystems [22,31]. The exploration of the coupling relationship between the coastal pressure system, the coastal resource system, and the socio-economic system and the exploration of the driving mechanism of CECC change can effectively solve the contradiction between man and nature and optimize the allocation and utilization of coastal resources [32,33]. Unfortunately, there is a lack of research on the above content. Therefore, this study combined multi-source data and an ecological analysis model to explore the dynamic monitoring and evaluation of CECC in Shandong Province.

Taking the coastal area of Shandong Province as an example, this study aims to solve a scientific problem: how can multi-source data and an ecological analysis model be combined to realize dynamic monitoring and evaluation of CECC? Therefore, the main research contents of this paper are as follows: (1) Based on multi-source data, a multi-level CECC evaluation system for Shandong Province was constructed, and the coastal ecological carrying capacity of Shandong Province was calculated by a state–space model. (2) The contribution degree model was used to analyze the contribution degree of CECC subsystems to CECC. (3) Using the system coupling degree model to analyze the coupling coordination degree between the carrying capacity subsystems. (4) Exploring the driving factors of the change in CECC with the help of geographical detectors.

2. Study Method

2.1. Study Region

The study area covers the coastal regions of Shandong Province, including Binzhou City, Dongying City, Weifang City, Yantai City, Weihai City, Qingdao City, and Rizhao City (Figure 1). The longitude range is from 117° E to 121° E, and the latitude range is from 35° N to 39° N. The coastal areas of Shandong Province are situated between the Yellow Sea and the Bohai Sea, facing the Liaodong Peninsula across the Bohai Strait. The study area is surrounded by sea on three sides and has a temperate monsoon climate with four distinct seasons. The terrain is flat, dominated by plains, hills, and mountains. The main industries include manufacturing, marine industry, and port transportation. The coastal areas of the study area are rich in natural resources, such as tidal flats, minerals, and islands. In addition, the study area has 51 excellent harbor sites suitable for constructing deep-water berths, providing favorable conditions for the vigorous development of the marine economy in Shandong Province.

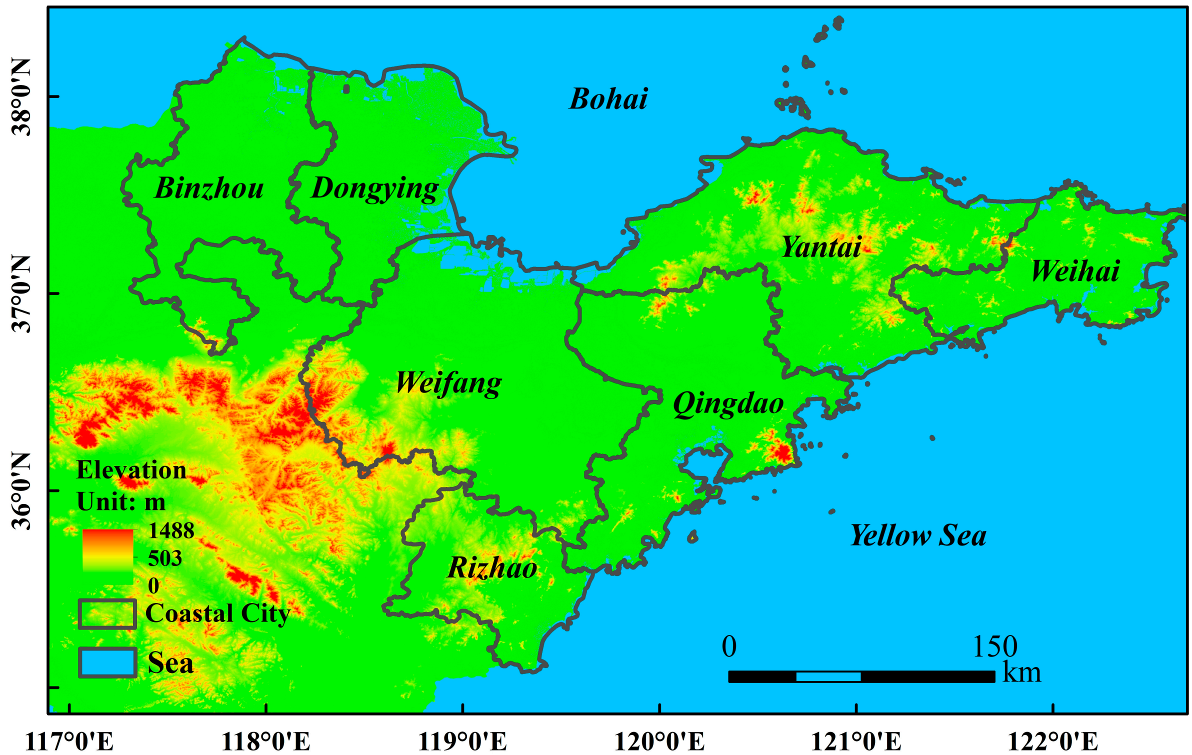

Figure 1. The study area.

In the past decade, Shandong Province has actively responded to China's strategy of becoming a maritime power. By 2023, its marine gross domestic product (GDP) exceeded 1.7 trillion yuan, ranking second in the country. However, the ecological vulnerability of the coastal areas in Shandong Province has been declining [34], and the ecological environment is facing significant pressure. Issues such as high fragmentation of coastal ecological landscapes, water scarcity, and intensified shoreline development are becoming more prominent. Therefore, the assessment and analysis of CECC in Shandong Province are crucial.

2.2. Data Source

This study constructed a CECC assessment system for the coastal areas of Shandong Province, including three criterion layers (pressure layer, state layer, and response layer), four primary indicators (environmental pressure, population pressure, coastal resources, and economic development–social support), and 20 secondary indicators (Table 1). The data sources for these indicators include the statistical yearbooks of Shandong Province and various cities, a municipal statistical bulletin of national economic and social development, a bulletin on the state of China's marine ecological environment, and remote sensing image data (Table 2).

Table 1. Evaluation index system of CECC.

Criterion Layers	Factor Layers	No.	Indicators	Attributes	Units
Pressure	Environmental pressure	X1	Industrial wastewater discharge	Negative	10^4 ton
		X2	Land use intensity	Negative	/
		X3	Coastline utilization degree	Negative	/
		X4	Million GPD energy consumption	Negative	tce/10^4 yuan
	Population Pressure	X5	Population density	Negative	capita/km^2
		X6	Passenger traffic	Negative	10^4 capita
State	Coastal resource	X7	Per capita wetland area	positive	m^2/capita
		X8	Net primary productivity of vegetation	positive	gC/m^2
		X9	Fishery resources	positive	10^4 ton
		X10	Per capita water resources	positive	m^3/capita
		X11	Vegetation coverage	positive	%
		X12	Nearshore water quality	positive	/
Response	Economic development–Social support	X13	Per capita GDP	Negative	10^4 yuan/capita
		X14	Port throughput	Negative	10^4 ton
		X15	Urbanization rate	Negative	%
		X16	Marine economy	positive	10^8 yuan
		X17	Social security and employment input	positive	10^4 yuan
		X18	Educational input	positive	10^4 yuan
		X19	Scientific and technological input	positive	10^4 yuan
		X20	Environmental protection input	positive	10^4 yuan

Table 2. Data type and resource.

Indicators	Data Type	Data Period	Data Source
X1, X4, X5, X6, X9, X10, X13, X15, X17, X18, X19 and X20	txt	2010–2020	«Shandong Statistical Yearbook»
X14 and X16	txt	2010–2020	«Municipal Statistical Bulletin of national economic and social development»
X12	txt	2010–2020	«Bulletin on the state of China's Marine ecological environment»
X2 and X7	Vector	2010–2020	https://www.resdc.cn/DOI/DOI.aspx?DOIID=54 (accessed on 2 July 2018)
X3	Grid	2010–2020	Extraction from Landsat8 OLI
X8	Grid	2005–2015	https://doi.org/10.3974/geodb.2019.03.02.V1
X11	Grid	2010–2020	https://doi.org/10.1016/j.rse.2019.111395.

2.3. Data Processing Method

Firstly, 20 indicators are standardized according to positive and negative attributes, then the weight of each indicator is determined according to the entropy method and analytic hierarchy process, and finally, the state space model is used to calculate the comprehensive ecological carrying capacity of the coastal zone. The specific research route is shown in Figure 2.

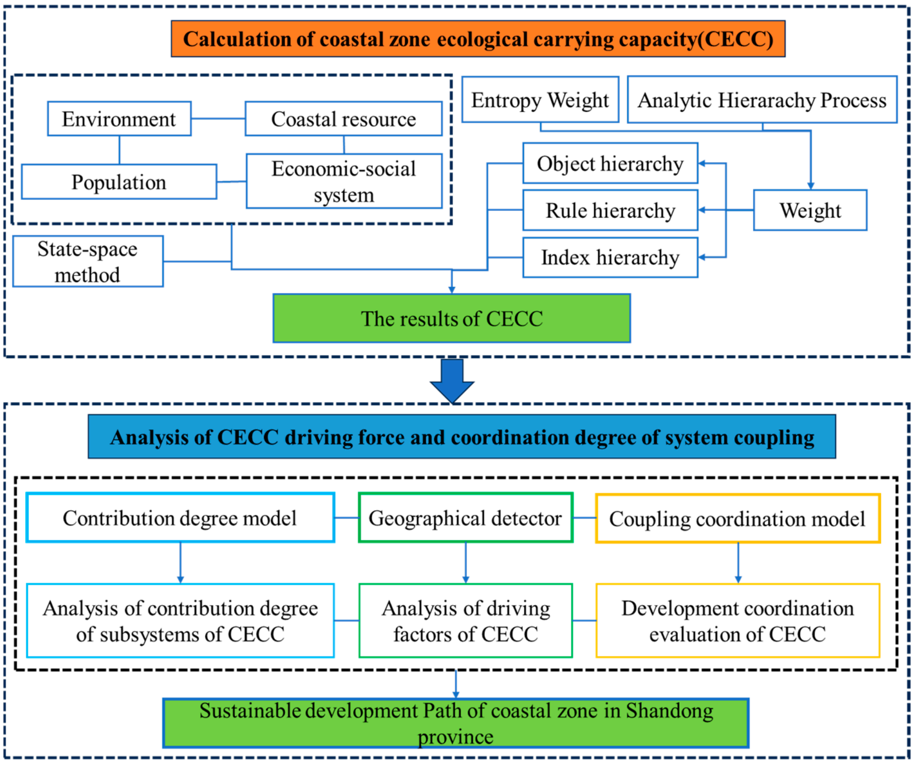

Figure 2. Research route.

2.3.1. Index Standardization

The adoption of range standardization for each indicator effectively eliminates the influence of indicator dimensions [35], ensuring that all indicators are normalized within the range of [0, 1]. Taking into account the positive/negative impact of indicators on the research content, standardization is carried out according to Formulas (1) and (2).

$$\text{For positive indicators}: \ X_{ij} = \frac{N_{ij} - N_{iMin}}{N_{iMax} - N_{iMin}} \tag{1}$$

$$\text{For positive indicators}: \ X_{ij} = \frac{N_{iMax} - N_{ij}}{N_{iMax} - N_{iMin}} \tag{2}$$

where i represents the number of years for indicators, j denotes the number of indicators, X_{ij} is the standardized result of the indicator, N_{ij} represents the actual value of each indicator in the corresponding year, and N_{iMin} and N_{iMax}, respectively, denote the minimum and maximum values of a certain indicator in the year i.

2.3.2. Weight Calculation

The determination of weights is a crucial step to ensure the quantification and objectivity of coastal ecological carrying capacity assessment. The entropy method, based on the concept of information entropy, calculates the weights of indicators by computing the entropy of each indicator, providing an objective weight calculation method [36,37]. The calculation principle is defined in Equations (3)–(5). Analytic Hierarchy Process (AHP) is a quantitative analysis method for multi-criteria decision-making with a certain degree of subjectivity. It involves constructing a hierarchy structure, establishing judgment matrices, calculating weights, and consistency testing to assist decision-makers in decision-making and evaluation [38–40]. Therefore, the combination of the entropy method and the analytic hierarchy process can obtain more scientific weights. The combination of them works as follows: Firstly, the weights W_{j1} and W_{j2} of each index are independently calculated by using the analytic hierarchy process and the entropy method, respectively. Then, these two groups of weights are averaged to obtain the final weights of each index. Considering the regional characteristics, we calculate the corresponding weights of all coastal cities in Shandong Province.

$$P_{ij} = \frac{X_{ij}}{\sum_{i=1}^{n} X_{ij}} \ (i = 1, 2, \cdots, n;\ j = 1, 2, \cdots m) \tag{3}$$

$$E_j = -\ln(n)^{-1} \sum_{i=1}^{n} P_{ij} \ln P_{ij} \ \left(P_{ij} = 0,\ \ln P_{ij} = 0\right) \tag{4}$$

$$W_{j2} = \frac{1 - E_j}{\sum_{j=1}^{m} (1 - E_j)} \tag{5}$$

In the equation, P_{ij} represents the proportion of the j-th indicator, X_{ij} is the standardized result of the indicator, E_j represents the information entropy of the j-th indicator, and W_{j2} reflects the weight of each indicator in the entropy method. The final weight of each indicator is defined as the average of the results from the AHP and the entropy method, i.e., $W_j = 0.5 \times (W_{j1} + W_{j2})$. The results are presented in Table 3.

Table 3. Weights of indicators in seven coastal cities.

Indicators	Weight						
	Qingda	**Dongying**	**Yantai**	**Weifang**	**Weihai**	**Rizhao**	**BinZhou**
X1	0.03	0.027	0.023	0.017	0.03	0.016	0.033
X2	0.075	0.065	0.066	0.055	0.063	0.068	0.054
X3	0.047	0.048	0.057	0.044	0.053	0.037	0.033
X4	0.024	0.027	0.024	0.022	0.025	0.023	0.025
X5	0.142	0.156	0.149	0.156	0.141	0.150	0.160
X6	0.036	0.043	0.040	0.037	0.038	0.036	0.043
X7	0.041	0.036	0.041	0.042	0.04	0.046	0.044
X8	0.031	0.038	0.039	0.041	0.046	0.033	0.051
X9	0.063	0.052	0.045	0.059	0.039	0.055	0.035
X10	0.077	0.074	0.081	0.084	0.074	0.089	0.076
X11	0.026	0.034	0.028	0.024	0.037	0.024	0.026
X12	0.035	0.027	0.041	0.094	0.053	0.028	0.027
X13	0.063	0.054	0.061	0.06	0.052	0.062	0.077
X14	0.03	0.041	0.037	0.026	0.027	0.027	0.031
X15	0.038	0.057	0.042	0.032	0.046	0.072	0.052
X16	0.079	0.075	0.079	0.072	0.074	0.076	0.076
X17	0.043	0.041	0.044	0.041	0.047	0.044	0.042
X18	0.032	0.034	0.032	0.03	0.033	0.033	0.031
X19	0.034	0.034	0.033	0.026	0.034	0.041	0.038
X20	0.054	0.038	0.038	0.037	0.05	0.039	0.047

2.3.3. Application of State–Space Method in CECC Calculation

The state–space method is a mathematical modeling approach that utilizes Euclidean geometric space to quantitatively describe and analyze the behavior of dynamic systems. It effectively provides a comprehensive and macroscopic perspective on the ecological carrying capacity of coastal zones [41,42]. This method's application principle in carrying capacity is represented by Equation (6).

$$CECC = \sqrt{\sum_{j=1}^{m} W_j X_{ij}^2} (i = 1, 2, \cdots, n) \tag{6}$$

In the equation, $CECC$ represents the coastal ecological carrying capacity of coastal zones, W_j reflects the weight of the $j-th$ indicator, and X_{ij} denotes the standardized results of each indicator.

2.3.4. Contribution Degree Model

The contribution degree model, which is used to evaluate and measure the contribution of individuals or factors to the overall outcome [43]. In this study, this model is employed to calculate the contribution of the four primary indicators of CECC, analyzing the reasons for changes in comprehensive ecological carrying capacity from a relatively macroscopic perspective. The calculation formulas are given by (7) and (8).

$$CECC_K = \sqrt{\sum_{j=1}^{o} W_j X_j^2}(K = 1,2,3,\cdots,m; j = 1,2,\cdots,n) \tag{7}$$

$$CD_K = \left(\frac{CECC_K}{CECC}\right)^2 \tag{8}$$

In the equation, $CECC_K$ represents the carrying capacity of the $K-th$ primary indicator, and CD_K denotes the contribution degree of the $K-th$ primary indicator to the overall carrying capacity.

2.3.5. Coupling Coordination Model

Coupling coordination degree is used to measure the degree of coordination between various modules in the overall project [44,45]. The principle is described by Equations (9) to (13).

$$Y_{ij} = W_j X_{ij}^2 \tag{9}$$

$$M_j^+ = \sqrt{\sum_{j=1}^{m}\left(Y_j^+ - Y_{ij}\right)^2};\ M_j^- = \sqrt{\sum_{j=1}^{m}\left(Y_j^- - Y_{ij}\right)^2}; \tag{10}$$

$$U = \frac{M_j^-}{M_j^- + M_j^+} \tag{11}$$

$$C = \left[\frac{\prod_{i=1}^{K} CECC_K}{\left(\frac{\sum_{i=1}^{K} CECC_K}{K}\right)^K}\right]^{\frac{1}{K}} \tag{12}$$

$$D = \sqrt{C \times U} \tag{13}$$

where Y_{ij} represents the weighted standardized value of indicator j in year i, Y_j^+ and Y_j^- are the ideal values for positive and negative indicators, respectively, i.e., the maximum and minimum values of indicator j in year i. M_j^+ and M_j^- represent the Euclidean distances from Y_{ij} to the positive and negative ideal values, respectively. U reflects the proximity of the actual value to the ideal value, C represents the system coupling degree, and D denotes the coupling coordination degree. The interpretation of D values is as follows: $0.0 \leq D < 0.2$, low coordination; $0.2 \leq D < 0.4$, moderate coordination; $0.4 \leq D < 0.6$, good coordination; $0.6 \leq D < 0.8$, high coordination; $0.8 \leq D \leq 1.0$, perfect coordination.

2.3.6. Geographic Detector

A geographic detector is a statistical method used to detect spatial differentiation and reveal the driving forces behind it. It has promising applications in fields such as biomedicine, environmental protection, and social sciences [46]. By exploring the spatial similarity between independent and dependent variables, it can uncover and analyze the characteristics of spatial data changes and driving factors [47]. The implementation principle is described by Equations (14) to (15).

$$q = 1 - \frac{SSW}{SST} \quad (14)$$

$$SSW = \sum_{i=1}^{n} M_i \sigma_i^2; SST = M\sigma^2 \quad (15)$$

where q represents the explanatory power of the independent variable on the dependent variable, with a larger value indicating a greater influence of the independent variable on the spatial distribution of the dependent variable. $i = 1, 2, \cdots, n$, is the number of layers or categories of the independent or dependent variable, where M_i and M denote the number of units in $i - th$ layer and globally, respectively. σ_i^2 and σ^2 represent the variance within $i - th$ layer and across the entire region, respectively. SSW and SST, respectively, represent the total within-group variance and total global variance.

3. Result

3.1. Temporal and Spatial Variations of CECC and Sub-System Carrying Capacity

Based on the CECC evaluation system, the calculation results of the CECC and the carrying capacity of the four primary indicators (subsystems) in Shandong Province from 2010 to 2020 are presented in Figure 3, and the annual change rate of the carrying capacity is shown in Table 4.

The results indicated significant spatiotemporal differences in CECC. The overall CECC in Shandong Province (the mean CECC of each city in the corresponding year) showed a "U"-shaped development trend, fluctuating between 0.632 and 0.707 (Figure 3). During 2010–2020, the annual change rates of environmental carrying capacity (ECC), population carrying capacity (PCC), resource carrying capacity (CRCC), and economic–social carrying capacity (ESCC) were −2.60%, −4.86%, −0.49%, and 1.99%, respectively (Table 4). In terms of time difference, the decline of overall CECC in Shandong Province was the most significant from 2010 to 2013, and the annual change rate was as high as −6.29%. However, the upward trend of CECC in 2016–2019 and 2019–2020 is very remarkable, with annual rates of change of 6.73% and 5.74%, respectively. It is worth noting that from 2016 to 2020, in addition to the population carrying capacity showing a decline, the other subsystems showed an upward trend. At the municipal level, the CECC of most coastal cities in Shandong Province presents a "U"-shaped development trend. The CECC of each city reached its peak in 2016, and the CECC turned a corner this year. In terms of spatial differences, the average CECC of each municipality over a 10-year period showed the spatial pattern of "Weihai > Dongying > Yantai > Rizhao > Qingdao > Binzhou > Weifang", and from 2019 to 2020, except Dongying and Weifang, the CECC of other cities experienced an upward trend.

The four subsystems of carrying capacity also exhibited significant spatiotemporal differences. Apart from population carrying capacity, the primary indicators of carrying capacity all decreased from 2010 to 2013 and increased from 2016 to 2020. The changes in overall environmental carrying capacity (ECC), population carrying capacity (PCC), resource carrying capacity (CRCC), and economic–social carrying capacity (ESCC) in Shandong Province from 2010 to 2020 were −0.08, −0.19, −0.02, and 0.07, respectively. Additionally, from 2010 to 2020, Dongying and Rizhao were cities with relatively significant changes in ECC. The cities where ECC, PCC, and CRCC decreased the most over the 10-year period were Rizhao, Weifang, and Binzhou, while the areas where CRCC and ESCC increased significantly were Weihai.

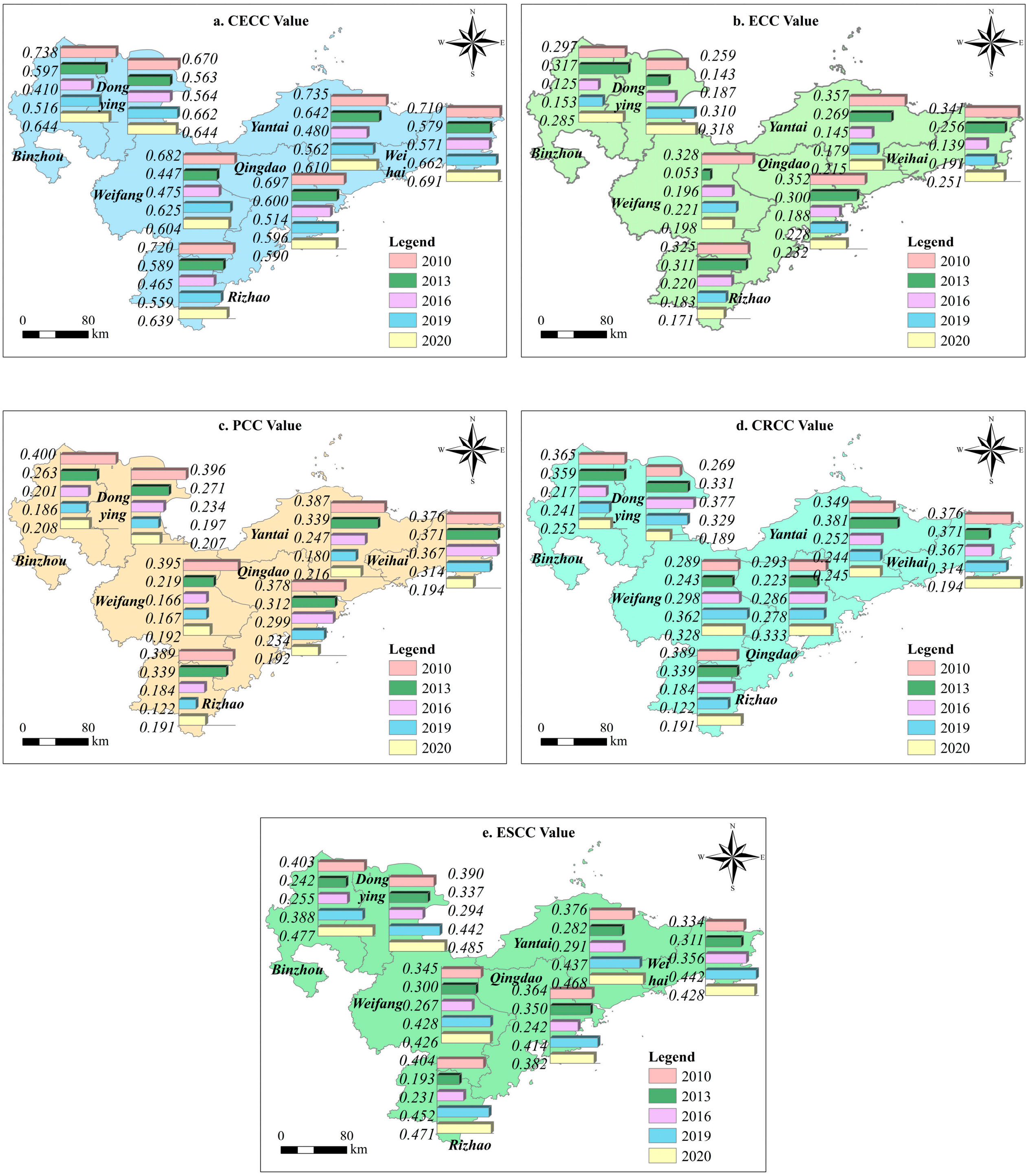

Figure 3. Spatial distribution of various carrying capacities in the Shandong coastal area from 2010 to 2020. (Note: (**a**–**e**) represents the spatial distribution of CECC, ECC, PCC, CRCC, and ESCC, respectively).

Table 4. Annual rate of change in carrying capacity in the Shandong coastal area from 2010 to 2020.

Region	Carrying Capacity	Period				
		2010–2013	2013–2016	2016–2019	2019–2020	2010–2020
Total	CECC	−6.29	−4.46	6.73	5.74	−1.07
	ECC	−9.00	−9.08	7.39	13.99	−2.60
	PCC	−7.46	−6.57	−5.81	−0.08	−4.86
	CRCC	−3.06	−1.85	1.70	5.42	−0.49
	ESCC	−7.67	−1.29	18.38	4.43	1.99
Qingdao	CECC	−4.64	−4.75	5.31	−1.10	−1.54
	ECC	−4.91	−12.48	7.20	1.80	−3.40
	PCC	−5.83	−1.47	−7.21	−17.95	−4.93
	CRCC	−7.99	9.38	−0.89	19.80	1.36
	ESCC	−1.29	−10.28	23.67	−7.70	0.49
Dongying	CECC	−5.32	0.07	5.77	−2.68	−0.38
	ECC	−14.87	10.19	21.77	2.69	2.28
	PCC	−10.56	−4.52	−5.23	4.97	−4.77
	CRCC	7.72	4.56	−4.26	−42.50	−2.98
	ESCC	−4.58	−4.21	16.76	9.74	2.43
Yantai	CECC	−4.24	−8.42	5.70	8.67	−1.70
	ECC	−8.25	−15.39	7.95	20.17	−3.97
	PCC	−4.14	−9.03	−9.01	19.76	−4.42
	CRCC	3.00	−11.26	−1.08	0.52	−2.98
	ESCC	−8.30	1.00	16.84	7.08	2.47
Weifang	CECC	−11.51	2.11	10.53	−3.37	−1.15
	ECC	−27.96	90.15	4.25	−10.20	−3.95
	PCC	−14.89	−8.06	0.36	14.75	−5.14
	CRCC	−5.28	7.51	7.17	−9.43	1.35
	ESCC	−4.34	−3.68	20.12	−0.50	2.35
Weihai	CECC	−6.15	−0.46	5.32	4.39	−0.26
	ECC	−8.32	−15.22	12.57	31.05	−2.64
	PCC	−0.47	−0.35	−4.84	−38.21	−4.85
	CRCC	−16.22	4.33	18.09	34.25	2.02
	ESCC	−2.31	4.83	8.10	−3.25	2.81
Rizhao	CECC	−6.06	−7.01	6.68	14.30	−1.13
	ECC	−1.44	−9.73	−5.63	−6.41	−4.73
	PCC	−4.31	−15.27	−11.22	56.58	−5.10
	CRCC	0.07	−3.14	−4.84	42.64	1.06
	ESCC	−17.44	6.69	31.85	4.11	1.65
Binzhou	CECC	−6.33	−10.45	8.64	24.75	−1.26
	ECC	2.24	−20.20	7.57	85.65	−0.42
	PCC	−11.43	−7.86	−2.40	11.64	−4.80
	CRCC	−0.57	−13.19	3.72	4.63	−3.09
	ESCC	−13.33	1.88	17.29	22.93	1.83

3.2. Change in Each Indicator

The standardized values of each indicator from 2010 to 2020 are shown in Figure 4.

In the environmental and population pressure systems, In the past ten years, the coastal areas of Shandong Province have implemented sewage discharge control and energy conservation and emission reduction policies, resulting in a downward trend in industrial wastewater discharge (X1) and million GDP energy consumption (X4) (note: since they are negative indicators, their standardized values show an upward trend), providing good environmental conditions for regional sustainable development. The values of land use intensity (X2) and passenger transport volume (X6) fluctuated around the years 2019 and 2013, respectively. From 2010 to 2020, the population surge and urban expansion have led to a significant increase in the development and utilization degree and population density of the coastline, which has brought great pressure on sustainable coastal development.

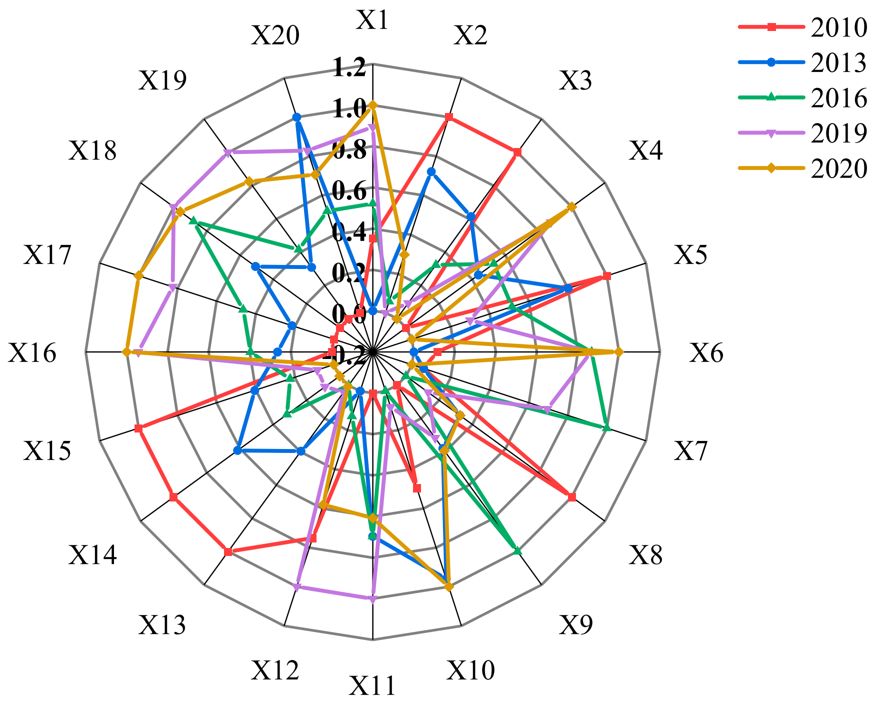

Figure 4. Changes in 20 indicators of CECC in Shandong Province from 2010 to 2020.

In the coastal resource system, the per capita wetland area (X7), net primary productivity of vegetation (X8), and fishery resources (X9) exhibited a trend of first decreasing and then increasing, with 2016 being an important turning point for changes in coastal resource carrying capacity. The per capita water resources (X10), vegetation coverage (X11), and nearshore water quality (X12) fluctuated from 2010 to 2020.

In the economic development and social support system, the decrease in port throughput (X14) and urbanization rate (X15) values has brought a significant burden to coastal areas. At the same time, the values of total marine economic output (X16), social security and employment input (X17), and education input (X18) have continued to increase over the decade, alleviating this pressure and promoting economic development in coastal areas. Per capita GDP (X13), scientific and technological input (X19), and environmental protection input (X20) have varied within a certain range, but their indicator values have all changed in a direction favorable to the economic development of coastal areas over the decade, to some extent alleviating multiple pressures and promoting the improvement of ecological carrying capacity.

3.3. Analysis of Contribution Degree

Figure 5 demonstrates the differences in the contribution degree (CD) of environmental pressure, population pressure, coastal resource economic development, and social support system to the CECC.

There were significant differences in the changes in CD for the four subsystems in coastal cities. From 2010 to 2020, except for Dongying and Binzhou, the CD of environmental pressure decreased in other cities, with the most significant changes observed in Rizhao (−13.17%) and Dongying (9.43%). The CD of coastal resources showed an upward trend in this decade, except for Dongying, Yantai, and Binzhou, with the most significant increases and decreases observed in Qingdao (14.19%) and Binzhou (−9.18%), respectively. The CD of population pressure in the seven coastal cities showed a fluctuating downward trend. However, the CD of economic development–social support in these cities was in the opposite trend to population pressure. The most significant changes were observed in Weifang (−23.4%) and Yantai (32.78%).

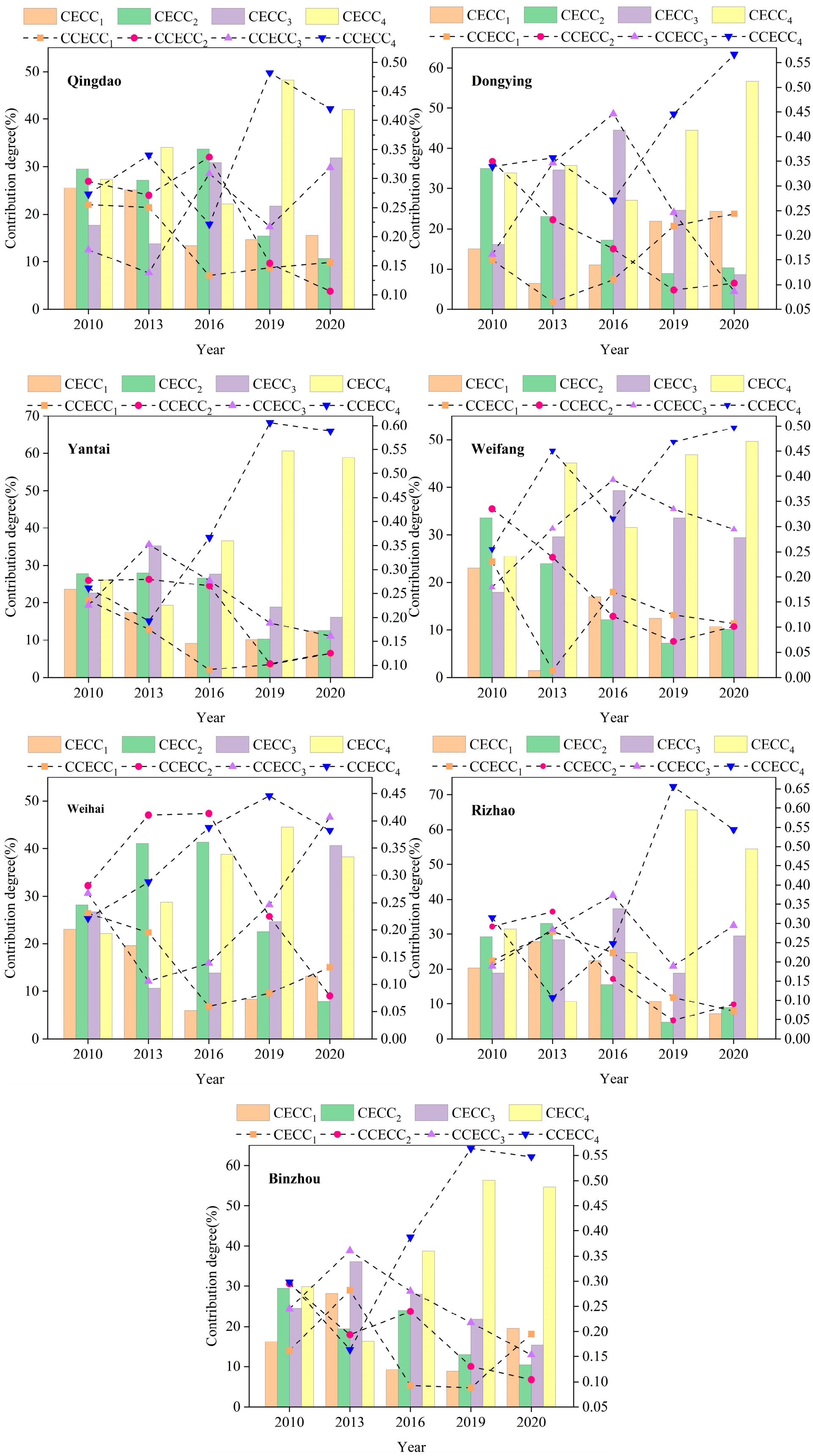

Figure 5. Contribution degree of factor layer indicators in coastal areas of Shandong Province from 2010 to 2020. (Note: $CECC_1$–$CECC_4$ represents the spatial distribution of ECC, PCC, CRCC, and ESCC, respectively. $CCECC_1$–$CCECC_4$ shows the contribution degree corresponding to the above parameters).

The trends in the changes in the CD of the four subsystems in each city exhibit significant differences. Regarding environmental pressure, Qingdao, Yantai, and Weihai showed a pattern of decreasing CD in environmental pressure followed by an increase, with peak and trough values observed in 2010 and 2016. In contrast, the CD of environmental pressure in Rizhao showed an opposite trend, while the CD in Weifang and Binzhou fluctuated within a certain range. In terms of population pressure, Dongying, Yantai, and Weifang exhibited a trend of decreasing CD in population pressure followed by an increase, with peak and trough values observed in 2010 and 2019. Conversely, Weihai demonstrated the opposite trend, and the population pressure CD in Qingdao, Rizhao, and Binzhou fluctuated. For coastal resources, Dongying, Yantai, Weifang, and Binzhou showed a trend of initially increasing and then decreasing CD in coastal resources. The changes in the CD of coastal resources in Qingdao and Rizhao were relatively complex. In the aspect of economic development and social support, except for Weihai showing a trend of initially increasing and then decreasing CD, the trends in other cities exhibited fluctuations, with the CD in 2020 being greater than in 2010.

4. Discussion and Suggestions

4.1. Analysis of Driving Factors of CECC

The analysis of the driving factors of CECC is an important foundation for supporting sustainable development in coastal areas [48,49]. By taking the change in each indicator as the independent variable and ecological carrying capacity as the dependent variable, we conducted a driving factor detection analysis using geographic detectors, with the results shown in Figure 6.

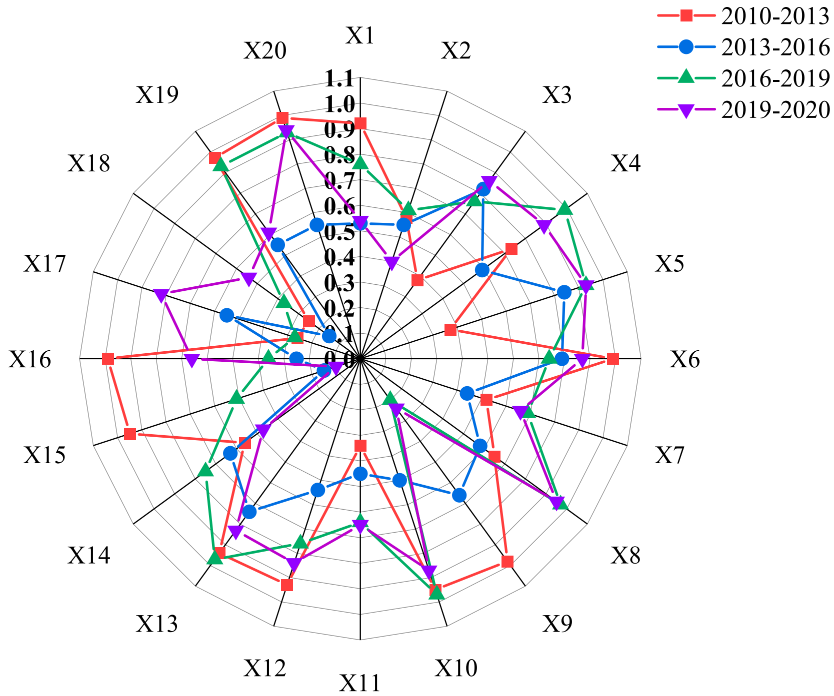

Figure 6. Detection results of driving factors of CECC in Shandong Province. (Note: X1–X20 represents the secondary index of the CECC evaluation system, and the results in the picture are the results of factor detection q value in the geographic detector).

As shown in Figure 6, from 2010 to 2013, the q value of factor detection of scientific and technological input (X19), environmental protection input (X20), passenger transport volume (X6), marine economy (X16), fishery resources (X9), and other indicators was at a high level, which indicated that they are the main factors driving the change in CECC. This indicated that although Shandong Province has increased its efforts in environmental protection and promoted the transformation of heavy industry to the green industry, for example, the discharge of industrial wastewater and million GPD energy consumption have decreased significantly, the rapid development of the marine economy and tourism industry, as well as the acceleration of urbanization in coastal areas [50–52], have exerted significant pressure on the coastal ecological environment, which was greater than the positive benefits brought by environmental protection input, resulting in a significant decline in CECC. In the following three years, the q values of population density (X5) and coastline utilization degree (X3) were much higher than other indicators, which was the main driving force for the change in CECC. During the period of 2016–2019, million GDP energy consumption (X4), net primary productivity of vegetation (X8), per capita water resources (X10), and per capita GDP (X13) emerged as the dominant factors influencing carrying capacity. Scientific and technological input and environmental protection input, to some extent, impacted carrying capacity. Shandong Province focused on the coordinated development of economic growth and environmental protection during this period, actively responding to energy conservation and emission reduction policies and optimizing and upgrading energy-intensive industries to green industries. This initiative facilitated economic development and the restoration of the coastal ecological environment, resulting in a significant increase in CECC. With the increase in environmental protection input and the optimization and upgrading of energy-intensive industries, the growth environment of vegetation in coastal areas and the nearshore water environment improved, leading to a further enhancement of CECC.

4.2. Coordination Between Economic Development and Environmental Protection

Urban economic carrying capacity is the basic condition for sustainable urban development [53–55], and in this study, the economic development–social support system is also the system with the largest weight ratio in ecological carrying capacity (about 37%). For example, from 2010 to 2013, the Qingdao municipal government increased investment in environmental protection to alleviate the huge pressure brought by resource depletion, population surge, and environmental pollution, resulting in a smaller decline in its ecological carrying capacity than other coastal cities in Shandong. From 2016 to 2019, the relevant governments increased investment in environmental protection, education, scientific and technological research and development, and social security and made use of the advantages of coastal areas to develop the economy rapidly, resulting in an upward trend in the contribution degree of the economic development–social support system of coastal cities in Shandong Province. This finding is consistent with other studies [56–58].

In addition, the premise of sustainable development is the coordinated development of economic growth and resource and environmental protection [59,60]. This study found that the problems of population surge, resource loss, and environmental pollution existed in the coastal areas of Shandong Province in the early stage of development, which destroyed the balance between economic development and resource and environmental protection and led to the continuous decline of CECC. However, after CECC drops to a certain threshold, with the compensation of resources and environmental carrying capacity by economic development and social support, the degree of coupling coordination between the subsystems of CECC is improved, and CECC recovers (Figure 7). This phenomenon fully proves that only by realizing the dynamic balance between economic growth and resources and environment can regional sustainable development be realized.

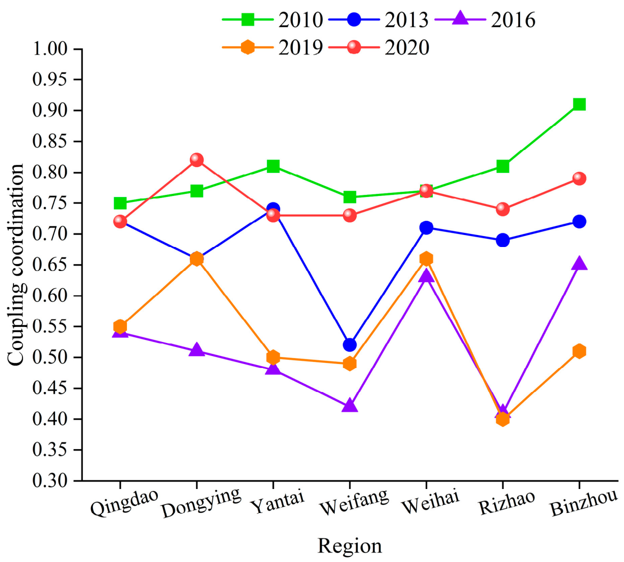

Figure 7. The coupling degree between the environmental system, population system, coastal resource system, and economic development—social development system in the coastal area of Shandong province.

4.3. Strengths and Weakness in This Study

By establishing the CECC monitoring and evaluation system in Shandong Province, this study dynamically monitored the change characteristics of CECC and analyzed the internal mechanism of the CECC subsystem (environment, population, coastal resources, economic development, and social support system) and the key driving factors of CECC change. On the one hand, it enhanced the research on the evaluation system of CECC in Shandong Province. On the other hand, it was beneficial for achieving dynamic monitoring of the coastal ecological environment and providing a practical basis for sustainable development in coastal regions. However, there are some shortcomings in this study: First, most of the index data comes from the statistical yearbook, and there are problems with the index coverage being not comprehensive, which may make the CECC quantification results inaccurate. Secondly, coastal ecosystems are often complex, nonlinear systems. Therefore, there may be some errors in the calculation of ecological carrying capacity using the state–space model. These defects affect the quantification of CECC in Shandong Province and the accuracy of related analysis results.

The research on the CECC is a comprehensive issue involving multiple interdisciplinary fields. In the future, by enhancing interdisciplinary collaboration, in-depth simulation of coupled dynamic models of internal subsystems of carrying capacity, such as economic development and environmental resources, will be conducted to formulate specific plans for regional green development.

4.4. Suggestions

Shandong coastal areas are rich in fishery resources and ports, and the rapid development of the marine economy is one of its advantageous industries [61,62]. Therefore, we suggest that the benefits of the marine economy should be fed back into environmental protection, social security and employment, education, and other work to improve socially sustainable development and promote the construction of the Shandong coastal zone into a dynamic area with sustainable development. Adhere to the green economic development model, namely, take sustainable development as the guide and achieve coordination between economic growth and environmental protection by improving resource utilization efficiency and reducing environmental pollution and ecological damage [63,64]. Specific measures are as follows:

(1) Delimit basic farmland protection areas, establish nature reserves, and restrict the development and utilization of land and coastlines. (2) Promote water conservation, develop agricultural and industrial water-saving technologies, strengthen the construction of urban water supply pipe networks, strictly control industrial wastewater discharge in coastal areas, and use coastal advantages to develop seawater desalination technology. (3) Promote the upgrading of marine fisheries, marine transportation, and other industries; strengthen regional cooperation; promote the complementary advantages of coastal areas and inland areas; and increase per capita income. (4) Rationally control population growth, promote the transformation and upgrading of energy-consuming industries to green industries, increase investment in environmental protection, improve education levels, and improve the social security system.

5. Conclusions

In this study, based on multi-source data, including remote sensing images, a dynamic monitoring model of CECC in Shandong Province was constructed by combining a multi-dimensional evaluation index system and a state space model. Secondly, a variety of ecological analysis models were used to evaluate the CECC driving mechanism and the balance between CECC subsystems in Shandong Province.

It was found that CECC in the study area showed a "U"-shaped development trend in the past 10 years, and the coastal ecosystems in Shandong were under great pressure, with significant spatio-temporal differences in carrying capacity of each dimension. Reasonable control of population growth, promoting the upgrading of energy-consuming industries to green industries, saving and protecting water resources, and strengthening the innovation of marine science and technology are important ways to promote the sustainable development of coastal areas in Shandong Province. The economic development–social support system has gradually become the dominant driving force for sustainable development in coastal zones. In addition, it was found that the degree of coordinated development between the economic development–social support system and the resource and environment system affects the sustainable development of the coastal zone. This coordination mechanism has enabled the relevant departments to pay more attention to the relationship between economic–social systems and natural ecosystems in the process of coastal management. Because of the difference between the goals and interests of economic development and ecological protection, decision-makers need to coordinate the interests of all parties and establish an effective coordination mechanism.

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