Analysis of the Coupling and Coordination of Ecological "Value-Risk" in Pingtan Island under Multiple Scenario Simulations

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Abstract. Pingtan Island is an island ecosystem with unique geographical location and rich ecological resources. Simulation research on its health condition can provide theory foundation for developing regional development strategy. In this study, Pingtan Island was selected as a research area and a multi-scenario soil use simulation was carried out using the PLUS model. A coupling coordination model "ESV-ERI" was developed to quantitatively evaluate the temporal changes of ESV and ERI in different development scenarios to assess the overall health of the island ecosystem. The results showed that: (1) Under the CP scenarios and EP scenarios, the total amount of ESV was 12.863billion yuan and 12.804 billion yuan, respectively, which showed that contributed to the enhancement of ecosystem services; (2) The EP scenario Significantly inhibited the Ecological hazard of landscape, and the mean ERI was only 0.0957; (3) The coordination degree of ESV and ERI is the highest in the NP scenario, indicating that the areas of severe imbalance and relative imbalance are only 2.87% and 7.52%; (4) Since regional coupling coordination is strongly governed by the land-use structure, achieving overall coordinated development requires an integrated approach that moves beyond a singular focus on ecological value or risk control.

1 Introduction

Ecosystem Service Value (ESV) and the Ecological Risk Index (ERI) serve as two fundamental metrics for evaluating regional ecosystem health. The ESV measures the direct and indirect benefits of the ecosystem [1,2]. This research helps to bridge the gap between human well-being and regional economic development, fostering a synergistic relationship. [3]. The ERI is designed to quantify potential adverse outcomes for the landscape ecosystem under natural or human-induced stress. Its analysis aims to reveal the spatial distribution patterns of these risks across a region. [4]. Given that an island constitutes a relatively self-contained ecosystem, its unique geography predisposes it to ecological fragility. This vulnerability, compounded by intensive human development, places its ecosystem under considerable strain. Therefore, ecological health assessment is critical for advancing its sustainable development.

ESV and ERI, as two dimensions to measure ecosystem health, are easy to lead to one-sided results when analyzed separately. The organic combination of the two can be achieved through the coordination analysis of the coupling coordination degree model (CCDM)[5], which more intuitively reveals the spatial coordination of ESV and ERI. The estimation of ESV and ERI depends on land use data, and land use prediction helps to realize the simulation of the two in different scenarios in the future. The commonly used land use prediction models include SD[6], CA markov[7], CLUS[8], FLUS[9] and PLUS[10]. Among them, the patch generating land use simulation model is widely used at this stage because of its unique patch generation mechanism, special driver analysis module and flexible multi scenario simulation ability. At present, many scholars have used this model for multi scenario simulation to realize the prediction of ESV[11]. Integrating multi-scenario simulations to quantify ESV and ERI, followed by a coupled coordination analysis for ecological health assessment, Provides the scientific basis for ecological protection and spatial planning.

Pingtan Island is China's 5th biggest island, with a special geographical location and an important strategic position. This study concentrates on Pingtan Island, making use of 2000, 2010 and 2020 data. The PLUS model was used to forecast land use patterns in 2030, with ESV and ERI under various scenarios. By introducing the coupling coordination degree model, the health status of Pingtan Island ecosystem is systematically evaluated, and the key areas suitable for development and construction and ecological restoration are identified. Finally, through the comparison of multiple scenarios, the optimal ecological sustainable development model is proposed, The purpose of this thesis is to provide a solid basis for the optimization of the regional land space and the construction of the ecological security mode.

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2 Study Area and Methods

2.1. Study Area

Pingtan Island is situated in Fuzhou City, Fujian Province, Southeast Ocean. It is the main island of Pingtan County. Its geographical location is 25 ° 32.0 'N and 119 ° 45.9' E. It is the biggest island in Fujian and the fifth largest in China. (Figure 1).

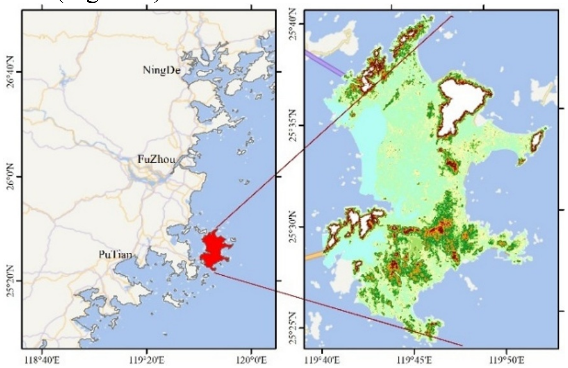

Figure.1 Geographical location map of islands in the research area.

2.2 Data

The remote sensing image data used in this study are from the Landsat series image data set in Google Earth engine platform, and the images of 2000, 2010 and 2020 are selected. This study employed 30-meter resolution Landsat 5 (2000, 2010) and Landsat 8 (2020) imagery. Annual composite images were generated from the monthly data (January-December) for each time point. Land use data was then generated on the Google Earth Engine platform by applying the Random Forest classification algorithm to the combined images.

The data on the boundary of the administrative area are derived from the Resource and Environment Science Data Platform (https://www.resdc.cn/). Data such as land area and crop output needed to calculate ESV are derived from the Pingtan Statistics Yearbook (https://www.pingtan.gov.cn/).

3 Methods

3.1 PLUS model simulation

The technical roadmap of this study is shown in Figure 2. Patch generating land use simulation (PLUS) model is a cellular automata (CA) model based on grid data proposed by Liang et al.[10], Land Expansion Analysis Strategy (LEAS) and the Multiple Random Seeds CA model (CARS). First, by using the same module, the contribution of each driving factor to the probability of change of each category is calculated. The study selected 12 drivers, including population and GDP, as shown in Table 1. The Markov chain model is applied to predict the demand of land cover, and the transformation probability of every category between 2020 and 2030 is obtained. According to the local cultivated land protection policy, land space planning policy and ecological restoration policy, the following four different development scenarios in the future are set[12], which are scenarios for Natural Development (ND); scenarios for the Protection of Cultivated Land (CP); scenarios for Economic Development (ED) and Ecological Priorities (EP).The final step involved the CARS module, which simulated the 2030 land cover scenarios by integrating the initial land cover data, categorical development probabilities, development-restricted areas, And the expected demand for each type of land use.

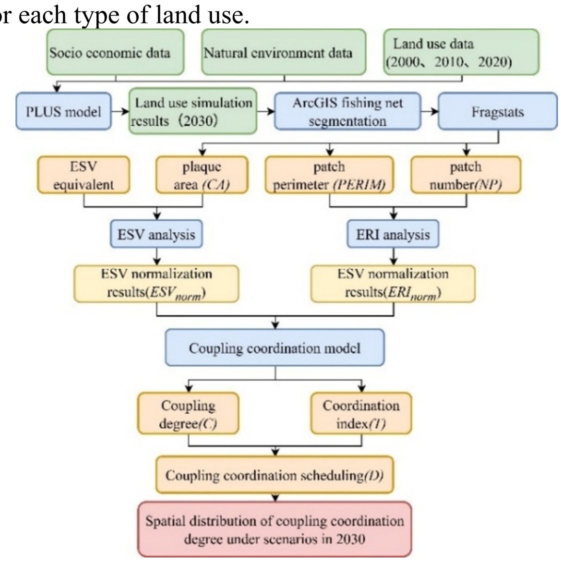

Figure. 2 Technology Roadmap.

Table.1 Types and sources of land-use change drivers.

Data type	Data name	Resolution	Source
Land use data	Land use data (2000, 2010, 2020)	30m	Random forest classification on GEE platform
Socio-economic data	population	1000m	Resource and Environmental Science Data Platform
	GDP	1000m	Resource and Environmental Science Data Platform
	Distance to primary road	300m	Euclidean distance analysis by ArcGIS
	Distance to secondary road	300m	Euclidean distance analysis by ArcGIS
	Distance to tertiary road	300m	Euclidean distance analysis by ArcGIS
	Distance from the county government	300m	Euclidean distance analysis by ArcGIS
Natural environmental data	Soil type	1000m	Resource and Environmental Science Data Platform
	annual average temperature	1000m	China Meteorological Administration
	average annual precipitation	1000m	China Meteorological Administration
	DEM	90m	Geospatial Data Cloud
	slope	90m	Geospatial Data Cloud
	Distance to waters	300m	Euclidean distance analysis by ArcGIS

3.2 ESV-ERI coupling coordination analysis

Before the calculation of ESV and ERI, the 500m × 500m evaluation unit[12] is used to cut the data predicted by PLUS model, and the ESV and ERI of each patch are calculated separately, so that the final coupling coordination analysis results are spatialized. The area, perimeter and number of each patch were calculated by Fragstats software, and the subsequent ESV and ERI were calculated based on the calculation results.

The equivalent factor of islands in the study area is calculated as follows:

$$E_d = \frac{1}{7}\left(\frac{P \times Q}{A}\right) \quad (1)$$

Where, E_d is the ESV equivalent factor per unit area (yuan/hm^2); P is average grain price in research area (yuan/t); Q is food production in the region. (T); A is the sow corn area in the study area(hm^2).

The unit area equivalent factor for ESV on Pingtan Island, calculated using the above formula, was 2355.977 yuan/hm^2. This value was then integrated with the method for evaluating construction land ESV proposed by Yuan et al[14], ESV coefficient in study area in Table 2.

Table.2 Study area ESV coefficient(yuan/(hm^2·a)).

forest land	building land	cultivated land	water body	grassland	unused land
18612.22	66250.07	27494.25	106843.6	-10649	3274.808

Finally, the final ecosystem services were calculated according to the results of land use classification and by-value coefficient. The calculation formula is:

$$ESV = \sum(A_k \times C_k) \quad (2)$$

Where A_k is the area of land type k within each assessment unit, C_k is the value coefficient of land type k, and ESV is the ESV within each assessment unit.

Table 3 shows the formula of ERI[15]. The result of the computation is distributed to the relevant evaluating unit, and the visualization of the ERI results.

Table.3 Landscape pattern index and its meaning.

Index	Calculation formula	Formula meaning
Landscape fragmentation index	$C_i = \frac{n_i}{A_i}$	A_i is the area of land use type i, and n_i is the number of patches
Landscape separation index	$N_i = \frac{A}{2A_i}\sqrt{\frac{n_i}{A_i}}$	A_i is the area of land use type i, and A is the total area
Landscape fractal dimension index	$F_i = 2\,ln(p_i\,/\,4)\,/\,ln\,A_i$	p_i is the perimeter of landscape type i
Landscape disturbance index	$E_i = aC_i + bN_i + cF_i$	a, b, and c is the weights of the corresponding indices, and $a + b + c = 1$. Referring to relevant literature [13] and considering the specific situation of the study area, the weights of each index are set to 0.5, 0.3 and 0.2.
Landscape loss index	$R_i = E_i \times V_i$	E_i is the landscape disturbance index, and V_i is the landscape vulnerability index
Landscape vulnerability index	Weighted score	On the basis of previous studies, landscape vulnerability is assigned to: 6, 5, 4, 3, 2, 1. After normalization, the vulnerability index V_i is obtained.
Landscape ecological risk index	$ERI = \sum_{i=1}^{n}\frac{A_{k_i}}{A_k} \times R_i$	R_i is the landscape loss index, A_{k_i} is the area of landscape type i in the k-th evaluation unit, A_k is the total area of the k-th evaluation unit, n denotes the landscape type, and ERI is the landscape ecological risk index. The higher the index, the higher the risk.

The correlation degree is calculated on the basis of ESV and ERI calculations. ESV is a positive indicator, while ERI is a negative indicator, and the order of magnitude of the two indicators is different. Therefore, the two indicators should be normalized first:

$$ESV_{norm} = \frac{(ESV - ESV_{min})}{(ESV_{max} - ESV_{min})} \quad (3)$$

$$ERI_{norm} = \frac{(ERI_{max} - ERI)}{(ERI_{max} - ERI_{min})} \quad (4)$$

The above ESV_{norm} and ERI_{norm} are the normalized ESV index and ERI index respectively. The standardized ESV_{norm} and ERI_{norm} are both positive indicators. On this basis, the coupling coordination degree is calculated:

$$C = 2 \times \frac{\sqrt{(ESV_{norm} \times ERI_{norm})}}{ESV_{norm} + ERI_{norm}} \quad (5)$$

$$T = \alpha \times ESV_{norm} + \beta \times ERI_{norm} \quad (6)$$

$$D = \sqrt{C \times T} \quad (7)$$

The above C is the coupling degree, and the value range of C is 0-1. When C tends to 1, it indicates that the coupling state of the two indexes is better. T is the coordination index, and α and β are the weights of both. In this study, ESV and ERI are regarded as equally important, that is, $\alpha = \beta = 0.5$, D is the coupling coordination, and the coupling coordination value is between 0 and 1. The value serves as a dual indicator: a decrease signals both a decline in ESV and a rise in ERI, and an increase concurrently reflects the opposite conditions.

4 Results and analysis

4.1 Land use simulation results

As summarized in Figure 3, which details the area and growth rate of each land category compared to 2020, distinct patterns emerge across scenarios. The CP scenario resulted in notable increases in forest (5.35%), cultivated (15.57%), and unused land (11.05%), with concurrent decreases in construction land (-11.76%), water (-6.14%), and grassland (-8.19%). In contrast, the ED scenario was characterized by a substantial expansion of construction land (31.38%), accompanied by declines across all other types. Conversely, in the EP scenario, all ecological land types experienced modest growth while construction land contracted by 8.87%.

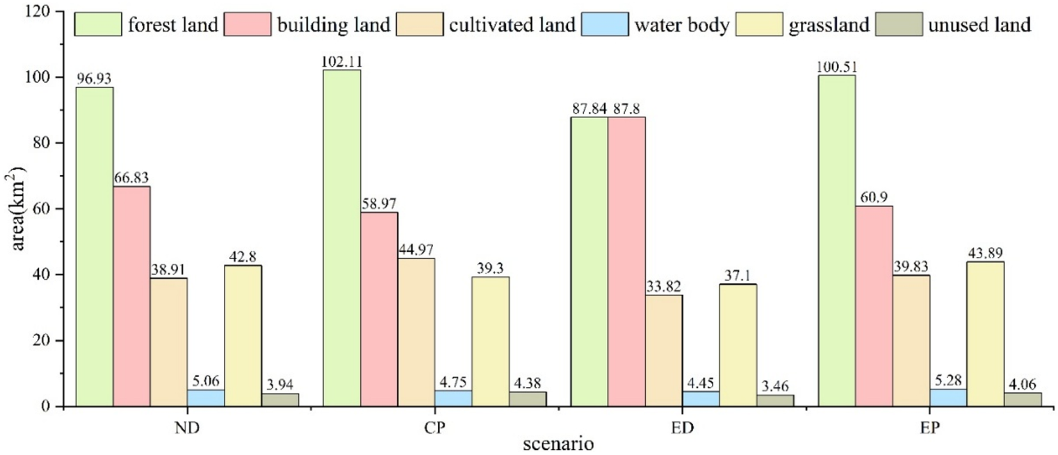

Figure.3 Multi-scenario simulation results of land use.

4.2 ESV and ERI calculation results

Based on the standard deviation and actual situation in research area, the overall ESV values of the natural development scenario, the cultivated land conservation scenario, the economic development scenario and the ecological priority scenario were 12.246 billion RMB, 12.863 billion RMB, 10.531 billion RMB, and 12.804 billion RMB respectively. The ecosystem service value is divided into very low value area (ESV<6000000), low value area (6000000< ESV <12000000), medium value area (12000000< ESV <18000000), high value area (18000000< ESV <24000000) and very high value area (ESV >1600000). The overall average ERI values of ND scenario, CP scenario, ED scenario and EP scenario are 0.1313, 0.1287, 0.1217 and 0.0957 respectively. The calculation results of landscape ecological risk index are divided into very low risk area (ERI<0.05), low risk area (0.05< ERI <0.15), medium risk area (0.15< ERI <0.25), high risk area (0.25< ERI <0.35) and very high risk area (ERI >0.35) based on standard deviation and actual situation in the study area. Classification results are illustrated in Figure 4.

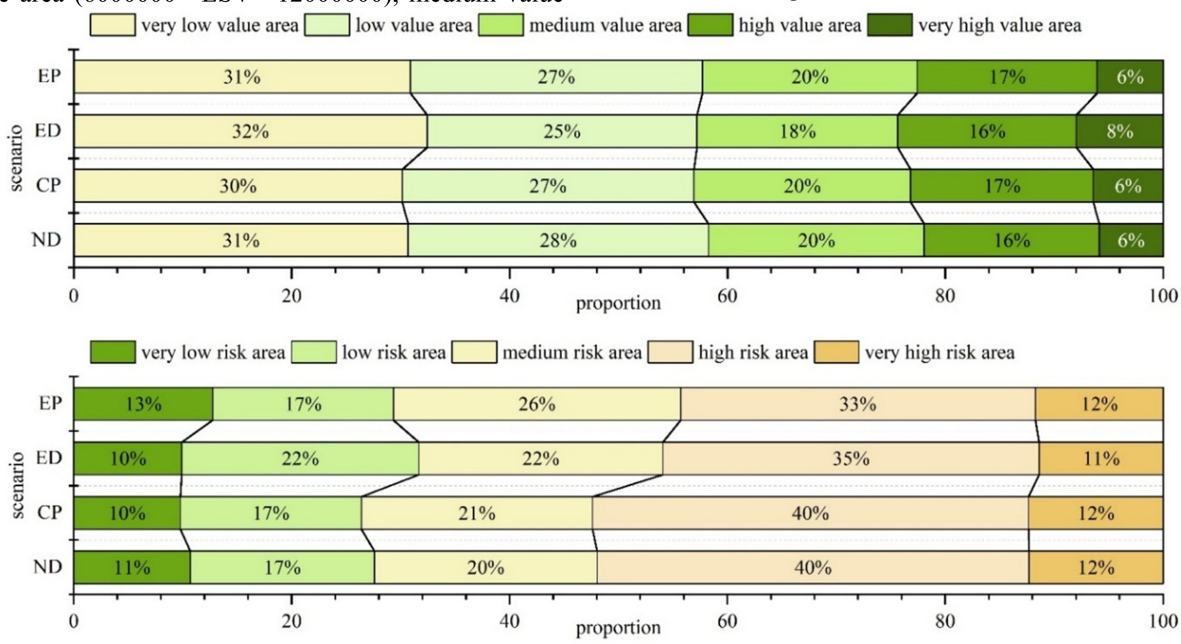

Figure.4 Statistics of ESV and ERI calculation results.

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Comparing the other three scenarios with the ND scenario, in the CP scenario, the areas of the extremely low-value and low-value regions slightly decrease, while the areas of the high-value and extremely high-value regions slightly increase; under the ED scenario, the areas of the extremely low-value and extremely high-value regions significantly increase, the area of the high-value region slightly increases, and the area of the low-value region significantly decreases. Under the EP scenario, the area of very low value area, high and high value area increased slightly, and low value area decreased slightly. Under the CP scenario, there was a slight decrease in the area at very low risk and low risk, while there was a slight increase in the area at high risk and very high risk; In the ED scenario, the area of very low and very high risk area has decreased slightly, the high risk area has decreased considerably and the low risk area has increased considerably; in the EP scenario, the area of very low risk and medium risk area has increased, the low risk region and the high risk area have decreased slightly, and the risk area has been reduced significantly.

4.3 Coupling coordination analysis

Classification of computational results of coupled coordination degree as highly uncoordinated (d<0.3), relatively uncoordinated (0.3<d<0.4), barely coordinated (0.4<d<0.5), relatively coordinated (0.5<d<0.6) and highly coordination (d>0.6). The results are shown in Figure 5, and the data statistics of coupling coordination degree calculation results are shown in Figure 6.

From the graph, it can be seen that the distribution of the coupling coordination degree on the spatial scale has some correlation with land use. The highly uncoordinated and relatively uncoordinated areas are roughly distributed in building land, the barely coordinated areas are roughly distributed in cultivated land and grassland, and the relatively coordinated and highly coordinated areas are roughly distributed in forest land. Under the four scenarios, the proportion of highly uncoordinated regions is relatively low. The proportion of relatively uncoordinated regions is the highest in the EP scenario, which is as high as 29.03%, followed by the CP scenario and the ED scenario, which are 17.11% and 16.02%, respectively. The proportion of ND scenario is the lowest, which is only 7.52%, and the proportion of barely coordinated regions is about 40%. The proportion of relatively coordinated regions is the highest in the ND scenario, which is as high as 37.62%, followed by the CP scenario, the ED scenario and the EP scenario, which are 28.10%, 25.20% and 15.79%, respectively. The proportion of highly coordination regions is relatively high in the ND scenario and the EDscenario, which are 16.36% and 12% respectively.The CP scenario and EP scenario were 4.23% and 2.68%, respectively.

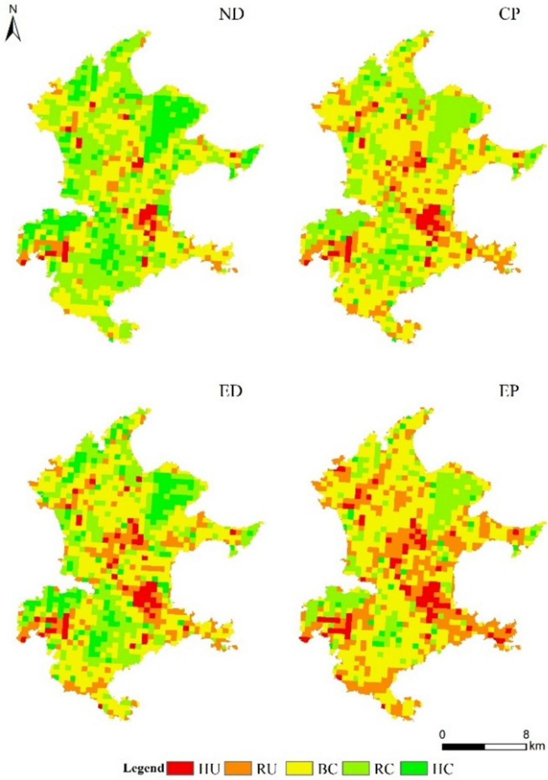

Figure.5 Calculation results of coupling coordination degree under various scenario simulations in 2030.

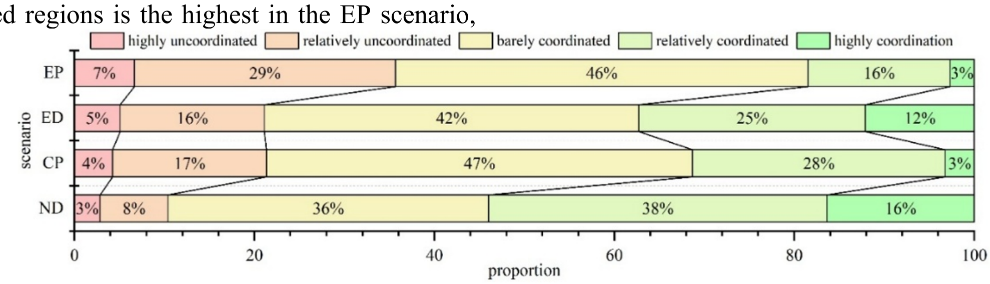

Figure.6 Statistics of coupling and coordination degree calculation results.

5 Conclusion and Discussion

5.1 Discussion

The multi-scenario simulation results show that the changes in area for each land category closely matched the land demand projections from the Markov chain. This alignment confirms the rationality of the land structure design, the effective spatial allocation of the CARS module, and the high reliability of the simulation. The Cultivated Land Conservation Scenario supports the growth of forest and arable land by controlling the spread of building land, water and grass; in the Economic Development Scenario, it is preferable to expand building land at the expense of other types of land; The ecological priority scenario not only keeps the basic stability of building land scale, but also promotes the small increase of forest, grassland and water ecosystem. The logic of land use change in each scenario is consistent with the corresponding policy objectives, reflecting the good applicability of the model.

Forest land serves as the primary contributor to ecosystem service functions, and its area is a direct determinant of regional ESV. Consequently, the CP and EP scenarios yielded the highest total ESV, a result directly attributable to their substantial forest coverage; In the ED scenario, due to the significant increase of construction land (ESV negative indicator), ESV decreased significantly, highlighting the direct impact of different land use structures on ecological benefits[16].

Landscape ecological risk statistics reveal no extensive high-risk zones under the economic development scenario. This pattern is likely attributable to the clustered distribution of construction land, which enhanced the overall stability of the landscape structure; Under the agricultural protection scenario, the least risk areas and the most extreme risk areas are included, reflecting that the concentration of agricultural land can exacerbate the fragmentation of the landscape and increase the environmental risk; The ecological priority scenario effectively inhibited the expansion of high and extremely high risk areas[17].

There is a slight difference between ESV and landscape ecological risk analysis. Natural development scenario has the highest degree of coordination, while the economic development scenario has the lowest; The ecological priority scenario performs well in ESV and risk analysis, but the coupling coordination degree is poor, mainly because the spatial distribution of ESV high-value area and low-risk area does not match, which reflects the unbalanced regional development under this scenario, and there are potential sustainability risks, From the simulation scenario, there is a certain difference between this result and the previous research results on land [18], which may be caused by the small island area and the harsh restrictions on land type distribution, which is similar to the research results of Xi and others on Zhoushan Island[19,20].

5.2 Conclusion

In this research, PLUS model was applied to analyze the ecosystem service value of Pingtan Island, and the interaction between the two indicators was analyzed. The following conclusions can be drawn:

(1) The ESV evaluation identified the Cultivated Land Protection and EP scenarios as the most effective in enhancing ecosystem services, with total values reaching 12.863 billion yuan and 12.804 billion yuan, respectively.

(2) According to the environmental risk assessment results, it was found that EP scenario was the most effective one, and the average of landscape ecological risk index was only 0.0957.

(3) Among all scenarios, the ND scenario was characterized by the optimal level of coordination between ESV and ERI, and the areas of highly and relatively uncoordinated areas are as low as 2.87% and 7.52%.

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