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A Multi-System Coupling Coordination Assessment to Achieve the Integrated Objectives of Forest Conservation, Marine Governance, and Socioeconomic Development in the Bay Area: A Case Study in the Bay Area of the Fujian River Delta

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Abstract: The bay area contains terrestrial forests and coastal mangroves with vital ecosystem functions, which provide essential ecosystem services such as carbon sequestration and biodiversity maintenance. Meanwhile, the bay area usually hosts intensive socioeconomic activities. High-intensity anthropogenic activities in the bay area have threatened the terrestrial ecosystem and marine environment. Harmonizing the relationship between terrestrial ecosystem conservation, marine environmental governance, and socioeconomic development is crucial for realizing the national "coordinated land and marine development" strategy and promoting sustainability in the bay area. This study constructed a coupling coordination assessment system of the terrestrial ecosystem, marine environmental system, and socioeconomic system. Taking the bay area of the Fujian River Delta as a case study, multiple ecological models were integrated to quantify the coupling coordination degree between these three systems and present its spatial distribution characteristics. Furthermore, the constraint types on the coupling coordination degree were spatially revealed in the bay area. The results suggested that there are significant spatial differences in the coupling coordination degree of the three systems in the bay area of the Fujian River Delta. The areas with a relatively low coupling coordination degree are mainly focused on the central part of the Xiamen Bay area and the southeastern part of the Quanzhou Bay area. Regions with high socioeconomic development tend to present weak terrestrial or marine eco-environmental conditions. The critical constraint factor of the coupling coordination degree in the Zhangzhou Bay area is its backward socioeconomic development level. The backwardness of both the terrestrial ecosystem and marine environmental system exists in most districts of the Xiamen Bay area. In addition, the marine environmental conditions in the Xiamen Bay area are worse than those in the Quanzhou Bay Area and the Zhangzhou Bay area.

Keywords: terrestrial ecosystem; marine environmental system; socioeconomic system; coupling coordination degree; coordinated land and marine development; the bay area of the Fujian River Delta

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1. Introduction

Since the 18th National Congress of the Communist Party of China, the Chinese government has launched relevant policies to strengthen the construction of ecological civilization, promote green development and build a solid ecological security barrier, promote the coordinated development of the social economy and the ecological environment, and establish a development pattern of harmonious coexistence between humans and nature [1–3].

A regional coordinated development strategy was put forward, clarifying that coordination should be placed in a prominent position in regional development, emphasizing the need to "adhere to the coordinated land and marine development, accelerate the construction of a strong marine state". The "Coordinated land and marine development" was enhanced to meet the national strategic status. The bay area is a special place where terrestrial and marine areas meet and includes various ecosystems, such as forest and marine ecosystems. These ecosystems (especially forests and oceans) are critical habitats for many species to live, reproduce, forage, and migrate, and they provide a strong guarantee for biodiversity in the bay area [4]. In addition, forest and marine ecosystems provide diverse services for human production and livelihoods, contribute to the global urbanization process, and support intensive socioeconomic activities, the value of which is hard to measure [5]. Meanwhile, forest and marine ecosystems in the bay area are among the most threatened natural systems. Rapid socioeconomic development and high-intensity anthropogenic activities will threaten terrestrial forests and the marine environment. How to rationally coordinate the relationship between forest conservation, marine environmental governance, and socioeconomic development, to promote integrated and coordinated land and marine development, and achieve sustainable development in the bay area, which considers both terrestrial and marine places, has become an urgent issue to be addressed. Therefore, in order to promote forest conservation and ocean governance in the bay area and advance the coordinated development of forest and marine ecosystems with the economy and society, it is especially vital to conduct a multi-objective coupling coordination assessment that considers both the land and ocean.

Current studies have been conducted on coordinating regional ecological environment and socioeconomic development [6–8]. The commonly applied approaches include the coupling coordination degree model, linear regression equations, principal component analysis, etc. Among these, the coupling coordination degree model can avoid the influence of subjective factors and quantify the inter-regional synergistic effect. It is effective in reflecting the mutual influence and interaction between two or more systems [9,10], which is of guiding significance for the realization of sustainable development among multiple systems in multiple regions, has a certain degree of objectivity and universal applicability, and is a valuable tool for the assessment of the level regional coordinated development [11]. Some studies have assessed the regional coupling coordination degree between two or three systems. Luo et al. [12] analyzed the coupling coordination and interaction between low-carbon development and the ecological environment in the Yellow River Basin and explored the pathway to sustainable urban development. Cheng et al. [13] established a coupling coordination model including a green lifestyle to assess regional green competitiveness, explored the interprovincial interactions between economic society, ecological environment, and natural resources, and provided policy recommendations for enhancing green competitiveness. Liu et al. [14] presented the spatial and temporal characteristics of the coupling and coordination between interprovincial urbanization and the ecological environment in China, employing the coupling coordination degree model and the global–local spatial autocorrelation method. They provided suggestions for formulating urbanization development policies. Han et al. [15] examined the coupling coordination relationship between the economy, resources, and the environment in the Beijing–Tianjin–Hebei urban agglomeration. They proposed an effective way to realize urban sustainable development, which provides experience for promoting the coupling coordination of the economy, resources, and the environment in other urban agglomerations. Generally, most previous studies focused on the coupling coordination relationships between two or three systems that relate to terrestrial ecosystems, urbanization, natural resources, and industrial and economic development [16–18]. At the same time, fewer have considered both the terrestrial ecosystem and the marine environmental system together in the bay area.

This study aimed to establish a coupling coordination assessment system integrating the terrestrial ecosystem, marine environmental system, and socioeconomic system with synergistic objectives toward forest conservation, marine governance, and socioeconomic development. Taking the bay area of the Fujian River Delta as a case study, the entropy-weighted TOPSIS (technique for order of preference by similarity to ideal solution) method, principal component analysis, and the coupling coordination degree model are applied to explore the spatial distribution characteristics and the coupling coordination relationship between the three systems in the bay area of the Fujian River Delta. Furthermore, various spatial zoning is conducted to reveal the backward types and distribution patterns for coupling coordination around the bay area.

2. Materials and Methods

2.1. Study Area

The bay area of the Fujian River Delta consists of Xiamen Bay area, Quanzhou Bay area, and Zhangzhou Bay area, including 17 coastal districts and counties (6 in Quanzhou City, 6 in Xiamen City, and 5 in Zhangzhou City) (Figure 1). It is characterized by the typical integration of forests, mountains, and oceans in the coastal belt of Fujian Province in China. It is currently in a critical period of rapid development and transformation. With increasing urbanization, human activities exert enormous pressure on both terrestrial forest areas and marine areas. The destruction and degradation of forest and marine ecosystems have led to an imbalance between the terrestrial ecosystem, marine environmental system, and socioeconomic system [19]. Therefore, the formulation of reasonable and targeted policies and measures for managing the bay area is essential for promoting synergies among forest conservation, marine governance, and socioeconomic development and for advancing the progress of sustainable development around the bay area of the Fujian River Delta.

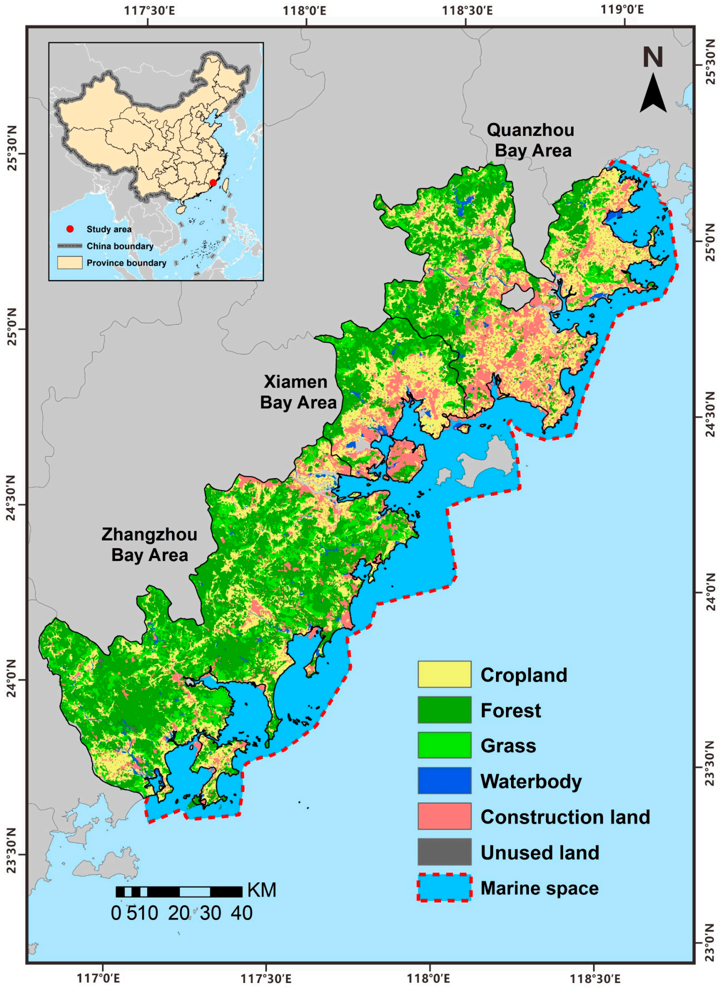

Figure 1. The location and LULC of the bay area of the Fujian River Delta.

2.2. Construction of Framework and Assessment System

Coupling is the level of interdependence of two or more systems. Coordination refers to the benign relationship between various systems or elements. Coupling coordination can measure the degree of harmonization between various systems. In order to achieve the synergistic objectives relating to forest conservation, marine governance, and socioeconomic development in the bay area, to mitigate the impacts of anthropogenic activities on both terrestrial and marine ecosystems, and to coordinate the relationship between natural resource depletion and socioeconomic development, this study constructed a multi-objective integrated assessment system that includes the terrestrial ecosystem [20,21], marine environmental system, and socioeconomic system [2,22,23] (Figure 2) to present the degree of coupling coordination between these three systems in the bay area and to identify the interactions and impacts across various systems. It contributes to the formulation of management measures and policy recommendations for the achievement of sustainability in the bay area.

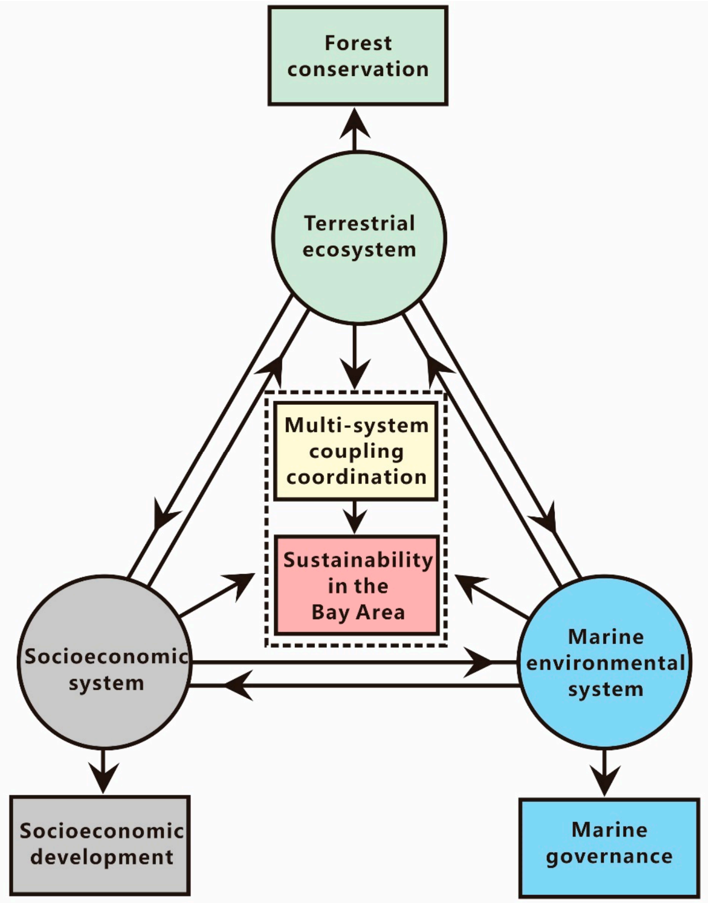

Figure 2. Systems' construction of terrestrial ecosystem, marine environmental system, and socioeconomic system for bay area.

The terrestrial ecosystem is characterized by ecosystem vigor, ecosystem organization and structure, and ecosystem resilience (Table 1). Carbon sequestration reflects the ability of vegetation to absorb carbon dioxide by photosynthesis, which indicates the ecosystem's vitality to a certain extent [20]. Habitat quality can present ecosystem vigor depending on the condition of the habitat and the biodiversity level [21]. Hence, carbon sequestration capacity and habitat quality were selected to characterize ecosystem vigor. The landscape pattern index, involving the diversity index, contagion index, fragmentation index, evenness index, and shape index, can be employed to quantify the state of the ecosystem's organization and structure [20]. The ecological resilience index reflects an ecosystem's ability, potential, and difficulty to be faced, to achieve a return to its original state after damage [20] (i.e., its level of resilience). Carbon sequestration and habitat quality need to be calculated by the InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) model, and the landscape pattern index can be obtained by Fragstats 4.2 software. The ecological resilience index can be calculated using Equation (3).

Table 1. Construction of a multi-objective integrated assessment system for bay area.

Target Layer	Rule Layer	Indicator Layer	*X*	Attribute	Data Sources
Terrestrial ecosystem (target: forest conservation)	Ecosystem vigor	Carbon sequestration capacity	*X*1	Positive	Calculated by InVEST model
		Habitat quality	*X*2	Positive	Calculated by InVEST model
	Ecosystem organization and structure	Landscape pattern index	*X*3	Positive	Calculated by Fragstats software
	Ecosystem resilience	Ecological resilience index	*X*4	Positive	Calculated using Equation (3)
Marine environmental system (target: marine governance)	Marine water quality	Percentage of Class I and Class II marine water quality	*X*5	Positive	Marine Environment Bulletin of Fujian Province
	Marine climate	Ocean temperature anomaly	*X*6	Negative	NASA Earth observation data
	Marine atmosphere	Optical thickness of marine aerosol particles (AOD)	*X*7	Negative	NASA Earth observation data
Socioeconomic system (target: socioeconomic development)	Economy	Economic density	*X*8	Positive	Statistical yearbooks
		Percentage of tertiary sector value added	*X*9	Positive	Statistical yearbooks
		Disposable income per capita	*X*10	Positive	Statistical yearbooks
	Science and education	Percentage of science and education expenditure to fiscal expenditure	*X*11	Positive	Statistical yearbooks
	Consumption	Total retail sales of consumer goods per capita	*X*12	Positive	Statistical yearbooks
	Urbanization	Urbanization rate	*X*13	Positive	Statistical yearbooks
	Medical treatment	Number of beds in healthcare facilities per 1000 population	*X*14	Positive	Statistical yearbooks

Note: The landscape pattern index is intended to reflect ecosystem organization and structure in terms of landscape pattern, which integrates (1) Shannon's diversity index, (2) contagion index, (3) fragmentation index, (4) Shannon's evenness index, and (5) shape index.

The marine environmental system includes three dimensions, i.e., marine water quality, marine atmosphere, and marine climate (Table 1). Marine water quality is mainly reflected through the percentage of Class I and II marine water quality, which indicates the proportional area of seawater under the regional jurisdiction with great water quality. The marine atmosphere is indicated by the optical thickness of marine aerosol particles (AOD), a crucial physical quantity representing the degree of atmospheric turbidity. Generally, a higher AOD leads to lower atmospheric visibility. Therefore, this indicator was selected to quantify the degree of turbidity in the marine atmosphere, reflecting the impact of anthropogenic activities on the surrounding marine environment. Marine temperature anomaly is the degree of variability in the current marine temperature compared to that in standard years (i.e., average marine temperature from 2002 to 2010), which can be applied to reflect changes in marine climate to a certain extent, with a greater degree of variability in marine temperature indicating a greater degree of marine climate change.

The level of economy, science and education, consumption, urbanization, and medical treatment characterizes the socioeconomic system [2,22,23]. Economic density, percentage of tertiary sector value added, and disposable income per capita were selected to represent the level of regional economic development. Economic density is a key indicator of the strength of regional economic development. The percentage of tertiary sector value added and disposable income per capita can reflect the degree of regional economic transformation and development. Disposable income per capita refers to the portion of a resident's total cash income that can be used for the resident's daily life. The percentage of science and education expenditure to fiscal expenditure can demonstrate the degree of emphasis placed on science and education by the regional government and society, as well as the overall level of development of science and education. The total retail sales of consumer goods per capita indicate the resident's consumption level and capacity. The urbanization rate quantifies the level of regional urbanization. The number of beds in healthcare facilities per 1000 population is utilized to measure the development level of regional medical treatment.

2.3. Data Processing

2.3.1. Data Processing for Terrestrial Ecosystem Indicators

(1) Carbon sequestration capacity assessment

The study conducted the spatial quantification of carbon sequestration capacity through the carbon sequestration module of the InVEST model [24,25], which considers four types of carbon pools (aboveground carbon stocks, belowground carbon stocks, soil, and dead organic matter carbon stocks). The calculations are presented as follows:

$$C = C_{above} + C_{below} + C_{dead} + C_{soil} \tag{1}$$

where C is carbon stock, C_{above} is aboveground carbon stock. C_{below} is underground carbon stock, C_{dead} is dead organic matter carbon stock, and C_{soil} is soil carbon stock. The carbon density parameters required for the model are referenced to related literature with regions that are the same or similar to the study area [26] and national GHG inventory guidelines issued by the IPCC.

(2) Habitat quality assessment

The spatial distribution of habitat quality in the bay area was obtained through the habitat quality module of the InVEST model [24]. This module considers the proximity of habitats to various types of land use and the intensity of land use. Specific parameter settings include the maximum influence distance and weight of the stress factors, the habitat quality of each land use type and its sensitivity to the stress factors, etc. The relevant parameter settings refer to the appropriate literature that closely matches the characteristics of the study area [21]. The specific equations are as follows:

$$M_{dj} = N_p \left[1 - \left(\frac{D^r{}_{dp}}{D^r{}_{dp} + a^r} \right) \right] \tag{2}$$

where M_{dj} is the habitat quality of pixel d in land use type p. D_{dp} is the magnitude of stress suffered by pixel d in land use type p. a is the half-saturation constant; N_p is the habitat suitability of land use type p, and r is the default parameter of the model.

(3) Calculation of landscape pattern index

Five representative landscape pattern factors were selected and measured by the Fragstats model [27–30], i.e., Shannon's diversity index, contagion index, fragmentation index, shape index, and Shannon's evenness index. Of these, Shannon's diversity index can represent the characteristics of landscape diversity, and the contagion index can describe the landscape's connectivity and extension pattern. The shape index can reflect the degree of landscape spatial irregularity. Furthermore, Shannon's evenness index can reasonably evaluate the dominance of landscape patches.

(4) Calculation of ecological resilience index

The ecological resilience index is measured depending on the ecological resilience coefficients under various land use types [20,31]. The specific calculations are as follows:

$$E = \sum_{i=1}^{n} T_i \times EU_i \tag{3}$$

where E is the ecological resilience index, T_i is the area of land use type i, EU_i is the ecological resilience coefficient for land use type i.

2.3.2. Comprehensive Measurement and Assessment

The entropy-weighted TOPSIS method and principal component analysis were employed to conduct a comprehensive evaluation of each system. The principal component analysis can focus on critical issues to find the internal connection among various indicators when analyzing and solving complex problems, which simplifies the problem and improves efficiency. However, when using principal component analysis, the weight of the first principal component extracted may be too large, which squeezes the proportion of the remaining principal components, resulting in less objective weighting. The entropy-weighted method can objectively assign weight to the relevant indicators of each system [32,33]. Therefore, this study conducted a comprehensive evaluation of each system integrating the entropy-weighted TOPSIS method and the principal component analysis. The weight of each indicator determined by the entropy-weighted method is shown in Table 2. The calculations for the comprehensive evaluation were as follows:

Table 2. Weight factors of each indicator based on the entropy-weighted method.

Item	***X*1**	***X*2**	***X*3**	***X*4**	***X*5**	***X*6**	***X*7**
Weight	0.1846	0.3550	0.2871	0.1732	0.5144	0.3030	0.1826
Item	***X*8**	***X*9**	***X*10**	***X*11**	***X*12**	***X*13**	***X*14**
Weight	0.3236	0.0951	0.1417	0.0562	0.1898	0.1183	0.0752

(1) Comprehensive evaluation based on the entropy-weighted TOPSIS method

Step 1: Nondimensionalization. The indicators were normalized using the extreme value method, and the equations were applied for the positive indicators (Equation (4)) and the negative indicators (Equation (5)).

$$Y_{ij} = \frac{x_{ij} - \min\limits_{1 \le j \le k} x_{ij}}{\max\limits_{1 \le j \le k} x_{ij} - \min\limits_{1 \le j \le k} x_{ij}} \tag{4}$$

$$Y_{ij} = \frac{\max\limits_{1 \le j \le k} x_{ij} - x_{ij}}{\max\limits_{1 \le j \le k} x_{ij} - \min\limits_{1 \le j \le k} x_{ij}} \tag{5}$$

Step 2: Measurement of information entropy.

$$H_j = -m \sum_{i=1}^{k} \frac{Y_{ij}}{\sum\limits_{i=1}^{k} Y_{ij}} \ln \frac{Y_{ij}}{\sum\limits_{i=1}^{k} Y_{ij}}, \ m = (\ln k)^{-1} \tag{6}$$

Step 3: Determination of weights by the entropy-weighted method.

$$W_j = \frac{1 - H_j}{p - \sum\limits_{i=1}^{p} H_j} \tag{7}$$

where W_j is the weight for indicator j determined by the entropy-weighted method, H_j is the information entropy of indicator j. p is the number of indicators and k is the number of study samples.

Step 4: Determination of positive ideal solution and negative ideal solution.

The positive ideal solution:

$$Y^{+} = (\max_{1 \le i \le k} y_{i1}, \max_{1 \le i \le k} y_{i2}, \ldots, \max_{1 \le i \le k} y_{ip}) \tag{8}$$

The negative ideal solution:

$$Y^{-} = (\min_{1 \le i \le k} y_{i1}, \min_{1 \le i \le k} y_{i2}, \ldots, \min_{1 \le i \le k} y_{ip}) \tag{9}$$

Distance to the positive ideal solution:

$$s_i^{+} = \sqrt{\sum_{j=1}^{p} W_j (y_{ij} - Y_j^{+})^2} \tag{10}$$

Distance to the negative ideal solution:

$$s_i^{-} = \sqrt{\sum_{j=1}^{p} W_j (y_{ij} - Y_j^{-})^2} \tag{11}$$

Step 5: Calculation of the comprehensive evaluation value based on the entropy-weighted TOPSIS method.

$$S_i = \frac{s_i^{-}}{s_i^{-} + s_i^{+}};\ (i = 1,\ 2,\ \ldots,\ k;\ 0\ \le S_i\ \le\ 1) \tag{12}$$

where S_i is the comprehensive evaluation value based on the entropy-weighted TOPSIS method.

(2) Comprehensive evaluation based on the principal component analysis.

SPSS 22.0 software can conduct the principal component analysis and calculate factor loadings, eigenvalues ($\lambda_1 \ge \lambda_2 \ge \cdots \ge \lambda_p \ge 0$), eigenvectors ($u_1, u_2, \cdots, u_p$), and variance contributions (b_j).

$$\begin{cases} y_1 = u_{11}x_1 + u_{21}x_2 + \cdots u_{n1}x_n \\ y_2 = u_{11}x_1 + u_{21}x_2 + \cdots u_{n1}x_n \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ y_j = u_{11}x_1 + u_{21}x_2 + \cdots u_{nj}x_n \end{cases} \tag{13}$$

where y_1 is the first principal component, y_2 is the second principal component, and y_j is the jth principal component.

$$C = \sum_{j=1} b_j y_j \tag{14}$$

where C is the comprehensive evaluation value based on the principal component analysis.

(3) Comprehensive evaluation integrating the entropy-weighted TOPSIS method and the principal component analysis.

$$U_i = \frac{S_i + C_i}{2} \tag{15}$$

where S_i is the comprehensive evaluation value for sample i based on the entropy-weighted TOPSIS method. C_i is the comprehensive evaluation value for sample i based on the principal component analysis.

2.3.3. Calculation of Coupling Coordination Degree

Coupling coordination analysis can be utilized to reveal problems that may arise in achieving sustainable development. A multi-system coupling coordination analysis of the terrestrial ecosystem, marine environmental system, and socioeconomic system would contribute to sustainability in the bay area by promoting the integrated objectives of forest conservation, ocean governance, and socioeconomic development.

The coupling coordination degree model is employed to assess the strength of the coupling coordination and explore the interactions between the terrestrial ecosystem, marine environmental system, and socioeconomic system in the bay area. The calculations [34,35] are presented as follows:

$$C(U_1, U_2, \ldots, U_n) = n \times \left[\frac{U_1 \times U_2 \cdots \times U_n}{(U_1 + U_2 + \cdots + U_n)^n} \right]^{1/n} \tag{16}$$

where C is the coupling degree, taking the value of 0–1. U_1, $U_2, \ldots$ represent the comprehensive evaluation value of each system. n is the number of systems. The coupling degree only presents the strength of the coupling effect between multiple systems, which cannot reflect the coordination level. Therefore, the coupling coordination degree model is applied to comprehensively assess the coupling coordination degree between the three systems in the bay area.

$$D = \sqrt{C \times T} \tag{17}$$

$$T = \alpha U_1 + \beta U_2 + \gamma U_3 \tag{18}$$

where D is the coupling coordination degree, T is the multi-system comprehensive evaluation value, α, β, γ are the pending coefficients, and the pending coefficients are set to 1/3 according to the previous literature [17]. The natural breaks (Jenks) algorithm is employed to classify the bay area into a "high coupling coordination area, relatively high coupling coordination area, relatively low coupling coordination area, and low coupling coordination area" following the regional coupling coordination degree.

2.4. Data Sources

Land use or land cover data were obtained from Landsat TM remote sensing images by visual interpretation. Land use was divided into six primary land classifications (i.e., cropland, forest, grass, waterbody, construction land, and unused land) and 13 secondary land classifications (i.e., paddy land, dry land, forested land, shrub land, open forested land, high-cover grassland, low-cover grassland, rivers, reservoirs, mudflats, urban land, rural land, and transportation, industrial, and mining land). The accuracy was 30 m. The spatial vector data were from the national 1:4 million fundamental map. The percentage of Class I and Class II marine water quality was derived from the Marine Environment Bulletin of Fujian Province, and the optical thickness of marine aerosol particles was obtained from NASA Earth observation data. Socioeconomic data were mainly derived from the 2016 statistical yearbooks of Quanzhou City, Zhangzhou City, and Xiamen City.

3. Results

3.1. Spatial Distribution of the Comprehensive Levels of Various Systems in the Bay Area

The comprehensive assessment values of the various systems were divided into four classifications by the natural breaks (Jenks) algorithm. Figure 3 presents the spatial distribution of the terrestrial ecosystem, marine environmental system, and socioeconomic system in the bay area of the Fujian River Delta. The development levels of the terrestrial ecosystem and socioeconomic system in the bay area of the Fujian River Delta present a dramatically opposite spatial distribution pattern. The socioeconomic development level has significant spatial variability, with a distribution pattern that is high in the northeast and low in the southwest. The areas with a high socioeconomic development level mainly focus on the core areas of Xiamen Island (i.e., Siming District and Huli District) and southeast of Quanzhou Bay area (i.e., Shishi City, Fengze District, and Jinjiang City). Meanwhile, the overall socioeconomic development level of the Zhangzhou Bay area lags behind that of the Xiamen Bay area and the Quanzhou Bay area. Although Xiamen Island has excellent strength in its socioeconomic system, its terrestrial ecosystem lags significantly behind other bay areas in the Fujian River Delta. The overall terrestrial ecosystem development level in the Zhangzhou Bay area is higher than the average value of the bay area of the Fujian River Delta, with sound ecological environmental quality. In addition, most of the districts and counties in the Quanzhou Bay area have a low terrestrial ecosystem assessment value, especially in the southeast of the Quanzhou Bay area, which has the weakest level. The marine environmental condition in the bay area of the Fujian River Delta demonstrates a "dumbbell-shaped" spatial distribution pattern with a relatively high level in its northeast and southwest. However, the marine environmental conditions are relatively poor in the Xiamen Bay area and the northern part of the Zhangzhou Bay area.

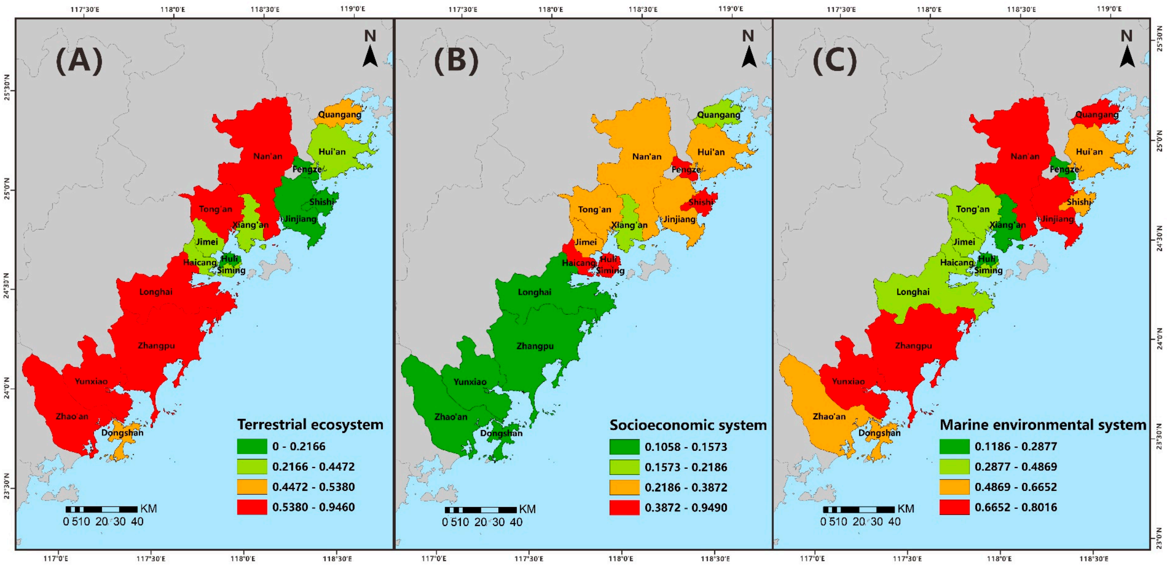

Figure 3. Spatial distribution of the development level of terrestrial ecosystem (**A**), socioeconomic system (**B**), and marine environmental system (**C**) in the bay area of the Fujian River Delta.

3.2. Analysis of the Interregional Coupling Coordination of Various Systems in the Bay Area

The three primary bay areas (Xiamen Bay area, Zhangzhou Bay area, and Quanzhou Bay area) in the Fujian River Delta failed to simultaneously achieve high coupling coordination between their terrestrial ecosystems, socioeconomic systems, and marine environmental systems (Table 3). There is a considerably low coupling coordination degree in the socioeconomic system between Xiamen Bay area and Zhangzhou Bay area and between Quanzhou Bay area and Zhangzhou Bay area, which indicates a low inter-regional socioeconomic synergistic development level with significant spatial differences. Moreover, there is a medium coupling coordination degree between the Xiamen Bay area and the Quanzhou Bay area over the three systems, which could potentially improve the synergic development in forest conservation, marine governance, and socioeconomic development for the two bay areas. A relatively high coupling coordination degree between the Zhangzhou Bay area and the Xiamen Bay area is present in terms of the terrestrial ecosystem. Such a relatively high coupling coordination degree between the Zhangzhou Bay area and the Quanzhou Bay area is demonstrated in terms of the terrestrial ecosystem and the marine environmental system.

Table 3. Interregional coupling coordination of the bay areas of the Fujian River Delta.

Type	Terrestrial Ecosystem	Marine Environmental System	Socioeconomic System
Xiamen Bay area–Zhangzhou Bay area	0.7741	0.6866	0.3894
Xiamen Bay area–Quanzhou Bay area	0.5750	0.6755	0.6039
Quanzhou Bay area–Zhangzhou Bay area	0.7795	0.8233	0.3092

3.3. Multi-System Coupling Coordination Assessment in the Bay Area

There is a large spatial difference in the coupling coordination degree between the terrestrial ecosystem, marine environmental system, and socioeconomic system across the districts and counties in the bay area of the Fujian River Delta (Figure 4). Compared to the Xiamen Bay area and the Quanzhou Bay area, the districts and counties in the Zhangzhou Bay area have the highest average coupling coordination degree. However, there is a relatively low coupling coordination degree between the terrestrial ecosystem, marine environmental system, and socioeconomic system in the southeastern districts and counties of Quanzhou Bay. Huli District in the Xiamen Bay area is the core area supporting Xiamen's socioeconomic development. Xiang'an and Haicang Districts are undergoing rapid urbanization and high-speed development. These areas exert enormous pressure on both terrestrial and marine ecosystems, resulting in a low degree of coupling coordination between the terrestrial ecosystem, marine environmental system, and socioeconomic system.

The significant spatial variation in the coupling coordination degree is related to each system's uneven development of districts and counties in the bay area (Figure 5). To reveal the existing coupling coordination problem and identify key constraints to sustainable development in the bay area, the average level of each system was employed as a threshold value to screen out districts and counties with various lagging development types (Figure 6). This is conducive to discovering the reasons for poor regional coupling coordination and provides a foundation for establishing targeted sustainability management measures. Of the regions, 47% have terrestrial ecosystem conditions that are weaker than the threshold level. Many forests have been destroyed, and their ecological functions have been degraded. These areas are mainly concentrated in the districts and counties of the Quanzhou Bay area and around Xiamen Bay, Maluan Bay, and Xinglin Bay. The marine environmental condition is below the critical level in 47% of the areas, mainly focused in the marine space of the Xiamen Bay area. Moreover, 65% of regions with socioeconomic development below the threshold are primarily distributed throughout the entire Zhangzhou Bay area, most of the districts and counties in the Quanzhou Bay area, and Tong'an district and Xiang'an district in Xiamen Bay. In general, 41% of districts and counties in the bay area of the Fujian River Delta suffer from a backwardness problem in one of the systems. While more than half of the districts and counties are in areas where two systems are lagging simultaneously, these districts face two types of outstanding issues that must be addressed. Hui'an County and Jinjiang City in the Quanzhou Bay area are simultaneously confronted with backwardness in their terrestrial ecosystems and socioeconomic systems. The Tong'an District in Xiamen Bay area and Longhai City in the Zhangzhou Bay area face backwardness in both the marine environmental system and the socioeconomic system. The problem of underdevelopment in both the terrestrial ecosystem and marine environmental system involves the Fengze District in the Quanzhou Bay area and the Jimei, Haicang, Huli, and Siming Districts in the Xiamen Bay area.

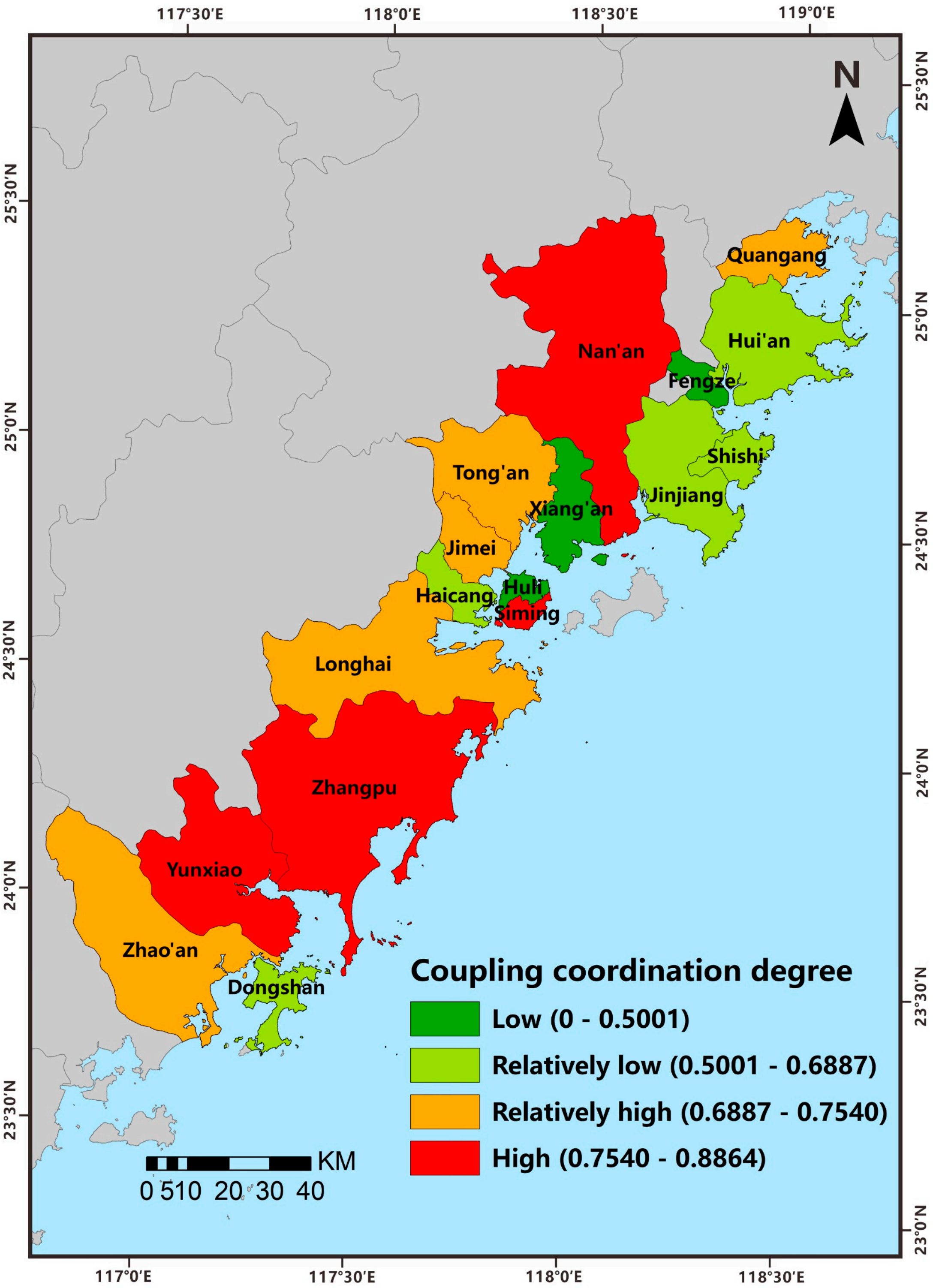

Figure 4. Spatial distribution of coupling coordination degree between terrestrial ecosystem, marine environmental system, and socioeconomic system in the bay area of the Fujian River Delta.

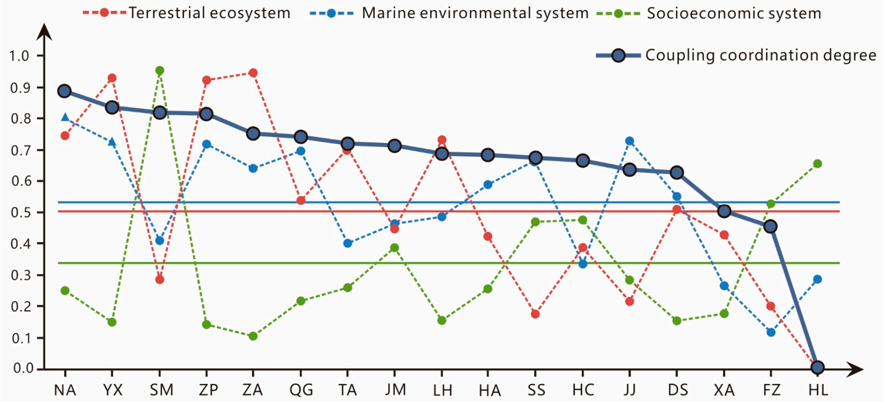

Figure 5. Overlapping map of the coupling coordination degree and the development level of each system in the bay area (the parallel lines in the figure are the average of the development level of each system. NA: Nan'an, YX: Yunxiao, SM: Siming, ZP: Zhangpu, ZA: Zhao'an, QG: Quangang, TA: Tong'an, JM: Jimei, LH: Longhai, HA: Hui'an, SS: Shishi, HC: Haicang, JJ: Jinjiang, DS: Dongshan, XA: Xiang'an, FZ: Fengze, HL: Huli).

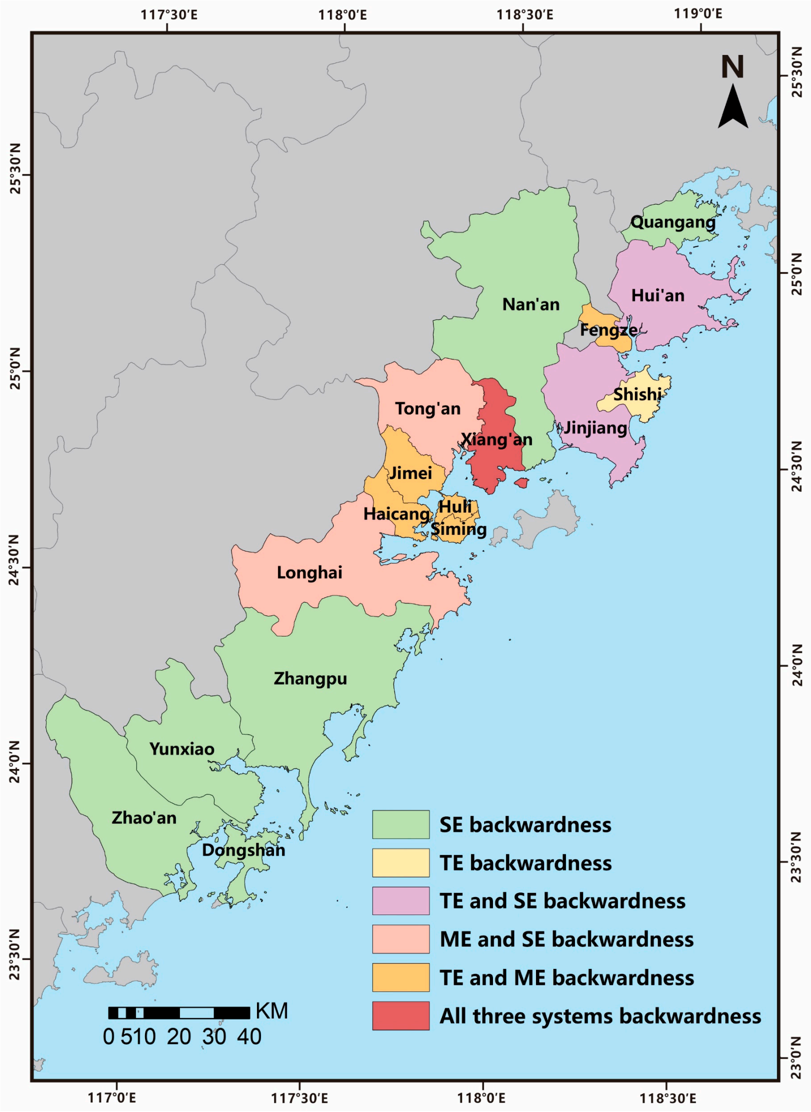

Figure 6. The map revealing the spatial view of the constraint types on the coupling coordination of the bay area of the Fujian River Delta (TE: terrestrial ecosystem, ME: marine environmental system, SE: socioeconomic system).

Notably, Xiang'an District in the Xiamen Bay area is the only area where all three systems are simultaneously backward. Its development level in terms of terrestrial ecosystem, marine environmental system, and socioeconomic system is lower than the average level of the bay area of the Fujian River Delta. The phenomenon of double backwardness involving the terrestrial ecosystem and the marine environmental system is present in Xiamen Bay. The increasing anthropogenic economic activities have doubled their impacts on terrestrial forests and the marine environment.

4. Discussion

4.1. Differences in the Development Level Among Various Systems in the Bay Area

In terms of each system's development level, regions with lower socioeconomic development tend to have a higher terrestrial ecological and marine environmental level, while regions with high socioeconomic development level tend to witness threats to their ecosystems. This is mainly because the ecological carrying capacity depends on resource endowment and the interaction between humans and the environment, which is closely related to anthropological socioeconomic activities [36]. Large natural resource exploitation and utilization tend to occur in regions with a high socioeconomic development level. The occupation of terrestrial forest ecosystems by high-intensity anthropogenic activities has led to the destruction of forest ecosystem structures and the degradation of forest function, which has profoundly impacted the health of forest ecosystems. Meanwhile, the pollution of the atmosphere, water, and soil generated by human socioeconomic activities has triggered severe damage to the regional ecological environment and threatened terrestrial and marine ecosystems.

Notably, the terrestrial ecosystem, socioeconomic system, and marine environmental system in the Xiang'an District of the Xiamen Bay area all present a low development level. Although Xiang'an District possesses superior location conditions and a sound natural ecological foundation, preliminary urban construction and development lacked attention to ecosystem protection and inadequate holistic and integrated planning for regional development, which led to the disorderly occupation of ecological environmental resources and marine ecological spaces and the underutilization of advantageous resources [37]. Furthermore, although Longhai City has a sound terrestrial ecosystem, its marine environment and socioeconomic development are not satisfactory. The Jiulong River estuary is located in Longhai City, and drains into the Taiwan Strait. The natural mangrove forests distributed around the Jiulong River estuary have gradually disappeared due to human exploitation activities over the past half-century [38]. This has impacted the function of mangrove ecosystems and weakened the purification effect from the natural mangrove forests on marine water quality. In addition, nutrient fluxes from Longhai City and its neighboring areas delivered to the nearshore marine area have increased over the years [39].

4.2. Causes for Spatial Variation in Coupling Coordination Degree in the Bay Area

The leading causes underlying the low coupling coordination degree between the terrestrial ecosystem, marine environmental system, and socioeconomic system in Xiamen Bay are the backwardness of the regional terrestrial ecosystem and marine environmental system. In recent years, increasing urbanization and rapid socioeconomic development in Xiamen have threatened its ecology and environment and imposed pressure on both land and ocean, which is particularly obvious on Xiamen Island [19]. Moreover, Xiamen Bay, as the entrance to the ocean from the Jiulong River, has been receiving wastewater from the Jiulong River Basin and neighboring coastal areas for a long time. Over a long period, inorganic nitrogen and reactive phosphates have been the main pollutants exceeding the standards in Xiamen Bay [40,41], which have impacted the surrounding marine water quality. Therefore, poor terrestrial ecological and marine environmental conditions exist in the Haicang, Xiang'an, and Huli districts in the Xiamen Bay area, leading to a low regional multi-system coupling coordination degree. Xiang'an District has severe problems in all three systems. In its socioeconomic development process, reclamation activities, such as airport construction and aquaculture through reclamation, have continually squeezed the coastal ecological space. The accompanying problems, such as weakened hydrodynamics, siltation of waterways, and deterioration of marine water quality, have led to the exacerbation of both the terrestrial and marine ecological environment [37]. In addition, coastal sustainability is further impacted by the insufficient concepts and perceptions of coordinated land and marine development and eco-environmental protection in Xiang'an District. The main problem in the Zhangzhou Bay area is the relative backwardness of regional socioeconomic development owing to its agriculture-dominated industrial structure. Nevertheless, its overall terrestrial ecology and marine environment are in an excellent condition. Most districts and counties in the Quanzhou Bay area are experiencing backward terrestrial ecological conditions. As the highest performing economic city in Fujian Province, Quanzhou's rapid urbanization since the turn of the 21st century has continually reduced the ecological space and threatened its ecological stability. The industry-dominated industrial structure has placed a huge burden on natural resources, which has impacted its ecological carrying capacity. Hence, forest conservation and terrestrial ecosystem restoration are priority issues that need to be addressed in Quanzhou Bay in the future.

4.3. Variation in Interregional Coupling Coordination Degree in the Bay Area

Even though the People's Government of Fujian Province has been promoting the Xiamen–Zhangzhou–Quanzhou Metropolitan Area Integration Work Program since 2011, which aimed to harmonize and coordinate the resources across the three cities of Xiamen, Zhangzhou, and Quanzhou and promote resource sharing to improve the overall economic strength of the urban group, the coupling coordination degree of each system between the Xiamen Bay area and Zhangzhou Bay area and between Xiamen Bay area and Quanzhou Bay area is not very high, especially the coupling coordination degree of the socioeconomic system between the Xiamen Bay area and the Zhangzhou Bay area; and between the Quanzhou Bay area and the Zhangzhou Bay area, it is extremely low. Although Xiamen holds the highest socioeconomic development level in the bay area of the Fujian River Delta, it has not formed a good radiation effect on its neighboring regions. Quanzhou has great urban amenities but lacks the ability to influence, radiate, and serve its surrounding areas. Zhangzhou's poor infrastructure makes it vulnerable to the siphon effect, which hinders regional development. In addition, due to the different industrial structure characteristics and economic foundations across the three bay areas (Xiamen, Quanzhou, and Zhangzhou), it is difficult for them to achieve coordinated interregional development in the short term. As a sub-provincial city, Xiamen excels in finance, tourism, and port transportation. Zhangzhou mainly focuses on primary industry, and Quanzhou has great industrial strength. They are experiencing a critical stage in industrial transformation and upgrading, and there is insufficient interregional cooperation and exchange.

4.4. The Indicator Weights for Each System in the Bay Area

The study suggested that ecosystem vigor and habitat quality play a significant role in terrestrial ecosystems. Marine water quality (or percentage of Class I and Class II marine water quality) is highly important in the marine environmental system. Moreover, economic density and total retail sales of consumer goods per capita are essential in the socioeconomic system. These indicator weights were estimated in the area under examination (i.e., the bay area of the Fujian River Delta). Bay areas with varied terrestrial and marine eco-environmental conditions and socioeconomic development levels could present differentiated weights. In order to achieve sustainability in the bay areas, the estimation of weights can be improved and optimized, in combination with extended future studies in other bay areas, such as the Guangdong–Hong Kong–Macao Greater Bay area, the Yangtze River Estuary–Hangzhou Bay area, and Bohai Bay area.

4.5. Implications for Sustainability in the Bay Area

This study proposes suggestions to promote the sustainable development of the bay area. (1) While paying attention to the terrestrial ecosystem's health, marine environmental protection needs to be given equal priority, and the synergistic management and consistent conservation of the land and the sea should be the core task to promote the sustainable development of the bay area. (2) It should exert the role of economic growth in the core area of the socioeconomic system and promote industrial transformation and upgrading in districts and counties lagging in regional development. (3) The land pressure on the regions with excellent socioeconomic development at the expense of serious ecological space occupation should be alleviated to realize interregional synergistic development involving the terrestrial ecosystem, marine environmental system, and socioeconomic system of the bay area.

5. Conclusions

The study conducted a novel multi-system coupling coordination assessment applicable to the bay area, integrating the terrestrial ecosystem, marine environmental system, and socioeconomic system. The established assessment system considers marine factors and covers various terrestrial and marine evaluation indicators, which provided a paradigm for measurement and comparison and were experimentally employed in the bay area of the Fujian River Delta, though future efforts are necessary in more bay areas (such as the Guangdong–Hong Kong–Macao Greater Bay area, the Yangtze River Estuary–Hangzhou Bay area, and Bohai Bay area) to optimize the parameters of the paradigm for promoting the achievement of land–ocean integrated sustainability in bay areas.

The case study found that there are large spatial differences in the coupling coordination degree between the terrestrial ecosystem, marine environmental system, and socioeconomic system in the bay area of the Fujian River Delta. The areas with a relatively low degree of coupling coordination are mainly concentrated in the central part of the Xiamen Bay area and the southeastern part of the Quanzhou Bay area. The uneven development level of each system has an impact on the coupling coordination degree to constrain the sustainability in the bay area. Areas with high socioeconomic development tend to experience poor terrestrial ecosystem conditions or marine environmental conditions. The key factor constraining multi-system coupling coordination and sustainable development in the Xiamen Bay area is its poor marine environmental condition; the critical constraining factor in the Quanzhou Bay area is its weak terrestrial ecosystem condition, and the essential constraining factor in the Zhangzhou Bay area is its backward socioeconomic development.

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