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Special Issue Reprint

Marine Bearing Capacity and Economic Growth

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Guest Editor

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This is a reprint of the Special Issue, published open access by the journal *Water* (ISSN 2073-4441), freely accessible at: https://www.mdpi.com/journal/water/special_issues/P37C18T20T.

For citation purposes, cite each article independently as indicated on the article page online and as indicated below:

Lastname, A.A.; Lastname, B.B. Article Title. *Journal Name* **Year**, *Volume Number*, Page Range.

ISBN 978-3-7258-4679-5 (Hbk)
ISBN 978-3-7258-4680-1 (PDF)
https://doi.org/10.3390/books978-3-7258-4680-1

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About the Editor

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Shuhong Wang is a professor, doctoral supervisor, Shandong Taishan Scholar Young Expert, Elsevier China Highly Cited Scholar and Top 2% Global Scientist, and Shandong Big Data Industry Pilot Expert, and is currently the Vice Dean of the School of International Economics and Trade of Shandong University of Finance and Economics. He has been committed to teaching, scientific research, and practical application in the fields of trade and environment, biodiversity, the marine economy, and climate change for a long time. He has presided over more than ten national and provincial projects, such as the National Social Science Post-Funding, the National Natural Science Foundation, and the Ministry of Education Social Science Fund. He has won several provincial and ministerial awards, such as the Ministry of Education's Outstanding Scientific Research Achievement Award for Higher Education Institutions and the Shandong Province Social Science Outstanding Achievement Award. He has published more than 100 academic articles in journals such as *Economic Research*, *Management World*, *Omega*, *IJPE*, *IJPR*, *JEM*, and *Energy Economics*. He has also published seven books.

Preface

This Reprint addresses the urgent need to understand and manage the complex interactions between marine carrying capacity and economic development, particularly in the context of rapid coastal growth and mounting environmental pressures. The scope of the Reprint encompasses a range of interdisciplinary studies that investigate the sustainability of marine resource use, the transformation of marine industries, and the policies required to balance economic advancement with ecological protection.

The motivation for compiling this Reprint stems from the growing recognition that the health of the marine environment is fundamentally linked to the long-term viability of economic growth in coastal regions. As environmental degradation and climate change intensify, assessing and enhancing the marine carrying capacity has become an essential part of marine governance and strategic planning.

This Reprint aims to bring together the latest research findings, modeling tools, and policy perspectives that inform sustainable marine development. It is intended for a broad audience, including academic researchers, policymakers, environmental planners, and stakeholders engaged in the marine economy and ecological protection. We hope that the insights offered in this Reprint will contribute to more coordinated, resilient, and sustainable pathways for marine economic growth.

Shuhong Wang
Guest Editor

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Editorial

Marine Carrying Capacity and Economic Growth

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1. Introduction

Developments in science and technology and the increasing scope of human activities have led to the gradual realization of the potential of oceans in terms of their resources, environment, space, and strategic value. Because of their ecological and economic value, marine resources have become important to the survival and development of the human race. Marine resources are not a single type of ecological resource; rather, they combine economic, social, and ecological elements. In exploiting marine resources, we should not only consider economic objectives but must also consider the influence of this exploitation and utilization on the local natural environment. Additionally, the economic and environmental influences on society of exploiting marine resources should be evaluated. Because of the dynamic nature of marine resource exploitation, marine materials or environmental factors that were previously neglected have become economically useful against the backdrop of technical progress and social development. However, although the breadth and depth of ocean development have continued to increase, the fundamental state of marine resources in China remains poor, with low occupancy per capita and inefficient resource utilization.

China faces the dual problem of transforming its economy while ensuring sustainable economic and environmental development. Hence, an unyielding demand for resources and resulting energy shortages are expected to confer restrictions on Chinese social development for some time. The impetus behind the development of marine resources has been increasing. Nevertheless, it remains difficult to meet the present resource consumption requirements. The traditional economic growth model in China, with a high degree of pollution, high consumption, and low profit, has caused significant damage to the environment. Moreover, low prices have meant that resources have been excessively exploited and wasted. If the exploitation and utilization of marine resources become as extensive, inconsistent, and unsustainable as those of land resources, irreversible damage will occur. Presently, the exploitation and utilization of marine resources are at an early stage. Resource shortages can be overcome by enhancing the protection of marine resources and nurturing mutual relationships.

2. Main Contribution of This Special Issue

Based on a rigorous peer review process, ten papers were selected for publication in this Special Issue. Their contributions and implications are discussed below:

Jiang et al. (contribution 1) focus on the green economic growth of marine fisheries and explore the relationship between environmental regulations (ERs), industrial structure (INS), and the green total factor productivity of marine fisheries (MGTFP). Against the backdrop of global climate change and increasing pressures on resources and the environment, a green fisheries economy has become key to achieving sustainable development. This study utilizes panel data from 11 coastal provinces and municipalities in China from

2014 to 2023 and, through a quantitative analysis, evaluates the implementation effects of ER policies on marine fisheries' production methods, INS, and MGTFP. When measuring the MGTFP, this study innovatively incorporates economic losses from fishery disasters as an undesirable output and employs the super-efficiency SBM-GML model for precise calculation. The results of the study show that ER promoted an increase in MGTFP, while the effect of REC was stronger. The mediating effect model suggests that the industry structure mediates this process. The results of the threshold effect analysis show that both ERC and ERM exhibit significant single-threshold effects. This study aims to provide empirical support and policy recommendations for the government to formulate more effective environmental protection policies and promote the transformation and upgrading of the marine fisheries sector, thereby fostering the green development of China's marine fisheries.

As the scale of the marine economy continues to expand, the problems of environmental pollution and the over-exploitation of marine resources have become increasingly severe. Yao and Wang (contribution 2) aim to promote sustainable growth of the marine economy, the rational utilization of resources, and the coordinated development of environmental protection. Their study first adopts the system dynamics (SD) model. It then uses the entropy method to weigh the evaluation indicators and create a coupling coordination degree (CCD) assessment simulation of the ecological environment of marine economic resources. They use the created SD model to build and simulate four standard scenarios: current, economic, resource, and environmental. Finally, they propose suitable recommendations for the long-term development of the marine economy based on the coordination evaluation results of the CCD model. They reach the following conclusions: (1) In the immediate term, the economic scenario is poorly coordinated, whereas the environmental scenario is more effectively coordinated. However, in the long-term development process, the resource scenario is reasonably well coordinated. (2) Particular attention must be given to improving the energy mix and protecting the natural environment to promote the sustainable development of the marine economy. (3) To achieve a virtuous cycle between marine economic development and environmental protection, governments, businesses, and all sectors of society must work together to formulate and implement relevant policies and initiatives.

Sun et al. (contribution 3) explore the impact of regional financial development on the sustainable growth of the marine economy across 14 coastal cities in Guangdong Province from 2004 to 2022. To assess this, a comprehensive index system was developed to measure marine economic sustainability, incorporating key factors such as capital investment, production efficiency, and processing and trade. Their findings indicate that financial development significantly enhances the sustainable growth of the marine economy. However, the interaction between financial development, technology digitalization, and low-carbon initiatives leads to diminishing returns in terms of sustainability. Through the use of the Moran index and the spatial Durbin model, the analysis reveals a dual outcome: while financial development positively influences a city's marine economic sustainability, it exerts negative spillover effects on neighboring cities. Previous studies have primarily focused on the relationship between financial development and the marine economy at the national or provincial level, leaving a gap in understanding these dynamics at the city level. Furthermore, the coordination between financial development and marine economic sustainability across cities within the same region remains largely unexplored. This study addresses these gaps by investigating city-level dynamics and examining intercity coordination between financial development and marine economic growth. The results offer a novel perspective for policymakers, highlighting strategies to balance regional financing for the marine economy with targeted investments in science, technology, digitalization, and low-carbon initiatives. This approach seeks to optimize resource allocation and mitigate potential substitution effects. Ultimately, this research contributes to a more nuanced understanding of the complex interplay between financial development and the marine economy at both city and regional levels.

Yu et al. (contribution 4) present a groundbreaking approach to evaluating the resilience of China's blue economy, shedding light on its critical role in promoting sustainable development along the nation's coastlines. By employing advanced methodologies such as social network analysis and the time-varying effect random graph model (TERGM), their research meticulously examines the period from 2007 to 2019. It uncovers the complex dynamics of resilience, focusing on the adversities of unbalanced growth and pinpointing pivotal factors which shape this resilience, including the stability of the marine economy, the rigor of environmental regulations, and the impact of technological progress. Through a strategic compilation of indicators, this analysis offers a detailed perspective on the multi-faceted nature of blue economy resilience. The outcomes underscore the necessity of enhancing network effectiveness and implementing specific measures to encourage sustainable expansion in coastal domains. Leveraging these insights, the authors advocate for targeted strategies to refine the resilience network's framework, aiming to bolster the sustainable evolution of marine economic activities. This study not only deepens the understanding of marine economic resilience but also charts a course for achieving a resilient and sustainable blue economy. It stands as an indispensable guide for policymakers and scholars in the realm of marine economics, offering a blueprint for navigating the challenges and opportunities within this vital sector.

Enhancing the marine carrying capacity (MCC) is of significant value in hastening the transformation of the marine economy and achieving marine economy high-quality development (MEHD). Chen et al. (contribution 5) explore the synergistic mechanism between the MCC and MEHD and create a comprehensive indicator system to measure the synergistic relationship between China's MCC and MEHD from 2006 to 2020. To achieve this, the authors used the improved TOPSIS model and the composite system synergism model and explored the influencing factors and their interactions using geographic probes. The research findings are as follows: (1) China's MCC and MEHD showed a growing trend during the study period, in which marine green development was at a higher level and the cultivation of marine knowledge improved significantly, but the general value of MEHD was relatively low. (2) In terms of the synergistic relationship, the degree of ordering of the two shows a sustained rising trend, and the degree of ordering of the development of the marine economy as a whole is higher than the MCC; the degree of synergy is increasing, but the general value of synergistic development is low. (3) The main factors driving the MCC and MEHD are the marine consumption capacity, the marine opening, and the marine industrial structure; the explanatory power of most factor interactions tends to decrease, and the explanatory power of the interactions between the development of a land-based economy, the marine industry structure, and the marine economy increase, while the impacts of the different factor interactions on the synergistic development are all greater than the factors. The influence of different factors on synergistic development is greater than the influence of each factor alone.

3. Conclusions and Future Directions

China is likely to become a marine power, thereby raising the significance of the oceans to an unprecedented level. Improving the quality of economic growth in China while guaranteeing the sustainable development of marine ecology and resources has been a major subject of recent debate. Because the resources per capita are relatively poor, developing marine resources to improve the marine carrying capacity is a problem in need of an urgent solution.

Therefore, it is important to link marine carrying capacity and economic growth. The development of the marine economy is based on the development and utilization of marine resources, which also causes pollution in the marine environment. Therefore, we must determine the proper threshold of earnings during this stage of economic growth and handle the relationships between resources, the environment, the economy, and human development effectively, ensuring coordination between these different subsystems, as well as a harmonious development balancing the environment and economy. Based on this Special Issue, we know that in important coastal areas, local conditions must be combined with economic growth to control pollutant discharge and stimulate the advancement and rationalization of marine industrial structures. The relationship between strong protection of resources and the environment on the one hand and the rate of social and economic development on the other must be handled carefully so that harmonious, orderly, and healthy development of marine systems can be achieved.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflicts of interest.

List of Contributions

1. Zheng, L.; Wang, S. Assessing Marine Resource Carrying Capacity: Methods, Economic Impacts, and Management Strategies. *Water* **2025**, *17*, 691.
2. Yao, W.; Wang, X. A Dynamic Simulation and Evaluation of the Coupling Coordination Degree of the Marine Economy–Resource–Environment System in China. *Water* **2024**, *16*, 2686.
3. Sun, S.; Zhang, Z.; Tan, M. Financial Mechanism for Sustainable Development of the Marine Economy with Respect to Technology, Digitalization, and Low Carbonization. *Water* **2024**, *16*, 2841.
4. Yu, L.; Duan, D.; Min, K.-S.; Wang, T. Advancing Marine-Bearing Capacity and Economic Growth: A Comprehensive Analysis of Blue Economy Resilience, Network Evolution, and Technological Influences in China's Coastal Areas. *Water* **2024**, *16*, 1019.
5. Chen, X.; Yu, Z.; Liang, C.; Di, Q. Where is the path to sustainable marine development? Evaluation and empirical analysis of the synergy between marine carrying capacity and marine economy high-quality development. *Water* **2024**, *16*, 394.

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Review

Assessing Marine Resource Carrying Capacity: Methods, Economic Impacts, and Management Strategies

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Abstract: In recent years, the marine economy has experienced rapid development, with increasing scale of marine exploration and utilization. Against this backdrop, the importance of the marine resource carrying capacity (MRCC) for sustainable development has become increasingly prominent. This paper reviews the research progress on MRCC, exploring its connotations, characteristics, measurement methods, and influencing factors. First, the paper briefly introduces MRCC from the perspectives of its connotation and characteristics, highlighting its crucial role in both marine resource development and ecological protection. Second, it summarizes relevant research on MRCC measurement methods from the viewpoints of single-factor evaluation and composite indicator assessment, analyzing the advantages, disadvantages, and appropriate application scenarios of each method. Furthermore, the paper analyzes the significant impact of human activities and economic development on MRCC, emphasizing that appropriate management strategies and policies can effectively mitigate the risk of MRCC decline. Finally, the paper suggests that future research should focus on improving the accuracy of assessment models, identifying the scope of impacts caused by carrying capacity changes, and utilizing policy and financial tools to address the challenges posed by carrying capacity decline, with the aim of achieving sustainable use of marine resources and promoting the healthy development of the marine economy.

Keywords: marine resource carrying capacity; sustainable development; ocean management; ecological protection

1. Introduction

The ocean, as humanity's "second territory" and a vital component of Earth's ecosystem, covers approximately 71% of the Earth's surface. It plays a crucial role in global ecological balance and is closely linked to human societal development and global environmental quality. The marine ecosystem holds abundant resources with the capacity to sustain and supply various forms of resources, including biological, mineral, and energy resources. These resources provide an indispensable material foundation for human survival and development, and they play an important role in supporting global economic growth.

With the rapid development of coastal economies around the world, nations have gradually recognized the unique advantages of the ocean in terms of resources, environment, space, and strategy (Wang & Xu, 2023) [1]. Marine resources, with their ecological and economic values, have gradually become one of the primary driving forces for human survival and social development. As society, economy, and technology progress, the value generated by these resources continues to increase (Zhao et al., 2014) [2]. Currently, the effective development and utilization of marine resources, alongside the acceleration of marine economic growth, has become a widely shared consensus among nations worldwide.

As a major maritime country, China has a long coastline, vast maritime areas, and abundant marine resources. The contribution of the marine economy to China's national economic growth has become increasingly significant. However, in recent years, with the large-scale development of marine resources, problems such as marine environmental pollution, resource depletion, and ecosystem degradation have begun to emerge. For instance, overfishing has led to a rapid decline in marine fish stocks, and the discharge of industrial and domestic wastewater from coastal areas has worsened seawater quality. At present, the ocean is under pressure from issues such as seawater acidification and resource depletion, presenting severe challenges to human sustainable development.

In this context, the study of the marine resource carrying capacity (MRCC) is of great significance for the rational exploitation of marine resources and balancing the relationship between marine resources and marine economic development. MRCC is generally understood as the ability of the quantity and quality of marine resources to support the economic development of a country or region, representing a critical aspect of sustainable economic development. Clarifying the connotations and characteristics of MRCC, accurately measuring its levels, and deeply studying its relationship with human activities and economic development are crucial for the proper management of marine resources. This is also vital for protecting the marine ecological environment and achieving sustainable economic growth.

This paper first reviews existing research on MRCC from perspectives such as its connotations and characteristics, the measurement of its levels, and empirical studies. The structure of this review is illustrated in Figure 1. Finally, based on current research, the paper outlines future directions for the study of MRCC.

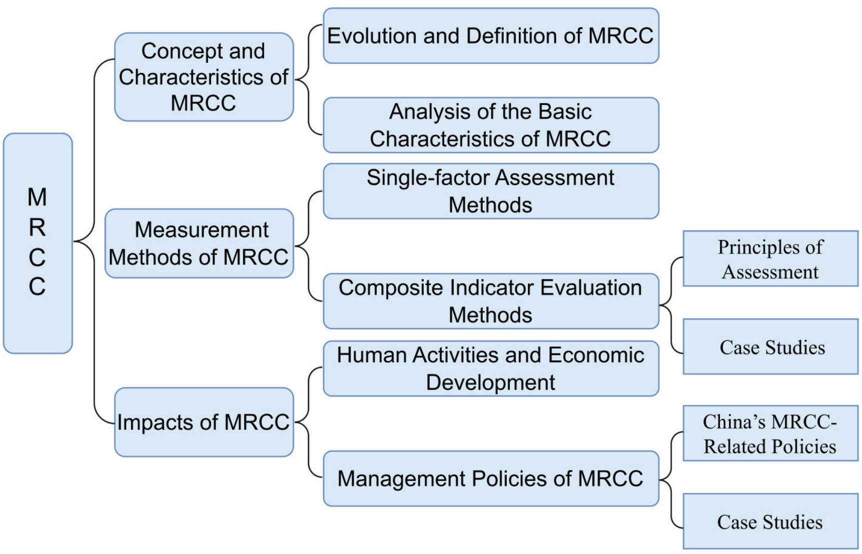

Figure 1. Framework diagram.

2. The Concept and Characteristics of MRCC

2.1. Evolution and Definition of MRCC

The concept of carrying capacity originated in the field of engineering geology, where it referred to the strength of a foundation capable of bearing the weight of a building—known as foundation bearing capacity. Maltus and Verhulst were the first to introduce this concept into the ecological field. After the 1960s, with the rapid growth of population and economy, the contradiction between social development and resource scarcity became increasingly prominent, leading to ecosystem degradation. There was growing attention to the condition of ecosystems. Therefore, the concept of carrying capacity related to resources and the environment began to gain focus. In the 1980s, UNESCO defined the term "resource carrying capacity" as the number of people that a region can sustainably support through the utilization of its natural and other resources over a foreseeable period. Subsequently, the concept of resource carrying capacity was widely applied across various fields, including environmental, economic, and social studies, giving rise to different types of carrying capacities such as mineral carrying capacity (Wang et al., 2016) [3], land carrying capacity (Han et al., 2021) [4], and water resource carrying capacity (Chen et al., 2022) [5].

In 1986, the United Nations Marine Pollution Group introduced the concept of marine environmental capacity, which refers to the maximum amount of a pollutant that environmental components within a region can accommodate without causing unacceptable environmental impacts (maximum load capacity). This concept was subsequently widely accepted internationally and evolved into the broader concept of marine ecological carrying capacity (MECC). In 1990, Carver and Mallet defined MRCC as the "maximum population size that an ecosystem can sustain". Later, scholars described it as the "annual production density of the ecosystem's maximum product" (Bacher et al., 1998) [6] or the "residence time, primary productivity, and clearance rate of marine biomass that the ecosystem can sustain" (Dame & Prins, 1998) [7]. Additionally, some scholars defined it as "the limit at which an ecosystem can maintain its structure and function without exceeding the acceptable limits set by water quality or other parameters" (Duarte, 2003) [8].

With the ongoing development of the marine economy and the continuous refinement of research in this area, MRCC now integrates a range of factors, including social, economic, environmental, and ecological elements. Scholars must consider not only the capacity of marine systems to provide resources for human activities but also the impact of socio-economic activities on marine ecosystems. Understanding the connotations of MRCC is crucial, as it helps clarify the spatial and qualitative imbalances of resources and facilitates understanding of environmental threshold points (Chadenas et al., 2008) [9].

In 2015, the China Oceanic Administration defined MRCC as the maximum impact that marine development activities can have on the nearshore marine ecological environment while maintaining a healthy ecological environment within a specific time frame and region. In their study of MRCC in Nantong City, Wei et al. (2014) [10] highlighted that ecosystems are composed of both natural processes and human activities. If these two aspects fail to develop in harmony, it could lead to disaster. Mao and Yu (2001) [11] also emphasized that MRCC's key function lies in its ability to support the coordination between economic development and environmental sustainability.

Therefore, based on existing research, the connotations of MRCC can be summarized into the following three main aspects (Sun et al., 2022) [12]:

1. Marine Environmental Protection

Marine environmental protection refers to the actions taken by humans to ensure sustainable socio-economic development by balancing the relationship between the marine environment and human activities. The report of the 20th National Congress of the Communist Party of China emphasizes the importance of "developing the marine economy, protecting the marine ecological environment, and accelerating the construction of a maritime power", which is a key task for advancing Chinese-style modernization. However, with the rapid development of the marine economy, various irrational human activities—such as wastewater discharge into the sea, land reclamation, and beach occupation—have severely threatened marine ecosystems. The contradiction between resource environmental supply and economic development needs is becoming increasingly apparent. Therefore, exploring ways to balance the coercive relationship between marine environmental protection and human activities is of significant importance for achieving healthy and green development in the marine economy.

2. Marine Resource Supply Capacity

This refers to the ability of marine resources to support human socio-economic development. It plays a crucial role in the development of human societies and economies. Thus, the supply capacity of marine resources must be emphasized, considering factors such as the quantity and potential value of these resources.

3. Economic Functions of Marine Industries

This refers to the role of marine industries, formed through the utilization of marine resources, in driving socio-economic progress. The mainland of China has a coastline exceeding 18,000 km, and the coastal zone holds abundant resources that effectively alleviate the "bottleneck" of land-based resources. These areas have become important new growth points for national economic development (Wang et al., 2021) [13]. In 2023, the total national marine gross output value was 99.097 trillion RMB, accounting for 7.9% of GDP, with a growth rate higher than the national GDP by 0.8%. The increasing output value and growth rate of the marine industry indicate a deeper utilization of marine resources and a gradually stronger driving force of the marine economy on human society.

2.2. Analysis of the Basic Characteristics of MRCC

The ocean, as a unique region, includes multiple areas such as internal waters, territorial seas, water bodies, seabeds, and subsoil resources. In studying MRCC, it is essential to consider both the generality of regional carrying capacity and the particularities of marine resources. Specifically, the generality of regional carrying capacity refers to the self-regulation ability of the region and the socio-economic development capacity within it. The particularity of marine resources mainly refers to the unique geographical structure, slow qualitative changes, and the scope of their impact (Gai et al., 2018) [14]. More specifically, the particularities of MRCC can be summarized in three key aspects:

1. Specificity of Marine Carrying Capacity Regions

Due to the distinct nature of the ocean compared to land, marine areas exhibit more complex geographical structures, such as internal waters, territorial seas, water bodies, seabeds, and subsoil resources. The carrying capacity of each type of marine topography varies. Taking China's marine areas as an example, the Bohai Sea is an enclosed inland sea with a relatively fragile ecosystem. The carrying capacity for fisheries in this region is heavily impacted by overfishing and environmental pollution. In contrast, the South China Sea is relatively vast and rich in marine biological resources, resulting in a higher fisheries resource carrying capacity. Therefore, when evaluating marine carrying capacity, it is necessary to define each region distinctly according to its characteristics.

2. Dynamics and Development of Marine Carrying Capacity

Marine carrying capacity reflects the relationship between human economic activities and marine ecosystems, influencing the scale and pace of socio-economic development in a region. When human activities exceed the carrying capacity of the marine ecosystem, it leads to resource depletion, slowing or even halting socio-economic development. Meanwhile, marine ecosystems possess self-regulation abilities. When human socio-economic activities remain within the limits of the marine carrying capacity, the ecosystem can self-regulate and reach a higher level of sustainability. With increasing environmental awareness and strengthened environmental protection measures, the ecological environment of some marine areas has improved, leading to an increase in MRCC.

3. Concentration and Extensiveness of the Impact Range of Marine Carrying Capacity

Marine carrying capacity impacts the scale and pace of socio-economic development, and its influence is primarily concentrated in coastal and surrounding areas. However, the influence of MRCC also extends geographically, impacting socio-economic development in other regions through economic trade and other channels. For example, in marine fisheries, the concentration is reflected in the fact that the fishing and aquaculture industries in coastal areas directly depend on the local MRCC, and the development of these industries has a significant impact on the local economy. The extensiveness of MRCC is evident in the fact that as the marine transport industry grows, coastal ports have become essential hubs for goods trade. Today, marine fishery products can be transported globally via shipping, which facilitates global trade and extends the impact of MRCC to inland regions.

3. MRCC Measurement Methods and Quantitative Analysis

As an ecological concept, carrying capacity assumes that, in the absence of environmental degradation, a finite number of individuals can be supported at a given consumption level. It reflects the relationship between the carrying object and the carrier, embodying the concept of sustainable development (Abernethy, 2001) [15]. The current methods for evaluating MRCC are mainly divided into single-factor assessments and composite indicator assessments.

3.1. Single-Factor Assessment Methods and Case Studies

Single-factor assessment involves evaluating a specific aspect of MRCC, such as fisheries resources, spatial resources, environmental, and ecological resource assessments (Christensen & Pauly, 1995; Michielsens et al., 2008) [16,17]. This method focuses on a single species or a specific region, allowing for in-depth analysis of the carrying capacity of a particular marine resource. However, it is difficult to comprehensively reflect the overall changes in MRCC and lacks a holistic consideration of the entire marine ecosystem (Liu et al., 2025) [18].

Most single-factor measurements focus on marine fisheries resources. For example, Byron et al. (2011) [19] built a framework centered on the Working Group on Aquaculture Regulations and used a mass balance model to assess the ecological carrying capacity for oyster farming. Filgueira and Grant (2009) [20] used a multiple box dynamic ecosystem model to study the carrying capacity for mussel farming on a small island in Canada. Their model, which compared data from 1998 and 1999, demonstrated that marine fisheries ecological carrying capacity levels are constantly changing and are influenced by environmental pressures. Suo et al. (2023) [21] measured the ecological carrying capacity of small-scale fisheries in the Pearl River. Yao et al. (2024) [22] studied the decline in fisheries resources due to overfishing in global marine ecosystems. Using the Ecosim model, they simulated the ecological carrying capacity of the Atlantic blue crab under different biomass scenarios.

Unlike the studies mentioned above that focus on the carrying capacity of fishery farming and specific species, some scholars have also measured the MRCC of coastal tourism. Mccoo and Lime (2001) [23] analyzed the development history of the concept of coastal tourism carrying capacity based on the neo-Malthusian perspective. Silva (2002) [24] measured the physical carrying capacity of beaches on the southwest coast of Spain during summer by assessing the number of individuals the beach could accommodate. The social carrying capacity was measured by the feeling of crowding on individuals that exceeded the number of beach users. Specifically, physical carrying capacity was measured using aerial photographic data, while social carrying capacity was assessed through user statistics, video images, and interview records. Later, Zhao et al. (2014) [2] measured the economic value of China's marine industries based on the marine economic accounts system, which includes principal accounts, elementary accounts, and natural capital accounts. By calculating the economic output of 12 major marine industries in China, they found that coastal tourism plays an important supporting role in the development of the marine economy. Additionally, the supporting roles of marine transportation and marine fisheries are also significant.

In contrast to the single-factor assessment cases mentioned above, the measurement of marine fishery resources' carrying capacity primarily revolves around ecological models, focusing on the relationship between organisms and the environment. The data sources and analytical perspectives in the measurement of coastal tourism carrying capacity, however, are more diversified.

3.2. Composite Indicator Evaluation Methods and Case Studies

The composite indicator evaluation method constructs a multi-factor indicator system, which enables a more comprehensive assessment of MRCC, effectively addressing the limitations of single-factor evaluation methods. As the concept of sustainable development has gradually gained traction, composite indicator evaluation has become one of the most popular and widely used methods for measuring ecological carrying capacity. The key to composite indicator evaluation lies in thoroughly considering the complexity of marine ecosystems and the interactivity of multiple factors. By establishing a comprehensive multi-factor indicator system, this method allows for a richer and more accurate evaluation of the carrying capacity of marine resources, environments, and more. Below, this section will introduce the composite indicator evaluation method in detail from three perspectives: the principles of indicator system construction, the evaluation system based on the "Pressure-State-Response" (PSR) framework, and emerging improved methods.

3.2.1. Principles for Constructing a Composite Indicator System

When establishing an evaluation system for MRCC, the following four principles should generally be followed (Liu, 2009) [25]:

1. Scientific Principle: The indicators should not overlap or omit any important factors. They need to be representative, and the indicators must be independent of each other. The final indicator system should provide a complete evaluation of the ecological carrying capacity. For example, when measuring the carrying capacity of marine fisheries, it is more representative to include species such as fish, shellfish, and crustaceans rather than just focusing on shellfish, as it better reflects the biological resource carrying capacity of a specific marine area.
2. Comparability Principle: The indicators should follow the same construction principles to ensure that they are interrelated and consistent. This enables comparison across different marine regions. For instance, when assessing MRCC in different marine areas, it is essential to use the same water quality indicators, such as chemical oxygen demand, nitrogen, and phosphorus levels, to ensure comparability of the assessment results.
3. Operational Principle: In the process of designing indicators, the requirements of the research objectives should be considered, but practical factors such as the availability of data and the ease of quantification should also be taken into account. For example, choosing easily accessible and quantifiable data, such as marine fishery yield or marine GDP, as indicators can improve the feasibility and efficiency of the measurement results.
4. Sustainability: The measurement of MRCC is a dynamic and evolving process, with different characteristics at different periods. Therefore, the selection of indicators should reflect sustainability, avoiding the use of short-term or incidental data.

3.2.2. Composite Indicator Evaluation Case Studies

PSR Framework

Early composite indicator methods were primarily based on the list of pressure and impact factors proposed by the European Union, using the PSR framework for carrying capacity evaluation (Lanz & Scheuer, 2001) [26]. The core of the PSR framework consists of three components:

− Pressure: This reflects the negative impacts of natural factors, human activities, and social development on the marine environment, such as water pollution and overfishing.
− State: This refers to the current status of the marine ecological environment at a given time, such as marine biodiversity, water quality, and coastal stability.
− Response: This refers to the measures and strategies taken by humans to improve the ecological environment and achieve sustainable marine development, such as the formulation of environmental protection policies and the implementation of marine ecological restoration projects.

The PSR framework is based on causal relationships and includes both qualitative and quantitative indicators. It systematically analyzes the impact relationship between human activities and the marine ecological environment.

Liu and Huo (2008) [27] constructed a coastal carrying capacity evaluation indicator system using the PSR conceptual model and conducted a qualitative analysis of the PSR framework. Although their composite indicator system could correctly evaluate MRCC to a certain extent, it lacked empirical data for further analysis. Li and Cui (2010) [28], on the other hand, chose indicators from three dimensions: pressure, bearing capacity, and regional exchange. These indicators included population density, the proportion of marine industry output to GDP, per capita marine area, the industrial wastewater compliance rate, and the number of marine technology projects to measure MRCC in Hebei Province. The weighting of different indicators was determined using the analytic hierarchy process (AHP). The results showed that although the carrying capacity of Hebei's coastal waters was in an overloaded state from 1996 to 2006, the bearing pressure was gradually decreasing. MRCC decreased from approximately 2.3 in 1996 to about 1.2 in 2006, gradually approaching a sustainable level (MRCC < 1). Song et al. (2013) [29] reviewed China's past use of marine resources and the development status of the marine economy. They confirmed that China's MRCC was in a sub-health state, meaning the overall development level of China's marine resources was still relatively backward, with a resource-intensive, inefficient production mode. Additionally, the development of China's islands was lagging, with issues such as insufficient transportation infrastructure, energy shortages, and freshwater scarcity. These factors significantly restricted the development of MRCC.

Building on the existing PSR framework, Wei et al. (2014) [10] proposed the "driving force-pressure-state-response-control" (D-PSR-C) conceptual model and used it to evaluate the comprehensive carrying capacity of marine, coastal land, and tidal flat areas in Nantong from 2005 to 2009. Their evaluation of MRCC indicated that marine biological resources and environmental quality played a crucial role in improving MRCC. For example, in Haian City, in 2008, the contributions of marine biological resources and environmental quality to the carrying capacity were 41.9% and 55.1%, respectively. In contrast, marine spatial resources and biological resources accounted for only 1.5%, suggesting significant potential for development.

From a developmental trend perspective, research based on the PSR framework has gradually shifted from theoretical construction to empirical application, evolving from simple frameworks to multidimensional ones.

Other Measurement Methods

In recent years, although the PSR framework has played an important role in measuring MRCC, there are still limitations in the accuracy of measurements and the in-depth study of influencing factors. To address these shortcomings, scholars have proposed various improvement methods and new measurement models.

First, Wang and Liu (2019) [30], based on the "limits to growth" theory, innovatively proposed a hexagonal interaction theory model that includes "pressure-support", "destructiveness-resilience", and "degradation-promotion" (PS-DR-DP) and used it to study the carrying capacity of some regions in China from 2010 to 2015. Du et al. (2020) [31] developed a hybrid model called DPPD, which combines four methods—driver–pressure-state–impact–response (DPSIR), principal component analysis (PCA), path analysis (PA), and decision-making trial and evaluation laboratory (DEMATEL)—to assess the environmental carrying capacity of 11 coastal regions in China. In this model, new driving and impact indicators were introduced on the basis of the traditional PSR model. Driving indicators included marine GDP, tourism income, etc., while impact indicators included marine primary productivity and red tide frequency. The results showed that the importance of each category of indicator followed this order: response > state > impact > pressure > driving factors.

Ma et al. (2017) [32] innovatively constructed the marine ecological carrying capacity (MECC) conceptual model based on the relationship between carrying object and carrier, and conducted MECC research for Dongtou Islands as a case study. They found that between 2009 and 2014, the MECC of Dongtou Islands showed a downward trend, with an annual average decline rate of 38.3%. Luo et al. (2020) [33] applied extension set theory to study the MRCC of Hainan Island and found that between 2016 and 2018, the island's marine ecological environment was in a moderate carrying capacity, sub-healthy state. They suggested that Hainan could enhance its carrying capacity by developing modern services, high-tech industries, etc. Ma et al. (2022) [34] conducted a comprehensive evaluation of MRCC in Wenzhou by considering four aspects: marine spatial development, fishery resources, environment, and ecology. They further referred to the work of Hao-xuan et al. (2020) [35] to analyze the logical relationship between carrying capacity and suitability, thereby refining the existing empirical results.

Meanwhile, Wang et al. (2017) [36] developed an integrated identification method based on the sources, sinks, transport, and transformation of pollutants. This method includes potential factor selection, horizontal independence testing, and control factor identification and allows for more precise measurement of environmental carrying capacity. The results indicated that since the 1980s, the MRCC of the coastal area of Qingdao has been affected by factors such as wastewater discharge, livestock production, nitrogen emissions, and wastewater treatment. The overall carrying capacity has been in an overloaded state, with an overload of approximately 65%. In the Jiaozhou Bay area, the impact was even more severe during the 1980s, with the overload being about twice as much as it is now.

In addition, Zhou et al. (2017) [37] integrated indicators such as industrial structure upgrading, pollutant emissions, river flow, and GDP from the perspective of pollution discharge and used the information entropy method to study the water environmental carrying capacity of Changzhou, China. They analyzed the impact of water environmental carrying capacity on industrial structure upgrading and spatial optimization, emphasizing the important role of water environmental carrying capacity in the sustainable development of the economy. Yang et al. (2023) [38], based on a system dynamics perspective and the principle of fishery ecological footprint, used a composite fuzzy evaluation method to study the MRCC of Liaoning Province. Specifically, they constructed a comprehensive evaluation indicator system, including marine catch, population density, fishery workforce, and per capita GDP, to measure MRCC. The results showed that since 2000, Liaoning's MRCC has been in an overloaded state, with tremendous pressure on the local marine environment. He (2023) [39], from the perspective of reducing marine environmental pollution, constructed a multi-dimensional composite indicator system that includes marine biodiversity, coastal vegetation structure, marine industries, marine pollution indices, and marine tourism. The AHP model was used to measure MRCC. Feng et al. (2025) [40], from an ecological network analysis perspective, measured the MRCC of the Jinggong Marine Ranch using the Ecopath and Ecosim models.

With the development of digital technologies, Wang et al. (2024) [41] collected satellite remote sensing data from the Wailingding marine ranch and constructed an MRCC indicator system at the levels of resources, environment, and ecology, including natural coastline, beach retention rate, temperature, and biodiversity index. The weights of the indicators were determined using a combination of the AHP and entropy methods, and a three-dimensional state-space model and weighted Bonferroni mean model were applied to measure MRCC levels. Bui and Tran (2022) [42] innovatively proposed the concept model of Marine Environmental Carrying Capacity Semi-Enclosed for Coastal Areas (SECAMECC) and used it to assess the MRCC of Da Nang Bay. Specifically, SECAMECC integrates data on terrain, hydrology, and water quality and applies new digital models such as 3D hydrodynamic models and the Land–Ocean Interactions in Coastal Zones model. It incorporates multi-dimensional water quality data, such as ammonium, phosphate, total suspended solids, and biochemical oxygen demand, to achieve a comprehensive MRCC assessment.

Overall, current research on MRCC measurement shows a trend of interdisciplinary integration and diversification of technological methods. The measurement of MRCC integrates knowledge from ecology, economics, information technology, and other disciplines, breaking down disciplinary barriers. Moreover, in addition to traditional mathematical models and analytical methods, emerging technologies such as satellite remote sensing data and big data analytics are being explored. These innovations significantly influence the traditional PSR framework system.

From the literature review, it is evident that, compared to developed countries, China's overall level of marine resource development and utilization is still relatively backward, with significant gaps in awareness, technological equipment, economic benefits, and scientific management. This has resulted in most of China's MRCC being in a sub-healthy state, which has gradually become one of the reasons hindering the further development and utilization of China's marine resources.

Through the above analysis, we compare and analyze the evaluation methods of existing MRCC, and the specific results are shown in the following table (Table 1).

Table 1. Comparison of MRCC assessment methods.

Assessment Method	Single-Factor Assessment Method	Comprehensive Indicator Assessment Method
Definition	Evaluate a specific aspect of MRCC individually.	Evaluate MRCC comprehensively by constructing a multi-factor indicator system.
Advantages	Allows for in-depth analysis of the carrying capacity of a specific type of marine resource.	Considers the complexity of marine ecosystems and the interactions of multiple factors, offering a more comprehensive and accurate evaluation.

Table 1. *Cont.*

Assessment Method	Single-Factor Assessment Method	Comprehensive Indicator Assessment Method
Disadvantages	Struggles to reflect the overall changes in MRCC and lacks a holistic approach.	Requires the construction of a complex indicator system, making data collection and analysis more challenging.
Research Focus	Suitable for in-depth research on specific resources or regions.	Suitable for comprehensive assessment of the carrying capacity of the entire marine ecosystem.

This table provides a clear side-by-side comparison of the strengths and weaknesses of single-factor and comprehensive indicator methods in MRCC assessment, helping to highlight their respective applications and limitations.

4. MRCC's Impact Studies

The level of MRCC is closely related to human activities, marine economic strength, and economic sustainable development. Eco-friendly social activities enhance local marine environmental quality, thus improving its carrying capacity and contributing to the healthy development of both the ecology and society. In contrast, destructive and environmentally harmful activities negatively affect MRCC, increasing the pressure for green development.

4.1. Impact of Human Activities and Economic Development

First, regarding the relationship between human activities and MRCC, Wei et al. (2014) [10] analyzed the impact of human activities on the comprehensive carrying capacity of the coastal zone in Nantong using the "driving force-pressure-state-response-control (D-PSR-C)" model. Their research highlighted the importance of promoting marine carrying capacity through environmental protection activities. As awareness of the importance of coastal ecosystem carrying capacity for social well-being grows, Wang et al. (2022) [43] studied the development of coastal ecosystem carrying capacity in South Korea. Their findings revealed that events like the Sewol Ferry disaster in 2014, the deployment of the THAAD missile defense system in 2018, and the bankruptcy of Hanjin Shipping in 2019 had a negative impact on South Korea's coastal ecosystem. To better promote harmonious development between people and the ocean, it is crucial to strengthen management over shipping routes and transport companies to avoid further environmental harm caused by mismanagement. This research sharply contrasts with the findings of Wei et al. (2014) [10], emphasizing that external economic and political events may also play a key role in MRCC.

Subsequently, scholars began exploring the relationship between MRCC and economic development. In China, scholars have focused on important coastal regions such as Guangdong, Guangxi, Shandong, Liaoning, and Shanghai. As China's economy developed following the opening-up policy, Guangdong Province's economy grew, but its marine ecological situation deteriorated. Therefore, Chen (2020) [44] studied the relationship between economic growth and marine ecology in Guangdong, concluding that a healthy ecological environment helps improve economic development capabilities. This can be achieved by optimizing industrial structures, promoting energy conservation, reducing emissions, and advocating for green consumption to enhance MRCC. With the rise of the concept of large marine ecosystems, Wang et al. (2023) [45] focused on the Yellow Sea's large marine ecosystem and confirmed that MRCC and economic development are closely linked: on one hand, carrying capacity is seriously threatened by human activities, while on the other hand, good carrying capacity is critical for the rapid development of sustainable economies.

With growing attention from the Chinese government to the Beibu Gulf urban agglomeration, Li et al. (2023) [46] studied MRCC and its development obstacles in seven coastal cities of Beibu Gulf from 2011 to 2021 (Zhanjiang, Yangjiang, Maoming, Qinzhou, Beihai, Fangchenggang, and Haikou). They pointed out that while MRCC has shown an upward trend in recent years, it is still influenced by factors such as per capita coastline length, import/export volume, and cargo throughput. To improve the marine resource and environmental carrying capacity of Beibu Gulf, controlling the import/export ratio and cargo throughput can optimize the relationship between marine ecological resources and economic growth, thus promoting stable economic and social development.

To better analyze the relationship between MRCC and economic development, scholars have also studied the degree of coordination between the two. For example, Yu and Di (2020) [47] explored the coordination between marine carrying capacity and marine economic development in 17 cities in China's Bohai Bay. They found that over time, the coordination between the two improved, but there were significant differences among northern, central, and southern cities. Northern cities benefited from early advantages, performing efficiently at first but declining later. In contrast, central and southern cities showed rapid growth. Furthermore, Chen et al. (2024) [48] examined the relationship between MRCC and high-quality marine economic development. They found that while the synergy between the two has increased, the overall coordination is still low and fluctuates. This fluctuation is primarily due to factors such as marine consumption capacity, degree of marine openness, and marine industrial structure. Zhang (2024) [49] extended the research to the coupling relationship between MRCC and regional development, constructing coupling degree and coupling coordination models to quantify the relationship. Despite regional variations in coupling coordination, the overall trend was upward. For instance, in Fujian Province, the coupling coordination degree increased from 0.030 to 0.719 over the study period.

4.2. Management Policies of MRCC

4.2.1. Review of China's MRCC-Related Policies

As awareness of MRCC continues to rise, an increasing number of people are recognizing the importance of strengthening the management of factors affecting marine resources. In 2012, China first proposed the "Maritime Power Strategy", and later implemented the "21st Century Maritime Silk Road" initiative. While China's pace of marine development has been accelerating, it is still struggling to meet the growing demand for resource consumption, and the state of marine resources remains critical. On one hand, the traditional economic growth model characterized by high pollution, high consumption, high input, and low return has caused significant marine environmental damage (Song et al., 2013) [29]. On the other hand, if marine resources are developed and utilized in the same unsustainable, excessive manner as land resources, they will inevitably face irreversible damage, resulting in severe negative consequences for future development.

To better manage and utilize marine resources, improve MRCC, and ensure sustainable development, China has issued a series of policies aimed at enhancing MRCC (see Table 2). These policies address a wide range of areas, from environmental protection and resource management to economic development and evaluation systems, highlighting the importance of sustainable and controlled marine resource use.

Table 2. China's MRCC-related policies.

Policy Direction	Policy Name	Issued Year
Overall plan	Overall Plan for Ecological Civilization System Reform	2015
	Opinions on Establishing and Supervising Implementation of Land and Space Planning System	2019
Marine Ecological Environment Protection and Restoration	National Major Marine Oil Spill Emergency Response Plan	2018
	Major Coastal Zone Ecological Protection and Restoration Project (2021–2035)	2020
	14th Five-Year Plan for Marine Ecological Environment Protection	2022
	White Paper on China's Marine Ecological Environment Protection	2024
Marine Resource Utilization and Management	Opinions on Accelerating the Green Development of Aquaculture	2019
	Notice from the Ministry of Natural Resources on Exploring and Advancing the Vertical Division of Marine Areas	2023
Marine Economic Development	14th Five-Year Plan for Marine Economic Development	2021

The table above clearly shows that China places great importance on the development and management of marine resources. A comprehensive policy framework has been formulated that addresses multiple aspects, including the protection and restoration of marine resources, resource utilization and management, marine economic development, and evaluation systems. These policies emphasize the supporting role of MRCC at the macro level and highlight the need for in-depth research on MRCC and the importance of managing the scale and intensity of marine resource development.

4.2.2. Case Studies on Managing MRCC

Management Methods of MRCC

From a community management perspective, Singleton (2000) [50] studied the extreme case of fishery resource management along the northwest Pacific coastline. He emphasized the importance of grassroots community participation in managing fishery resources and noted its significance in enhancing the precision of the management system. Specifically, he argued that although the relationship between the state and local communities in certain regions can be tense, and marine resource management practices may be relatively rudimentary, gradual improvements based on social trust could ultimately lead to the establishment of a more successful and efficient co-management natural resource management system. Strengthening community-based or co-management natural resource management systems could increase the likelihood of successfully establishing such systems. Day (2002) [51], through his retrospective analysis of zoning management practices in the Great Barrier Reef Marine Park, systematically outlined the evolution of zoning management strategies. He also concluded that combining different management approaches, including community management, enhances management effectiveness. Another example related to community-based management is the Coastcare Program in Australia (Clarke, 2006) [52]. This program proposed to involve communities in managing coastal areas and has been adopted by seven Australian states.

From a national management perspective, scholars have conducted research from various angles, such as multinational management comparisons and the management of specific national resources. Cicin-Sain and Belfiore (2005) [53] studied the practices of marine protected area management and integrated coastal zone management in countries like Australia, the Netherlands, the United States, Belize, the Philippines, and Tanzania. Their results revealed that human activities have a significant impact on marine sustainable development, and managing marine resources requires consideration of the ecological, biological, socio-economic, and governance connections between different countries.

Ward and Dillon (2012) [54] affirmed the effectiveness of Australia's existing water management policies. Specifically, the policies for managing reservoirs and groundwater, which utilize social, economic, and environmental resources, have significantly contributed to enhancing carrying capacity. Weiss et al. (2012) [55] analyzed the roles of knowledge exchange and policy influence in managing marine wildlife in northern Australia. They found that utilizing a network-based marine governance system is helpful for managing complex resources over large spatial scales. However, the disproportionate influence of top–down policies compared to accumulated knowledge could hinder evidence-based decision-making.

Disadvantages of MRCC Management

As highlighted by Murawski (2007) [56], marine resource management (EAM) faces several challenges, including conceptual frameworks with significant uncertainties between policy implementation and management, a lack of standardized principles, guidelines, and measurement standards. The complexity of ecosystem interactions and the unclear boundaries of environmental management also obstruct EAM's development, especially in cross-border management contexts. Although EAM and marine protected areas (MPAs) are often used interchangeably, they differ significantly in their scope and application.

Recognizing these challenges, governments, communities, and scholars are more actively engaging in the marine resource development and protection process, with the goal of establishing a more comprehensive marine resource management system. This has led to an increasing number of successful cases. For example, at the national level, China's marine functional zoning and the European Union's Marine Strategy Framework Directive have partially addressed the challenges encountered in the development of EAM.

Scholars have also conducted extensive research on these issues. O'Grady (2011) [57] reached conclusions that align closely with those of Murawski. While Murawski (2007) [56] emphasized broader conceptual issues, O'Grady (2011) [57] provided a specific example of a management model that overcame some of the challenges highlighted by Murawski. He pointed out the effectiveness of the "credit points" management model implemented in southern Canada to improve environmental carrying capacity. In this model, polluters can purchase credit points from landowners at sewage discharge points to obtain the right to discharge pollutants. The credit points were earned by contributing to pollution control measures. This water quality trading program has been highly successful, thanks to community cooperation, legislative support, and clear credit and cost determination. Another successful case involves the management of the Great Barrier Reef Marine Park. Day and Dobbs (2013) [58] proposed that joint cooperation between the marine park and the Queensland state government in policy implementation brings significant advantages during the implementation phase.

Management Efficiency of MRCC

From a resource management efficiency perspective, Sutton-Grier et al. (2014) [59] found that incorporating carbon resource regulation as an additional ecosystem service into the existing regulatory system can significantly improve EAM efficiency. With advancements in scientific technology, the efficiency and accuracy of carbon monitoring systems have steadily increased. Digital technology allows for more precise measurement of blue carbon movement and emission rates across different environments and marine habitats. From a legal perspective, this approach does not face significant legislative barriers, further ensuring the high efficiency of management. Wang et al. (2024) [60] also pointed out that the efficiency of natural resource management significantly affects sustainable economic development. They proposed development suggestions for China's natural resource asset management system, focusing on aspects such as resource ownership and the distribution of resource tax revenue.

These case studies highlight the complexity of marine resource management and emphasize the importance of a multi-level cooperative approach involving local communities and national policies. From community management to technological solutions, the integration of different approaches demonstrates the multifaceted nature of marine resource conservation and management. By comparing various methods, it is clear that no single approach is sufficient on its own. Effective MRCC management requires a holistic approach.

5. Conclusions and Suggestions

5.1. Conclusions

This paper systematically reviews the research progress on MRCC, delving into its connotation, characteristics, measurement methods, influencing factors, and management.

Firstly, MRCC is an important indicator for assessing the sustainable development of marine resources and economies. Its connotation includes three aspects: marine environmental protection, resource supply capacity, and the economic functions of marine industries. MRCC exhibits regional specificity, dynamics, and development potential, with concentrated and extensive impacts, which make it a critical factor in marine resource development and ecological protection.

Secondly, regarding measurement methods, this paper compares single-factor assessment and comprehensive indicator assessment methods. The single-factor approach allows for an in-depth analysis of the carrying capacity of specific marine resources but fails to fully reflect the overall changes in MRCC. The comprehensive indicator approach, by constructing a multi-factor indicator system, overcomes the limitations of single-factor assessment and has become the mainstream method for measuring MRCC. In recent years, with the development of digital technologies, scholars have proposed various improved measurement methods for the traditional PSR framework, such as the PS-DR-DP hexagonal model and DPPD hybrid model. These methods are more innovative in terms of data integration, indicator system construction, and model application, enhancing the accuracy and comprehensiveness of MRCC measurement.

Finally, this paper analyzes the impact of human activities and economic development on MRCC, noting that appropriate management methods and policies can effectively mitigate the risks of MRCC decline. A review of China's MRCC-related policies highlights the essential role of policies in marine resource development and ecological protection. Then, case studies from different regions suggest that integrated management methods, such as community participation and government collaboration, can better improve MRCC. The deficiencies in managing MRCC and the current management efficiency are also analyzed.

5.2. Suggestions

Although research on carrying capacity has a long history, MRCC research has only gained attention in recent years, and many significant issues still need further exploration.

Firstly, in the area of MRCC measurement, future research should focus on improving the accuracy of evaluation models. Although some progress has been made in MRCC assessment methods, issues such as complex data integration and subjective weighting of indicators still make it difficult to accurately reflect the actual carrying capacity of marine resources. Future studies could combine emerging technologies, such as big data and artificial intelligence, to optimize the construction of indicator systems and enable more precise dynamic assessments. For instance, real-time monitoring of marine environmental data using remote sensing technology and sensor networks, combined with machine learning algorithms for data analysis and prediction, could provide a more accurate reflection of MRCC trends.

Secondly, identifying the impact scope of MRCC changes is an important direction for future research. As a global system, changes in the carrying capacity of the ocean can affect not only local marine areas but may also influence global ecosystems through ocean circulation and species migration. However, research on this broader impact is still relatively scarce. Future studies could leverage geographic information systems (GIS) and global ocean models to establish dynamic monitoring networks for global MRCC (Xu et al., 2024) [61]. By monitoring the diffusion and movement paths of certain substances or species in the ocean, it will be possible to analyze the broader impact of MRCC changes. Additionally, more in-depth research is needed on the long-term impacts of cross-regional human activities, such as marine trade, deep-sea fishing, and cruise tourism, on MRCC. This will provide a scientific basis for developing global marine resource management policies.

Finally, effectively managing marine resources using policies and financial tools is an important way to address the challenges posed by MRCC decline. Future research should explore innovations in policies and financial tools, integrating community, societal, and governmental efforts, and combining multi-disciplinary theories and methods to construct a more comprehensive MRCC management system. This system would help jointly address the challenges of marine resource management. For example, developing marine resource protection funds to attract social capital for marine ecological protection, designing marine disaster insurance products to reduce risks for marine industries, and encouraging financial institutions to invest in marine technology innovation to promote the sustainable development of marine industries.

Funding: Humanities and Social Sciences Foundation, Ministry of Education of the People's Republic of China (grant No. 22YJA790058).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Wang, S.; Xu, S. Marine Economic Development and Conservation. *Water* **2023**, *15*, 2253. [CrossRef]
2. Zhao, R.; Hynes, S.; He, G.S. Defining and Quantifying China's Ocean Economy. *Mar. Policy* **2014**, *43*, 164–173. [CrossRef]
3. Wang, R.; Cheng, J.; Zhu, Y.; Xiong, W. Research on Diversity of Mineral Resources Carrying Capacity in Chinese Mining Cities. *Resour. Policy* **2016**, *47*, 108–114. [CrossRef]
4. Han, C.; Lu, B.; Zheng, J. Analysis and Prediction of Land Resources' Carrying Capacity in 31 Provinces of China from 2008 to 2016. *Sustainability* **2021**, *13*, 13383. [CrossRef]
5. Chen, S.; He, Y.; Tan, Q.; Hu, K.; Zhang, T.; Zhang, S. Comprehensive Assessment of Water Environmental Carrying Capacity for Sustainable Watershed Development. *J. Environ. Manag.* **2022**, *303*, 114065. [CrossRef] [PubMed]
6. Bacher, C.; Duarte, P.; Ferreira, J.G.; He'ral, M.; Raillard, O. Assessment and comparison of the Marennes-Ole'ron Bay (France) and Carlingford Lough (Ireland) Carrying Capacity with ecosystem models. *Aquat. Ecol.* **1998**, *31*, 379–394. [CrossRef]
7. Dame, R.F.; Prins, T.C. Bivalve carrying capacity in coastal ecosystems. *Aquat. Ecol.* **1998**, *31*, 409–421. [CrossRef]
8. Duarte, P. A review of current methods in the estimation of environmental carrying capacity for bivalve culture in Europe. *Determ. Environ. Carr. Capacit. Coast. Mar. Areas Prog. Constraints Future Options* **2003**, *11*, 37–51.
9. Chadenas, C.; Pouillaude, A.; Pottier, P. Assessing carrying capacities of coastal areas in France. *J. Coast. Conserv.* **2008**, *12*, 27–34. [CrossRef]
10. Wei, C.; Guo, Z.; Wu, J.; Ye, S. Constructing an Assessment Indices System to Analyze Integrated Regional Carrying Capacity in the Coastal Zones—A Case in Nantong. *Ocean Coast. Manag.* **2014**, *93*, 51–59. [CrossRef]
11. Mao, H.Y.; Yu, D.L. Regional carrying capacity in Bohai Rim. *Acta Geol. Sin.* **2001**, *56*, 363–371.
12. Sun, J.; Miao, J.; Mu, H.; Xu, J.; Zhai, N. Sustainable Development in Marine Economy: Assessing Carrying Capacity of Shandong Province in China. *Ocean Coast. Manag.* **2022**, *216*, 105981. [CrossRef]
13. Wang, S.; Lu, B.; Yin, K. Financial Development, Productivity, and High-Quality Development of the Marine Economy. *Mar. Policy* **2021**, *130*, 104553. [CrossRef]

14. Gai, M.; Zhong, L.D.; Ke, L.N. Spatio-temporal law and coordinated development of the carrying capacity of marine environmental resource and economic system in China. *Acta Ecol. Sin.* **2018**, *38*, 7921–7932. (In Chinese) [CrossRef]
15. Abernethy, V. Carrying Capacity: The Tradition and Policy Implications of Limits. *Ethics Sci. Environ. Polit.* **2001**, *1*, 9–18. [CrossRef]
16. Christensen, V.; Pauly, D. Fish production, catches and the carrying capacity of the world oceans. *Naga WorldFish Cent.* **1995**, *18*, 34–40. Available online: http://hdl.handle.net/20.500.12348/2787 (accessed on 14 January 2024).
17. Michielsens, C.G.; McAllister, M.K.; Kuikka, S.; Mäntyniemi, S.; Romakkaniemi, A.; Pakarinen, T.; Karlsson, L.; Uusitalo, L. Combining multiple Bayesian data analyses in a sequential framework for quantitative fisheries stock assessment. *Can. J. Fish. Aquat. Sci.* **2008**, *65*, 962–974. [CrossRef]
18. Liu, Z.; Lu, W.; Wang, T.; Zhang, Y.; He, L.; Yang, L.; Deng, L. The assessment of carrying capacity of marine fishery resources in China. *Front. Mar. Sci.* **2025**, *11*, 1518235. [CrossRef]
19. Byron, C.; Bengtson, D.; Costa-Pierce, B.; Calanni, J. Integrating Science into Management: Ecological Carrying Capacity of Bivalve Shellfish Aquaculture. *Mar. Policy* **2011**, *35*, 363–370. [CrossRef]
20. Filgueira, R.; Grant, J. A box model for ecosystem-level management of mussel culture carrying capacity in a coastal bay. *Ecosystems* **2009**, *12*, 1222–1233. [CrossRef]
21. Suo, A.; Li, H.; Zhou, W.; Jiao, M.; Zhang, L.; Yue, W. Estimation of ecological carrying capacity of small-scale fish in marine ranch of the Pearl River Estuary, China. *Reg. Stud. Mar. Sci.* **2023**, *61*, 102901. [CrossRef]
22. Yao, Y.; Zhang, S.; Gao, S.; Lu, J.; Fu, G. Release capacity of Portunus trituberculatus enhancement in coastal waters: A case study in the marine ranching area of Haizhou bay. *Estuar. Coast. Shelf Sci.* **2024**, *299*, 108684. [CrossRef]
23. Mccool, S.F.; Lime, D.W. Tourism carrying capacity: Tempting fantasy or useful reality? *J. Sustain. Tour.* **2001**, *9*, 372–388. [CrossRef]
24. da Silva, C.P. Beach Carrying Capacity Assessment: How Important Is It? *J. Coast. Res.* **2002**, *36*, 190–197. [CrossRef]
25. Liu, R. Design and evaluation of marine resources environmental loading index system. *J. Guangdong Ocean Univ. China* **2009**, *29*, 6–9. (In Chinese)
26. Lanz, K.; Scheuer, S. *EEB Handbook on EU Water Policy Under the Water Framework Directive*; European Environmental Bureau: Brussels, Belgium, 2001.
27. Liu, K.; Huo, J. Preliminary study on the influence factor and evaluation index system of coastal zone carrying capacity. *J. Ocean Univ. China* **2008**, *4*, 8–11. (In Chinese) [CrossRef]
28. Li, Z.W.; Cui, L.T. Assessment on the carrying capacity of Hebei province offshore. *Trans. Oceanol. Limnol.* **2010**, *4*, 87–94. (In Chinese) [CrossRef]
29. Song, M.; Zhang, L.; An, Q.; Wang, Z.; Li, Z. Statistical Analysis and Combination Forecasting of Environmental Efficiency and Its Influential Factors since China Entered the WTO: 2002–2010–2012. *J. Clean. Prod.* **2013**, *42*, 42–51. [CrossRef]
30. Wang, L.; Liu, H. Comprehensive evaluation of regional resources and environmental carrying capacity using a PS-DR-DP theoretical model. *J. Geogr. Sci.* **2019**, *29*, 363–376. [CrossRef]
31. Du, Y.-W.; Li, B.-Y.; Quan, X.-J. Construction and Application of DPPD Model for Evaluating Marine Resources and Environment Carrying Capacity in China. *J. Clean. Prod.* **2020**, *252*, 119655. [CrossRef]
32. Ma, P.; Ye, G.; Peng, X.; Liu, J.; Qi, J.; Jia, S. Development of an Index System for Evaluation of Ecological Carrying Capacity of Marine Ecosystems. *Ocean Coast. Manag.* **2017**, *144*, 23–30. [CrossRef]
33. Luo, X.; Wang, Z.; Yang, L.; Lu, L. Extension Evaluation of Marine Ecological Carrying Capacity: An Empirical Study Based on the Development of Tropical Marine Island Free Trade Ports in Developing Countries. *Trop. Conserv. Sci.* **2020**, *13*, 1940082920911343. [CrossRef]
34. Ma, R.; Ji, S.; Ma, J.; Shao, Z.; Zhu, B.; Ren, L.; Li, J.; Liu, L. Exploring Resource and Environmental Carrying Capacity and Suitability for Use in Marine Spatial Planning: A Case Study of Wenzhou, China. *Ocean Coast. Manag.* **2022**, *226*, 106258. [CrossRef]
35. Xia, H.-X.; Yue, W.-Z.; Wang, T.-Y.; Wu, T.; Chen, Y. Theoretical Thinking and Practical Scheme of "Double Evaluations" at Provincial Level: A Case Study of Zhejiang Province. *J. Nat. Resour.* **2020**, *35*, 2325–2338. [CrossRef]
36. Wang, S.; Li, K.; Liang, S.; Zhang, P.; Lin, G.; Wang, X. An Integrated Method for the Control Factor Identification of Resources and Environmental Carrying Capacity in Coastal Zones: A Case Study in Qingdao, China. *Ocean Coast. Manag.* **2017**, *142*, 90–97. [CrossRef]
37. Zhou, X.-Y.; Lei, K.; Meng, W.; Khu, S.-T. Industrial Structural Upgrading and Spatial Optimization Based on Water Environment Carrying Capacity. *J. Clean. Prod.* **2017**, *165*, 1462–1472. [CrossRef]
38. Yang, J.S.; Pan, X.W.; Yin, Z.Q.; Cui, J.R.; Sun, P.Q.; Gu, H.F.; Li, J.X.; Wang, Y.; Xu, M. The ecological footprint study of marine fisheries in Liaoning Province of China based on system dynamics. *Indian J. Fish.* **2023**, *70*, 18–27. [CrossRef]
39. He, Q. Modelling and analysis of the impact of renewable energy on mitigating ecological pollution of marine environment. *Desalina. Water Treat.* **2023**, *303*, 44–47. [CrossRef]

40. Feng, J.; Yu, H.; Wu, L.; Yuan, C.; Zhao, X.; Sun, H.; Cheng, C.; Li, Y.; Sun, J.; Li, Y.; et al. Evaluating Ecosystem Characteristics and Ecological Carrying Capacity for Marine Fauna Stock Enhancement Within a Marine Ranching System. *Animals* **2025**, *15*, 165. [CrossRef] [PubMed]
41. Wang, Z.; Yao, L.; Yu, J.; Chen, P.; Li, Z.; Yang, W. Evaluation of the ecological carrying capacity of Wailingding marine ranching in Zhuhai, China by high-resolution remote sensing. *Front. Mar. Sci.* **2024**, *11*, 1354407. [CrossRef]
42. Bui, L.T.; Tran, D.L. Assessing marine environmental carrying capacity in semi-enclosed coastal areas—Models and related databases. *Sci. Total Environ.* **2022**, *838*, 156043. [CrossRef] [PubMed]
43. Wang, C.; He, X.; Ma, M.; Xiong, L.; Zhang, W. Assessing Coastal Ecosystem Carrying Capacity by a Comprehensive Economy-Resources-Environment System: A Case Study of South Korea. *Ocean Coast. Manag.* **2022**, *227*, 106283. [CrossRef]
44. Chen, J. Influence and Evaluation of Economic Carrying Capacity in Guangdong Province from the Perspective of Trans-Regional Marine Ecological Environment Flow. *J. Coast. Res.* **2020**, *104*, 682–686. [CrossRef]
45. Wang, S.; Zhou, G.; Chen, Z.; Jiang, D.; Dai, G. Does the marine environmental carrying capacity of the Yellow Sea's large marine ecosystem maintain sustainable development?–Evidence from Shandong China. *Indoor Built Environ.* **2023**, *32*, 1579–1591. [CrossRef]
46. Li, Y.; Sun, L.; Wu, Z.; Liu, H. Evaluation and Obstacle Factors of Marine Resources and Environment Carrying Capacity in Beibu Gulf Urban Agglomeration. *Front. Mar. Sci.* **2023**, *10*, 1196196. [CrossRef]
47. Yu, Z.; Di, Q. The coordination between maritime economies and marine carrying capacity and their spatiotemporal evolution in the cities of the bohai rim in china. *Ecol. Model.* **2020**, *438*, 109192. [CrossRef]
48. Chen, X.; Yu, Z.; Liang, C.; Di, Q. Where Is the Path to Sustainable Marine Development? Evaluation and Empirical Analysis of the Synergy between Marine Carrying Capacity and Marine Economy High-Quality Development. *Water* **2024**, *16*, 394. [CrossRef]
49. Zhang, Y. Impact of the coupling relationship between marine industry and regional development on the marine economy. *J. Sea Res.* **2024**, *198*, 102486. [CrossRef]
50. Singleton, S. Co-operation or capture? The paradox of co-management and community participation in natural resource management and environmental policy-making. *Environ. Politics* **2000**, *9*, 1–21. [CrossRef]
51. Day, J.C. Zoning—Lessons from the Great Barrier Reef marine park. *Ocean Coast. Manag.* **2002**, *45*, 139–156. [CrossRef]
52. Clarke, B. Australia's Coastcare Program (1995–2002): Its Purpose, Components and Outcomes. *Geogr. Res.* **2006**, *44*, 310–322. [CrossRef]
53. Cicin-Sain, B.; Belfiore, S. Linking Marine Protected Areas to Integrated Coastal and Ocean Management: A Review of Theory and Practice. *Ocean Coast. Manag.* **2005**, *48*, 847–868. [CrossRef]
54. Ward, J.; Dillon, P. Principles to coordinate managed aquifer recharge with natural resource management policies in Australia. *Hydrogeol. J.* **2012**, *20*, 943–956. [CrossRef]
55. Weiss, K.; Hamann, M.; Kinney, M.; Marsh, H. Knowledge Exchange and Policy Influence in a Marine Resource Governance Network. *Glob. Environ. Chang.* **2012**, *22*, 178–188. [CrossRef]
56. Murawski, S.A. Ten Myths Concerning Ecosystem Approaches to Marine Resource Management. *Mar. Policy* **2007**, *31*, 681–690. [CrossRef]
57. O'Grady, D. Sociopolitical Conditions for Successful Water Quality Trading in the South Nation River Watershed, Ontario, Canada. *J. Am. Water Resour. Assoc.* **2011**, *47*, 39–51. [CrossRef]
58. Day, J.C.; Dobbs, K. Effective Governance of a Large and Complex Cross-Jurisdictional Marine Protected Area: Australia's Great Barrier Reef. *Mar. Policy* **2013**, *41*, 14–24. [CrossRef]
59. Sutton-Grier, A.E.; Moore, A.K.; Wiley, P.C.; Edwards, P.E.T. Incorporating Ecosystem Services into the Implementation of Existing U.S. Natural Resource Management Regulations: Operationalizing Carbon Sequestration and Storage. *Mar. Policy* **2014**, *43*, 246–253. [CrossRef]
60. Wang, S.; Xing, L.; Chen, X.; Song, M. Evaluating and Enhancing Natural Resource Asset Management Efficiency in China: A Data Envelopment Analysis Study. *Resour. Policy* **2024**, *92*, 105000. [CrossRef]
61. Xu, R.-Y.; Wang, K.-L.; Miao, Z. The Impact of Digital Technology Innovation on Green Total-Factor Energy Efficiency in China: Does Economic Development Matter? *Energy Policy* **2024**, *194*, 114342. [CrossRef]

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Article

Where Is the Path to Sustainable Marine Development? Evaluation and Empirical Analysis of the Synergy between Marine Carrying Capacity and Marine Economy High-Quality Development

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Abstract: Enhancing the marine carrying capacity (MCC) is of important value in hastening the transformation of the marine economy and realising the marine economy high-quality development (MEHD). We explore the synergistic mechanism between the MCC and MEHD and its comprehensive indicator system, measure the synergistic relationship between China's MCC and MEHD from 2006 to 2020 using the improved TOPSIS model and the composite system synergism model, and explore the influencing factors and their interactions using geographic probes. The research findings are (1) that China's MCC and MEHD show a growing trend during the study period, in which marine green development is at a higher level and the cultivation of marine knowledge improves most significantly, but the general value of the MEHD is relatively low. (2) In terms of the synergistic relationship, the degree of ordering of the two shows a sustained rising trend, and the degree of ordering of the marine economy development as a whole is higher than the MCC; the degree of synergy is increasing, but the general value of synergistic development is low. (3) The main factors driving the MCC and MEHD are the marine consumption capacity, the marine opening, and the marine industrial structure; the explanatory power of most factor interactions tends to decrease, and the explanatory power of the interactions among the development of land-based economy, the marine industry structure, and the marine economy increase, and the impacts of the different factor interactions on the synergistic development are all greater than the factors. The influence of different factors on synergistic development is greater than the influence of each factor alone.

Keywords: marine economy; marine carrying capacity; high-quality development; synergistic mechanism; composite system synergism model; driving factors

1. Introduction

Since the reform and opening up, China's rapid development of its marine economy, in order to achieve the goal of building a strong marine power, has laid a strong economic foundation [1]. However, it should also be seen that the advantages of resource endowment, changes in the demand structure, and the development of scientific and technological progress and other situations have been formed. The rapid expansion of the marine economy and the increase in the intensity of marine exploitation and utilisation have occurred [2]. The marine economy results in the over-exploitation of the coastal beaches and mudflats, and the scale of the reclamation, the reduction of the shallow marine biological resources, environmental pollution, and ecological damage are too large. The deterioration of the quality of nearshore seawater has led to other negative effects, which has aroused the attention of scholars and decision-makers, who are highly concerned about the overloading of marine resources and the environment [3]. As a quantitative indicator reflecting the ability of sustainable development of the marine human–land relationship, the MCC is an important basis for the judgement of marine cyclic development [4]. The MCC and the high quality of the marine economy have a mutually reinforcing role [5], and the study of the synergy between the MCC and the high-quality marine economy is of great practical significance for promoting the high-quality development of China's marine economy and building a strong marine country [6].

Currently, academics have studied the issue of the MCC from different perspectives. At the level of theoretical analysis, the concept of the MCC was first proposed and defined by Di [7], and it "refers to the ability or limit of the ocean to support the coordinated development of population, environment and economy within a certain period of time with the principle of sustainable use of marine resources and non-destruction of marine ecosystems, and through self-sustainability and self-regulation under the material standard of living in conformity with the social and cultural norms of the current stage". Later, many scholars have supplemented and improved its connotation [8,9] and explored its relationship, including the layout of marine industries and marine ecological compensation from a theoretical perspective [10–12]. At the level of empirical research, with the continuous improvement of the theoretical basis of the MCC, research has begun to transition from theory to empirical evidence, and academics have begun to try to borrow the more mature models and mathematical methods of analysis in the study of ecological carrying capacity and strive to construct the corresponding indicator system to quantitatively evaluate the MCC using the state space method [13,14], entropy [15], the fuzzy comprehensive judgement method [16], the projection tracing model [17], and so on. Some scholars combine the MCC with marine economic development and try to borrow quantitative mathematical models to explore the intrinsic connection between the two. Yu et al. [18], from the perspective of the MCC, used factor analysis to study the rationality of the spatial layout of the marine fishery, optimisation criteria, adaptive optimisation, and other issues. Shan et al. [19] studied the strategic choice of coastal tourism in China from the perspective of the MCC using hierarchical analysis and factor analysis.

For the research on marine economy, foreign countries focus on measuring the contribution of the marine economy to the national economy [20,21], the efficiency of the marine economy [22], and the marine economy development quality [23]. Domestic research mainly focuses on connotation definitions, evaluation systems, and countermeasure suggestions. There are more results on empirical cases to study the whole coastal area of China [24,25]; the evaluation indexes are the comprehensive index system method [26–29], and the evaluation methods mainly use the entropy-modified G2 assignment method, the improved CRITIC assignment method, etc., to confirm the weights and the value of development.

The fruitful results achieved around the issue of marine economics and the MCC have provided useful references for further findings on the issue of the MCC and the marine economy, but the relevant study is mostly limited to the marine economy or the MCC, and there are not many theoretical and empirical studies on the synergistic relationship between the MCC and the marine economy. Based on this, this paper studies the synergistic relationship between the MCC and MEHD according to the inherent requirements of the development of the MCC and MEHD. We construct an evaluation indicator for the MCC and MEHD and analyse the index from 2006 to 2020 with the help of the improved TOPSIS model and the synergistic model of the composite system. We analyse the evolution trend of the index, orderliness, and synergy between China's MCC and MEHD from 2006 to 2020. We use a geodetic detector model to approach the spatial driving factors and their interactions, with a view to enrich the research on the relationship between the MCC and the related theory of the marine economy. We also provide certain references for the formulation of the policies and planning for the enhancement of the MCC and the improvement of the efficiency of the economy in various regions.

2. Research Design and Methodology

2.1. Research Design

The research design and methodology adopted in this study are shown in Figure 1: (1) evaluation and analysis of the MCC and MEHD. First, in the literature research, appropriate evaluation indicators were selected for the MCC and marine economy. Second, the index was calculated using the improved TOPSIS model. Finally, we used the composite system synergy model to analyse the subsystem orderliness, composite system synergy, and change trends between China's MCC and the marine economy. (2) Analysis of synergy driving factors. First, we selected the possible influencing factors of composite system synergy on the basis of the previous literature and then measured the synergy driving force of six influencing factors on the synergy between China's MCC and the MEHD using a geodetector. Finally, we used the interaction detector in the Geodetector software (http://www.geodetector.cn/, accessed on 15 July 2023) to explore the degree of synergistic influence.

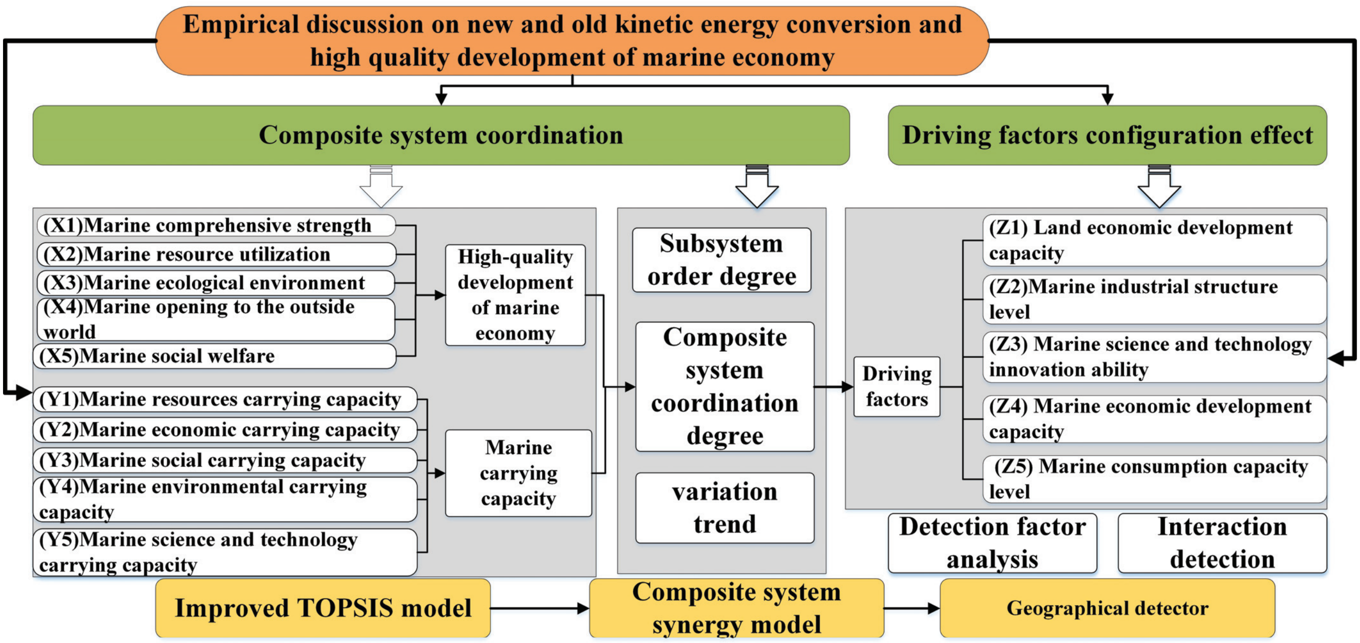


Figure 1. Research design.

2.2. Synergistic Relationship between Marine Carrying Capacity and Marine Economy High-Quality Development

Academics generally believe that the carrying marine capacity is a significant basis for the judgement of marine development. The MCC emphasises the sustainable use of marine resources and the ability to support economic and social development, and this carrying capacity makes the marine environment able to support the coordinated development of society, economy, resources, and environment [30,31]. Indicators that characterise the carrying capacity include the marine ecological capacity, the ability to supply inventory, and the degree of industrial development, through which the coastal socio-economic situation can be further analysed, thus enriching and deepening the cognition and understanding of the carrier (marine resources and environment), the carrying object (socio-economics), and the external environment (science, technology, innovation, and management) of the carrying capacity of the marine environment and resources, which will help to achieve the healthy development of marine ecosystems [32]. "The ocean is a strategic place for high-quality development", and refers to the process of production and life in the marine field; the human demand for a preferable life is met, the allocation of resource factors and output is efficient, the value of scientific development and technological upgrading is constantly improving, and the quality of products and services continues to grow, focusing on the coordinated development under the new concepts of development, such as innovation, coordination, greenness, openness, and sharing. Therefore, the MCC and MEHD are complementary but also have synergistic interaction, coordination, and symbiosis, and this paper uses the two interactive relationships as the main line to build the MCC and MEHD interaction mechanism analysis framework (Figure 2).

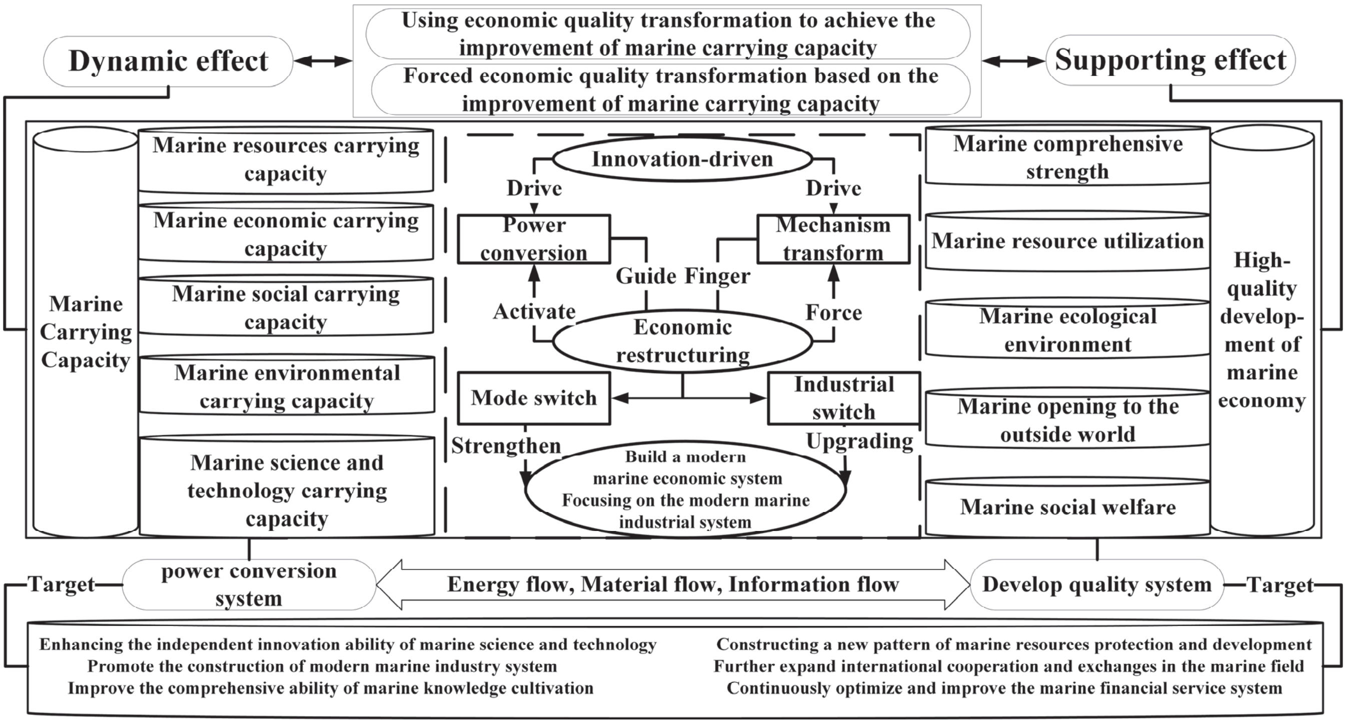


Figure 2. Mechanisms for synergistic development.

The marine economic carrying capacity is the core content of the MCC, mainly emphasising the increased momentum of the marine economy by the original labour force, resources, capital, and other traditional elements of the expansion of the scale of conversion to innovation, efficiency, quality, and other structural optimisation and upgrading. The marine social carrying capacity is a fundamental guarantee of the development of the MCC, embodied in the optimisation of the government's management services, and actively adjusts the constraints on marine economic constraints to provide institutional and policy protection [33]. The government's guarantee can promote the marine economy development with a high degree of efficiency and benefit; the marine economic structure transformation is a force for the development of the high-quality marine economy, which changes the structure of the marine economy and the system and can promote the allocation of marine economic resources and the transformation of the mode of economic development [34], and can then promote the optimisation and upgrading of the structure of the marine industry and promote the MEHD. The efficient use of marine resources is an important result of the enhancement of the MCC. The transformation of development mode has promoted a change in the marine economy from the traditional rough development to the high-quality, high-efficiency, and low energy consumption development mode. A change in the dominant industry is a manifestation of the MCC enhancement, which mainly embodies a change in the dominant marine industry from the traditional industry to the strategic emerging industry and a change in the high-level service industries. This results in the construction of a modernised ecoonmy. The emphasis of a modernised marine economy focusing on the modern marine industrial system is a significant target task for the marine economy [1].

2.3. Evaluation Indicator System

2.3.1. Selection Indicators of the Marine Carrying Capacity

We refer to the connotation and mechanism analysis of the MCC, with reference to the Guidelines on the Indicator System and Technical Methods for Monitoring and Early Warning of the Carrying Capacity of Marine Resources and Environment issued by the State Oceanic Administration in 2015 [35], and the Technical Procedures for Assessing the Carrying Capacity of Marine Resources in Nearshore Areas [32], a local standard issued by the Shandong Provincial Bureau of Quality and Technical Supervision, in 2017. Considering the current situation and characteristics of marine natural resources and integrating supply and marine resource demand factors, the MCC system is divided into five subsystems: marine resource carrying capacity, marine economic carrying capacity, marine social carrying capacity, marine environmental carrying capacity, and marine scientific and technological carrying capacity [36], and the indicator system is shown in Figure 3.

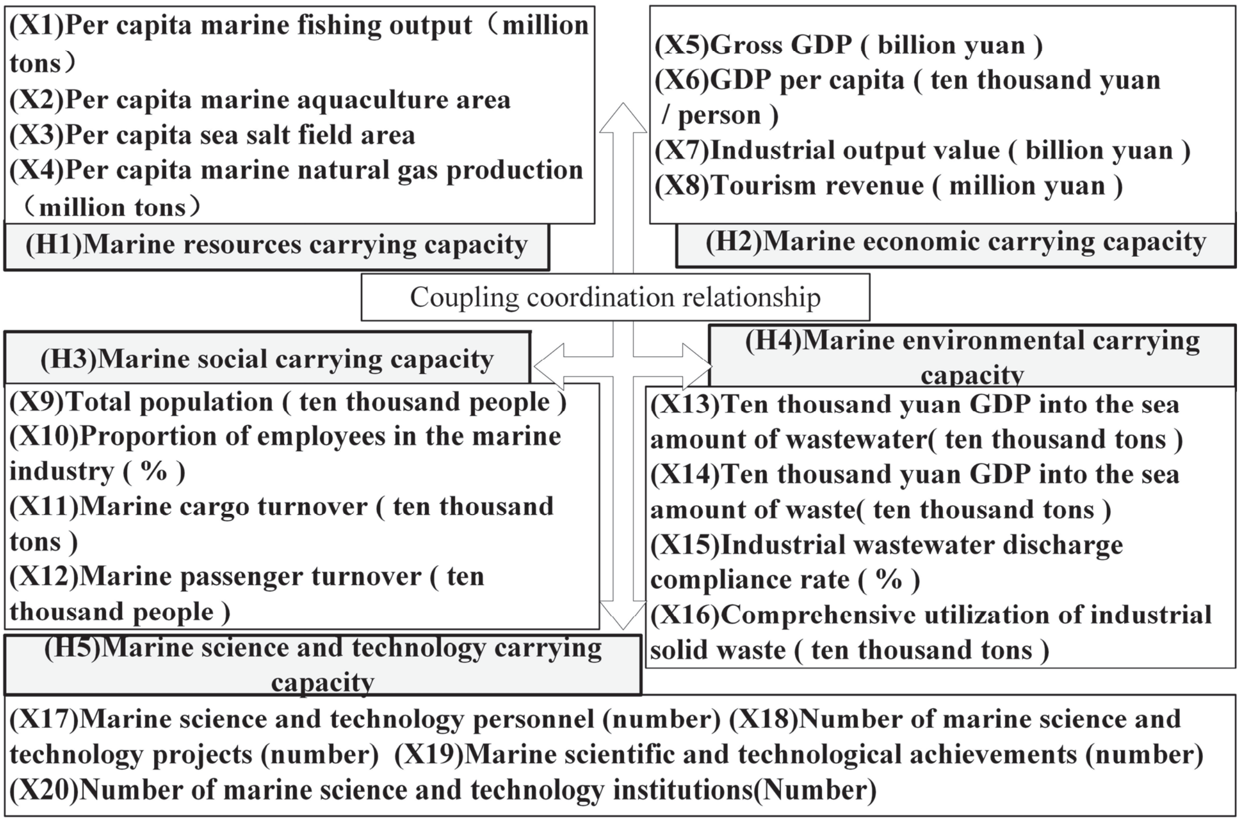


Figure 3. Indicator system of the marine carrying capacity.

2.3.2. Selection Indicators of Marine Economy High-Quality Development

The MEHD is a complex and comprehensive system, taking into account economic development, resource use, ecological environment, social welfare, and other aspects of integrated and coordinated development [37]. Based on the connotation and characteristics of high-quality development, following the concept and the law of marine economic development, the development objectives are marine economic growth, optimising and upgrading its structure, improving the output of ocean resource use and allocation, giving attention to the level of marine ecological environmental protection, ameliorating the level of openness of the marine economy, and improving the performance of social welfare [38]. To evaluate marine resource utilisation, marine ecological environment, marine openness to the outside world, and marine social welfare, an evaluation index system was constructed (Figure 4).

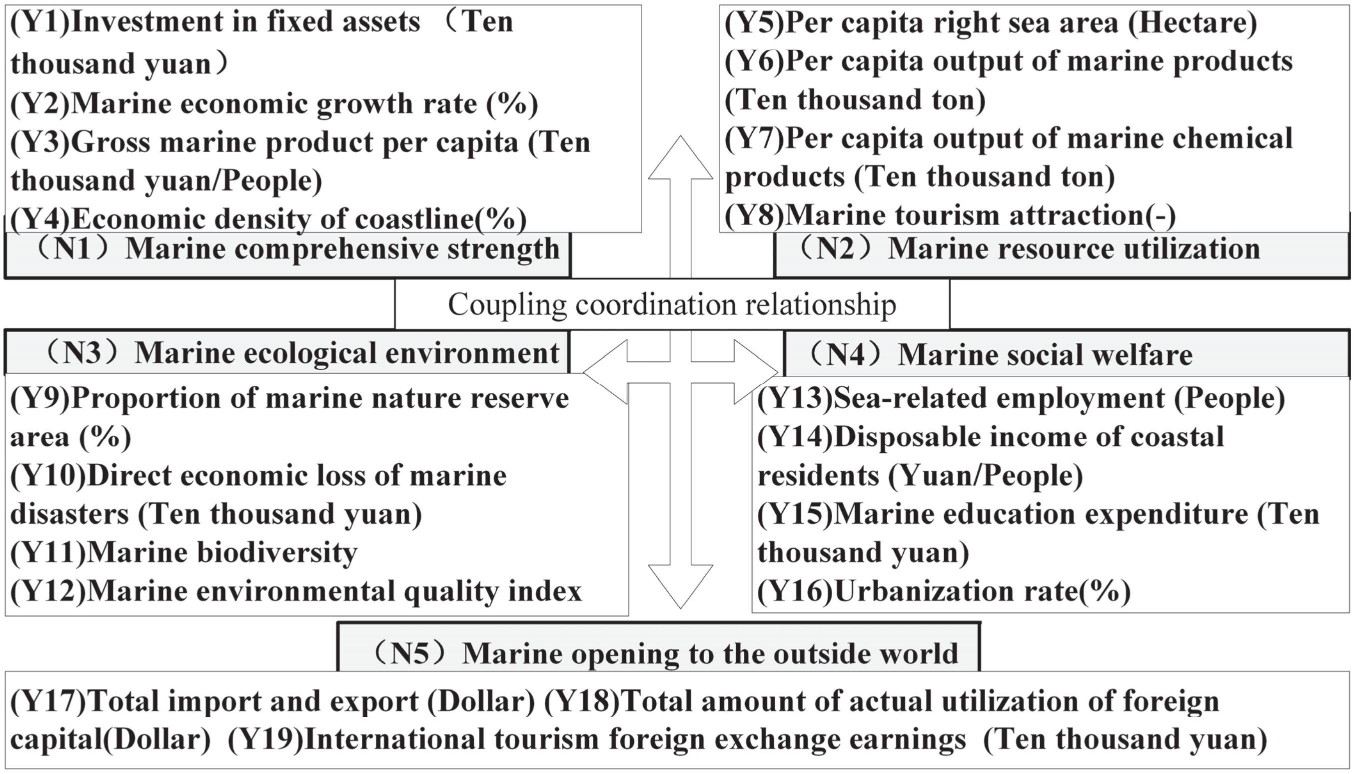


Figure 4. Indicator system of the high-quality development of the marine economy.

2.4. Methods

2.4.1. Entropy-Weighted TOPSIS Method

The main principle is to use the objective evaluation method and entropy weighting method to determine the index weights and use the TOPSIS model to analyse the MCC and MEHD index [39,40]. The detailed modelling steps are as follows:

The data standardisation evaluation matrix:

$$a_{ij} = \frac{x_{ij} - min(x_{ij})}{max(x_{ij}) - min(x_{ij})} \tag{1}$$

$$b_{ij} = \frac{max(x_{ij}) - x_{ij}}{max(x_{ij}) - min(x_{ij})} \tag{2}$$

where x_{ij} denotes the original data for indicator j in year i; $i = 1, 2, \ldots, n$; $j = 1, 2, \ldots, m$; $max(x_{ij})$ and $min(x_{ij})$ are the maximum and minimum values for all samples; and a_{ij} is the data after x_{ij} normalisation.

The weighted decision matrix:

$$v_{ij} = w_i a_{ij} \tag{3}$$

where v_{ij} represents the combined weight of each evaluation indicator.

Determine the positive and negative ideal solutions:

$$\begin{cases} a_j^+ = max\{a_{1j}, a_{2j}, \cdots a_{nj}\} \\ a_j^- = min\{a_{1j}, a_{2j}, \cdots a_{nj}\} \end{cases} \tag{4}$$

$$\begin{cases} v_j^+ = max\{v_{1j}, v_{2j}, \cdots v_{nj}\} \\ v_j^- = min\{v_{1j}, v_{2j}, \cdots v_{nj}\} \end{cases} \tag{5}$$

Positive and negative weighted distances:

$$c_i^+ = \sqrt{\sum_{j=1}^{n} w_j(p_{ij} - p_j^+)^2}, \quad c_i^- = \sqrt{\sum_{j=1}^{n} w_j\left(p_{ij} - p_j^-\right)^2} \tag{6}$$

Virtual negative ideal solutions and distances:

$$v_j^* = 2v_j^- - v_j^+,\ d_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - vp_j^+)^2},\ d_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2} \tag{7}$$

Determine the synthetic distance:

$$\begin{cases} L_i^+ = \alpha c_i^+ + \beta d_i^+ \\ L_i^- = \alpha c_i^- + \beta d_i^- \end{cases} (\alpha = \beta = 0.5) \tag{8}$$

(T_i) is calculated by applying the following formula:

$$T_i = \frac{L_i^-}{L_i^+ + L_i^-}\ (T_i \in [0, 1]) \tag{9}$$

Evaluate the MCC and MEHD process index. The above research methods are mainly completed by the "MATLABR2023b" operation.

2.4.2. Composite System Synergy Model

This paper constructs a composite system synergy model for the MCC and MEHD [41]. T refers to the total system of the MCC and MEHD in China. T_i refers to each subsystem.

Subsystem orderliness examines $U_i(T_{ik})$ as the order parameter of the MCC and marine economy, and orderliness is calculated by:

$$U_i(T_{ik}) \begin{cases} \frac{T_{ik} - b_{ik}}{a_{ik} - b_{ik}} \\ \frac{a_{ik} - T_{ik}}{a_{ik} - a_{ik}} \end{cases} \tag{10}$$

where $T_{ik} \in [a_{ik}, b_{ik}]$,$a_{ik}$,$b_{ik}$ are the min and max values of the kth element of i of the subsystem. Next, determine the linear weighted summation method of summation with the following formula:

$$U_i(T_i) = \sum_{j=1}^{n} U_i(T_{ik}) \times w_{ik} \tag{11}$$

To obtain the composite system synergy degree, set the initial moment t_0 development to moment t_1, and the subsystem order degree is $U_i^0(T_i), U_i^1(T_i), k = 1, 2, \cdots n$. Then, the t_0 to t_1 moments of the MCC and marine economy of the overall synergy degree are:

$$F = \theta \sum_{i=1}^{n} \gamma_i \left[\left| U_i^1(Ti) - U_i^0(T_i) \right| \right],\ \theta = \frac{min_i\left[U_i^1(Ti) - U_i^0(T_i)\right]}{\left|min_i\left[U_i^1(Ti) - U_i^0(T_i)\right]\right|} \tag{12}$$

where F is the synergy, θ is the stability of the system synergy, and γ_i represents the weighting factor. The greater the value of the composite system synergy is given by $F \in [-1, 1]$. In general, if the orderliness of one subsystem rises more, while the orderliness of another subsystem rises less or falls back, the whole system is in an unstable or uncoordinated state [42]. The above research methods are mainly completed by the "MATLABR2023b" operation.

With reference to the evaluation criteria between the degree of synergy and the degree of synergy of the system [43,44], the evaluation criteria for the synergy between the MCC and MEHD are given in this paper (Table 1).

Table 1. Composite system synergy evaluation criteria.

Synergy Degree	[−1, −0.6]	(−0.6, −0.2]	(−0.2, 0]	(0, 0.2]	(0.2, −0.6]	(0.6, −1]
Collaborative state	Highly non-synergy	Moderate non-synergy	Mild non-synergy	Mild synergy	Moderate synergy	Highly synergy

2.4.3. Geodetectors

The MCC and high-quality synergistic development are influenced by a variety of factors, and traditional methods need to meet more conditions for the analysis of such problems. The geographic probe is a method of identifying the relationship between multiple factors by combining the "factor force" metric proposed by Wang [45]. The correlation between factor variables and outcome variables is analysed, and different categories of variables are normalised under the same spatial scale through the classification analysis of each factor [46]. This paper introduces a geographic probe analysis to quantitatively detect the drivers of the MCC and high quality. The calculation formula is:

$$q = 1 - \frac{1}{n\sigma^2}\sum_{i=1}^{m} n_i\sigma_i^2 \quad (13)$$

where q is an indicator of the determinants of change in the MCC and high quality; n is the number; m is the type of each influencing factor; and n_i and σ_i^2 are the total number and variance of each study unit respectively. The above research methods are mainly completed by "ArcGIS 10.2" software.

3. Study Area and Data

3.1. Study Area

The study area includes 11 provinces along the Chinese coast. China's marine economy has developed steadily, with the gross marine product increasing from 696.93 billion CNY in 2006 to 903.85 billion CNY in 2021, with an increasing average growth rate between 2006 and 2021 (Figure 5). The marine economy has been strengthening, with the national marine GDP rising after 2010, reaching a peak of 17.10% in 2019. The share of China's marine GDP in the country's GDP was 9.55% in 2006 and declined after 2007, basically stabilising at 9.3% during 2007–2019. China's marine economy suffered a setback in 2020, with the national gross marine product falling by 10.52% compared to 2019, but a series of policies, such as "MEHQD", "developing the marine economy and building a strong marine nation", and "building a marine community", were adopted. "In 2021, the total output value reached a new level, exceeding 9 trillion for the first time, indicating a strong recovery of China's marine economy and the gradual release of economic vitality" [23].

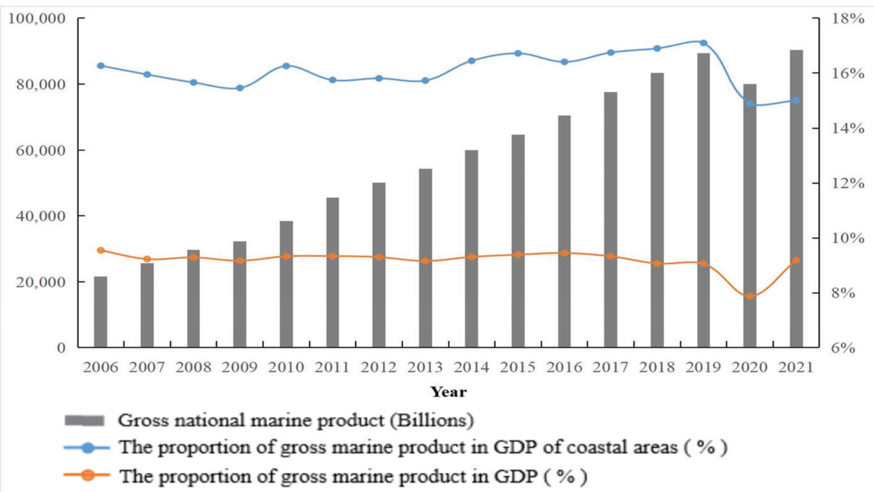


Figure 5. China's gross ocean product and its share in 2006–2021.

3.2. Index Weights

The main principle is to first determine the indicator weights using the objective evaluation entropy weighting method and then use the TOPSIS model to measure and evaluate the MCC and the high-quality development index. Firstly, the indicator data are standardised in the formula; then, the information entropy of each indicator is calculated in the formula, and objective weights are obtained in the equation, as shown in Figure 6.

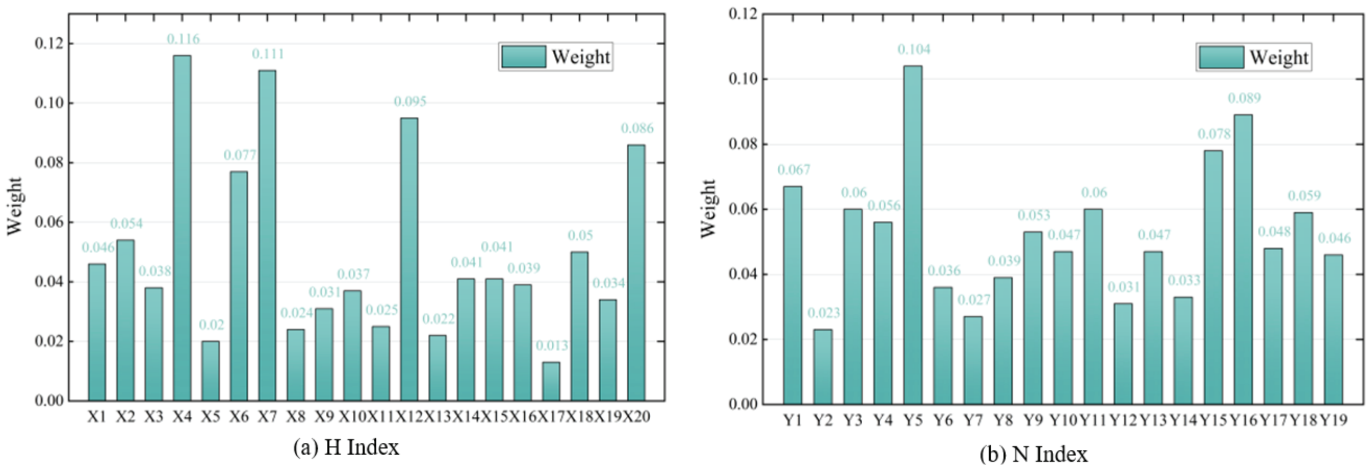


Figure 6. The weights of indexes with the entropy weight method.

In Figure 6a, the weights of the indicators of the MCC are relatively different. Among them, per capita marine natural gas production (X4), industrial output value (X7), marine passenger turnover (X12), and number of marine X20 are the most important indicators. Industrial output value (X7), marine passenger turnover (X12), and number of marine X20 are the most important indicators, indicating that these indicators are important factors affecting the MCC. The number of marine science and technology personnel (X17), marine science and technology innovation capacity, and green development capacity have smaller overall weights. This further indicates that marine technology and the upgrading of marine industries are important driving forces for the MCC.

In Figure 6b, the overall difference in the weighting of the indicators of quality marine economic development is relatively small. Among them, the highest index is for the area of the confirmed sea area per capita (Y5), indicating the area of the sea area. On the whole, marine social welfare and marine openness to the outside world have higher weight values than marine ecological environment and marine resource utilisation on the whole. This indicates that high-quality development needs to focus not only on efficiency but also on equity; realising the fruits of economic development to be shared fairly by all people is a necessary condition for its promotion. The continuously expanding openness to the outside world is the impetus for promoting marine economic and social development and is a fundamental way to achieve sustainable marine development.

3.3. Data Source

The data for the relevant indicators used were obtained from the China Marine Statistical Yearbook 2007–2021 and the China Marine Environmental Quality Bulletin of each coastal province for each year, and some data were obtained from the National Marine Innovation Index Report 2021 and the China Marine Economic Development Index 2021. Indicator data that were not available were filled in and processed with multiple interpolations according to the actual situation. With regard to the quantification of directional indicators, based on a large number of references and access to publicly available statistics and information, such as the China Statistical Yearbook and the Marine Environmental Quality Bulletin of each coastal province and municipality [47], relevant quantitative indicators were selected, and the quantitative indicators were weighted and summed up using the weighted comprehensive evaluation method.

4. Empirical Results

4.1. Characteristics of the Evolution of the Marine Carrying Capacity and Marine Economy High-Quality Development

4.1.1. Analysis of the Marine Carrying Capacity

Based on the five dimensions of marine resource carrying capacity (H1), marine economy carrying capacity (H2), marine society carrying capacity (H3), marine environment carrying capacity (H4), and marine science and technology carrying capacity (H5) in the MCC evaluation index system (H), a folding map of the MCC index from 2006 to 2020 was drawn (Figure 7).

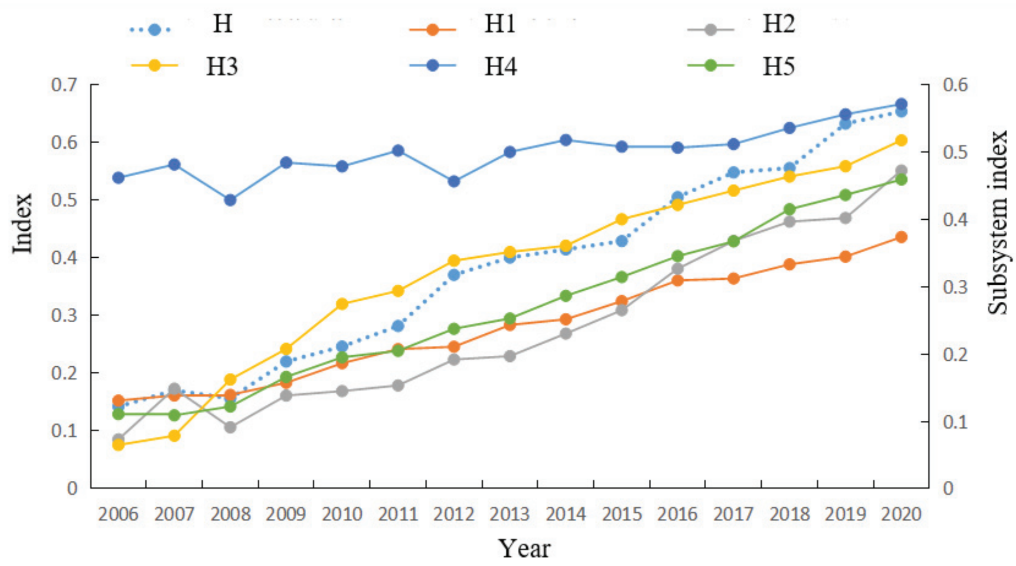


Figure 7. The trend of the marine carrying capacity.

Figure 7 shows that during the period 2006–2020, China's MCC index fluctuated and increased from 0.142 in 2006 to 0.654 in 2020, indicating that high-quality development contributes more to the carrying capacity of the marine area, and the index of the carrying capacity of the marine area has achieved a certain degree of improvement. Among the classified indicators of the MCC index system, the marine environment has been at a high level, and to achieve further improvement of the MCC index, it is necessary to increase the protection of the marine ecological environment and accelerate the restoration of the marine ecological environment [48]. The fluctuation trend of the carrying capacity of marine resources, marine economy, marine society, and marine science and technology is basically the same, accounting for a relatively high proportion in the MCC system, reflecting that technology, industry, knowledge, and finance are important factors. The MCC is enhanced and achieves a higher quality mainly through marine technological innovation, upgrading of the industrial structure, strengthening the cultivation of knowledge, and the ability of the marine society to develop. The higher percentage reflects that technology, industry, knowledge, and finance are important factors affecting the MCC.

This study analysed the the MCC index using the modified TOPSIS model and found that the impacts of the different dimensional indicators on the development of the MCC varied in different areas along China's coast. Figure 8a further shows the impact coefficients of five dimensions, namely marine resource, marine economic, marine social, marine environmental, and marine science and technology carrying capacity. From the view of the sub-dimension indicators, the marine environmental carrying capacity is most significantly improved, followed by the marine science and technology carrying capacity. This indicates the changes in the marine technology capacity, while an accelerated enhancement of the marine environment must increase the cultivation of new types of talent to talent to help the sustainability of the marine economy in the future. We should continue improve marine economic growth if the pulling role is not obvious, enhance the positioning of the marine innovation chain in each functional area, and optimise the spatial pattern of marine development. In the process of improving the MCC, there are still some obstacles in terms of ideological understanding, institutional mechanisms, laws, regulations, and policies, and there is pressure on the transformation of marine innovation, resulting in the application of marine science and the use efficiency is at a lower level, and the structural transformation is not in line with the situation. Therefore, the current important task is to make up for the short board of structural transformation and enhance the momentum of industrial and product structure change and upgrades.

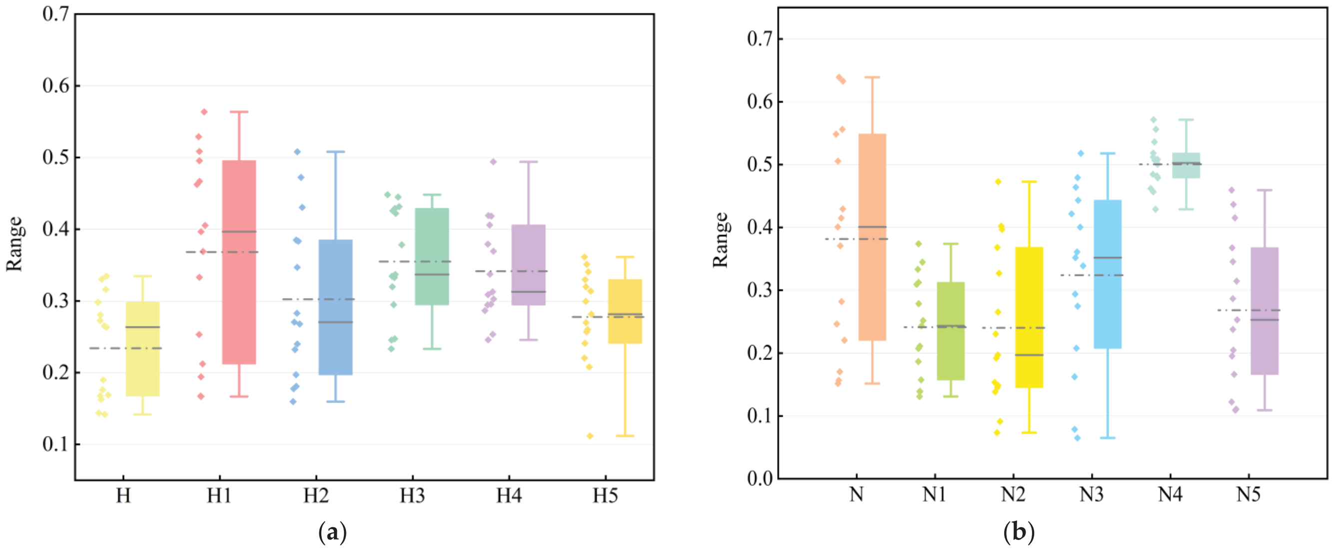


Figure 8. (**a**) Box diagram of the marine carrying capacity. (**b**) Box diagram of marine economy high-quality development.

4.1.2. Analysis of the Marine Economy Quality Development Index

Based on the index and the constructed evaluation index system, an evaluation chart of China's MEHD index by dimension from 2006 to 2020 was drawn (Figure 9).

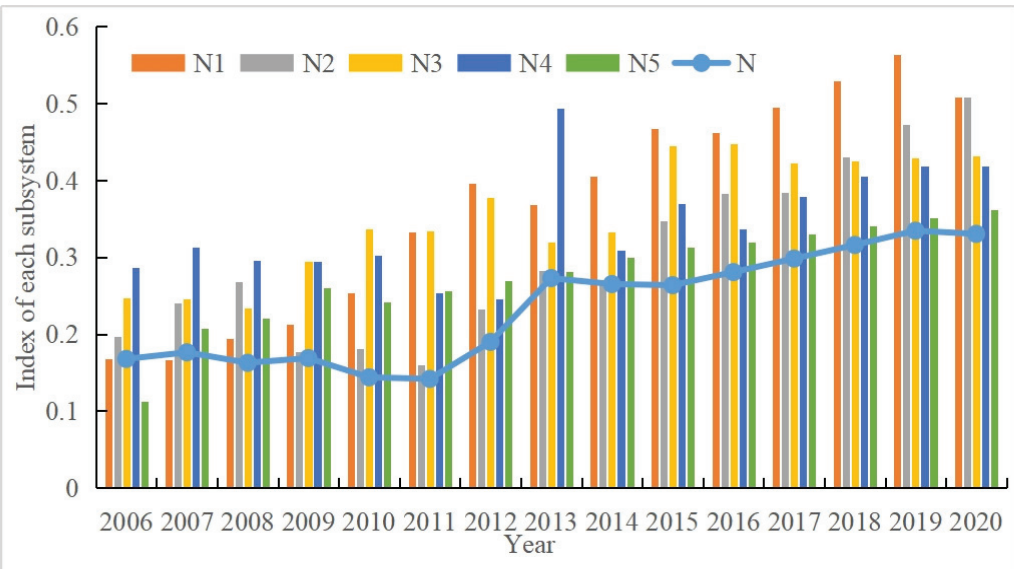


Figure 9. The trend of the high-quality development index of the marine economy.

Figure 9 shows that the overall level is relatively low, indicating that the MEHD is facing significant pressure in the conversion of fundamental benefits. Further conversion of momentum and development momentum still needs to improve. In the classification indicators of the MEHD, the marine resources and marine social welfare are relatively low, indicating that there is still room for further development in terms of opening up to the outside world, and marine welfare still needs to be further increased. The overall level of the marine ecological environment is not high and shows a strong wave dynamic trend, indicating that China's coastal areas still need to be strengthened in terms of marine ecological protection, marine resource utilisation, and pollution control. It is necessary to continuously enhance the protection of the marine ecological environment, reduce the discharge of wastewater and solid waste, improve governance efficiency, take the path of sustainable development, and achieve coexistence between humans and nature.

A box plot used to display a set of data dispersion is further used to analyse the MEHD index (Figure 8b). It can be found in Figure 8b that the distribution of H4 and H1 is relatively concentrated, while the distribution of H2 is relatively dispersed. Among the sub-dimensional indicators of the MEHD, the H4 distribution is the most uniform, and the H3 distribution is the most uneven. This information can be obtained by comparing the distance from the median to the upper quartile and the lower quartile. It shows that high-quality opening up is an important driving force for the MEHD. The MEHD requires the coordinated use of domestic and international markets, resources, and technologies to improve the quality of opening up and the development linkage. H3 is the best, and the overall situation of H2, H3, and H5 is not ideal. This information can be obtained from the median position, and the analysis data can be found. Innovation is the key to promoting the MEHD. The purpose is to produce greater social welfare, and the sharing of results is an essential requirement for the benefit of the people.

4.2. Synergistic Analysis of the Marine Carrying Capacity and Marine Economy High-Quality Development

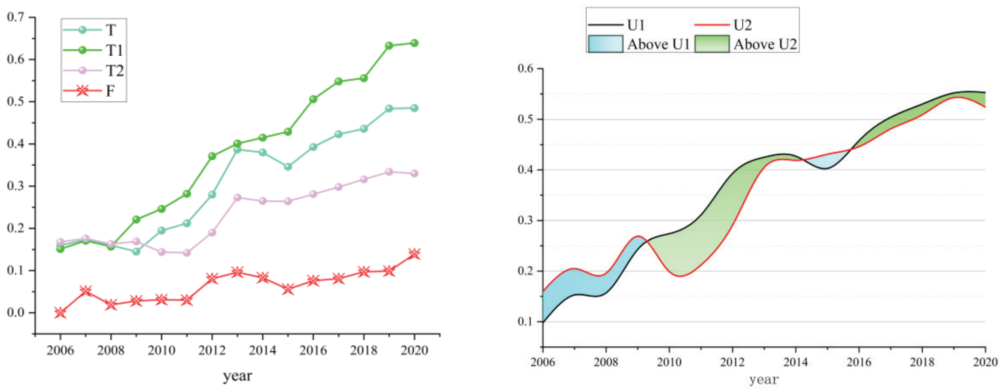
With the help of the composite system synergy model, the comprehensive development index, and orderliness, the synergy of the MCC and the MEHD system of the marine economy were obtained (Table 2).

Table 2. Composite synergy index of the marine carrying capacity and marine economy high-quality development.

Year	System Comprehensive Development Index (T)	Marine Carrying Capacity (N)	High-Quality Development Index (H)	Order Degree of Marine Carrying Capacity Subsystem (U1)	Order Degree of High-Quality Development Subsystem (U2)	Composite System Coordination Degree (F)	Standards
2006	0.160	0.151	0.168	0.098	0.160	-	-
2007	0.173	0.171	0.176	0.153	0.205	0.156	Mild non-synergy
2008	0.160	0.157	0.163	0.157	0.196	0.191	Mild non-synergy
2009	0.145	0.221	0.169	0.243	0.269	0.281	Mild synergy
2010	0.195	0.246	0.144	0.274	0.199	0.309	Mild synergy
2011	0.212	0.282	0.142	0.311	0.212	0.304	Mild synergy
2012	0.280	0.371	0.190	0.393	0.291	0.281	Mild synergy
2013	0.387	0.401	0.273	0.425	0.405	0.296	Mild synergy
2014	0.380	0.415	0.265	0.427	0.419	0.383	Mild synergy
2015	0.346	0.429	0.264	0.403	0.431	0.356	Mild synergy
2016	0.393	0.506	0.281	0.458	0.446	0.376	Mild synergy
2017	0.423	0.548	0.298	0.504	0.481	0.381	Mild synergy
2018	0.436	0.556	0.316	0.530	0.509	0.397	Mild synergy
2019	0.484	0.633	0.334	0.552	0.543	0.409	Moderate synergy
2020	0.485	0.639	0.330	0.553	0.524	0.339	Mild synergy

From the comprehensive development index of the system, the MCC and the high-quality development subsystems show a gradual upward trend, and the comprehensive index of the system also shows an upward trend. The degree of order of the MCC subsystem is between 0.098 and 0.553, with an overall upward trend in the degree of order; the degree of order of the high-quality development subsystem in the marine economy fluctuates and rises between 0.160 and 0.524; this indicates that the positive ordinal coefficients within the two subsystems play an increasingly important role in the development of the subsystems, and at the same time prompt the level of the carrying capacity in China's coastal provinces to continue to improve. The level of the MEHD is constantly improving. According to the evaluation criteria of composite system synergy in Table 2, the coordination degree of the subsystems has been at the level of mild synergy for a long time and only achieved moderate coordination in 2019, indicating that there is still a difference in the level of development of the subsystems. Among them, the synergy degree rose in 2007–2010. With the level of the MCC rising, the MEHD continues to improve; at this time, the rate of improvement of the MCC lags behind the MEHD, but the gap between the two is gradually narrowing. In 2011–2014, the synergy degree gradually rose. The orderly degree of the MEHD lags behind the MCC. In 2015, the orderly degree of the MEHD rose and widened the gap with the MCC; in 2016–2019, the orderly degree of the MCC was higher than the MEHD, but the gap between the two is gradually narrowing, and the degree of synergy is constantly rising. In 2020, due to the impact of the epidemic, key indicators, such as foreign exchange earnings from international tourism, affected the MEHD, and the degree of orderliness lagged behind the MCC, making the degree of synergy lower.

According to the composite system synergy model, the MCC index and high-quality development index can be obtained, and the specific measurement results are shown in Figure 10a. Generally speaking, the larger the MCC index, the smaller the gap between the level of the MEHD required by the actual marine development transition in the region and the ideal level of the MEHD required by the level of marine transition in each region during the same period, indicating that the MCC is leading to better marine quality synergy.



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

Figure 10. (**a**) Overall trend. (**b**) Collaborative change trend.

In Figure 10b, it can be seen that the 2006–2020 China coastal MCC (U1) driven MEHD (U2) synergy index is at a high level overall, indicating that the MCC has driven the MEHD more effectively. In 2006–2009, the MCC and MEHD index increased significantly, representing that synergy improved. In 2009–2014, the MCC and MEHD synergy index resulted in some areas of the integration index rising, but the overall trend fluctuated downward. In 2016–2020, the MCC led to significantly MEHD. The overall picture shows that China is still in the stage where the MCC leads to high quality, which is the main path of synergistic development. China has not yet entered the stage where the synergy is mainly driven by high quality in the ocean and still needs to further accelerate the process of the MCC and high-quality synergy.

4.3. Analysis of Driving Factors

4.3.1. Selection of Driver Indicators

In order to further explore the synergistic drivers, an empirical test was conducted using Chinese coastal data with the help of a geographical detector model. The geographical characteristics of China's coastal regions vary greatly, the distribution of marine resources varies greatly, and marine science development is disparate. There are significant differences in the development strategies of the marine economy, the layout of industrial structures, and the construction of marine culture in different regions, which have different impacts on the MCC and MEHD. According to the existing research results [31,32], six factors, land-based economic development, marine industry structure, marine science and technology innovation, marine economic development, marine consumption capacity, and marine openness, were finally selected to detect and then analyse the spatial divergence of their influencing factors, and the indicators were selected as detailed in Table 3.

Table 3. Geodetection results of the impact factors.

Level Measurement of Factor	2006	2010	2015	2020
(Z1) Land economic development capacity	0.338	0.459	0.564	0.688
(Z2) Marine industrial structure level	0.864	0.746	0.920	0.763
(Z3) Marine science and technology innovation	0.574	0.654	0.825	0.734
(Z4) Marine economic development capacity	0.426	0.528	0.747	0.573
(Z5) Marine consumption capacity level	0.831	0.857	0.842	0.652
(Z6) Marine opening capacity level	0.711	0.743	0.768	0.663

4.3.2. Analysis Based on Detection Factors

With the help of ArcGIS10.2 software, the six influencing factors were converted into type variables, and the size of the q-values of the six influencing factors on the synergistic driving force was measured by geographic probes (Table 3). The larger q-values indicate a greater synergistic influence.

(1) The level of marine consumption capacity (Z5), marine openness capacity (Z6), and marine industry structure level (Z2) belong to the same level, and the influence index is high. This indicates that the level of marine consumption capacity, the ability to open up to the outside world, and the level of marine industry structure have a high influence on the synergistic MCC and MEHD. China's marine economy has a lot of room for external development, which can promote cooperation in knowledge, technology, experience, and talents, which, in turn, has an impact on the conversion of the MCC; the development of new marine industries driven by scientific and technological innovation enhances the conversion of the MCC and promotes industrial upgrading to realise the conversion of kinetic energy. In 2006–2020, for all three factors, the q-values are above 0.7, and the difference in each region result in differences in the influence of the q-value of each detection factor on synergy in different periods, while the influence the q-value fluctuates and changes the trend [49].

(2) The impact of marine science and technology innovation capability (Z3) on synergy is at a medium level. The q-values of the number of invention patents owned by marine research institutions during the study period are 0.574, 0.654, 0.825, and 0.734, respectively. The increase in the number of invention patents owned by marine research institutions means that the level of marine science and technological innovation has been improved to a certain extent. The MEHD enhances the level of marine economic kinetic energy conversion. Under the strategy of innovation-driven development and science and technology for the sea, the coverage of marine science and technology innovation has gradually expanded, the fields involved have gradually become more extensive, and the momentum of the conversion of the kinetic energy of the marine economy is sufficient.

(3) The impact of land-based economic development capacity (Z1) and marine economic development capacity (Z4) on synergy is at a relatively low level. Land-based economic development is an important factor influencing the MEHD, and to a large extent guides the development direction of the marine economy, which relies on the land-based economy for its development, so the future development of the marine economy should pay more attention to the synergistic development of the sea and land. With the deepening of the opening up and regional policies, regional development is gradually taking shape, and the link between land-based economic development supporting marine economic development is further strengthened.

4.3.3. Influence Factor Interaction Detection

The interaction detector in the Geodetector software (http://www.geodetector.cn/ (accessed on 15 July 2023)) was further used to explore the extent to which any two factors, when acting together, have a synergistic impact on the MCC and marine economy quality development, and the results are shown in Table 4.

Table 4. Interaction detection results from different influencing factors.

Year	Z1∩Z2	Z1∩Z3	Z1∩Z4	Z1∩Z5	Z1∩Z6	Z2∩Z3	Z2∩Z4	Z2∩Z5	Z2∩Z6	Z3∩Z4	Z3∩Z5	Z3∩Z6	Z4∩Z5	Z4∩Z6	Z5∩Z6
2006	BE	NE	NE	BE	NE	BE	BE	BE	BE	NE	NE	NE	BE	BE	BE
2010	BE	NE	BE	BE	NE	NE	BE	BE	BE	NE	BE	BE	BE	BE	BE
2015	BE	BE	NE	BE	NE	BE	BE	BE	BE	BE	BE	BE	BE	NE	BE
2020	BE	BE	NE	BE	NE	BE	BE	NE	BE	NE	BE	NE	NE	NE	BE

Note: NE represents non-linear enhancement; BE represents bi-factor enhancement.

Based on the results of the factor interaction detection, the interaction of each factor has a multiple two-factor strengthening relationship, indicating that the spatial differentiation of synergistic development is the result of the joint influence of multiple forms of agglomeration. The explanatory kinetic energy of most of the factor interactions tends to decrease, while the explanatory kinetic energy of the interactions of land-based economic development capacity (Z1), marine industry structure level (Z2), and marine economic development capacity (Z4) increases. In terms of the time period, there are six types of interaction scenarios in 2006–2007 that have a non-linear enhancement effect, i.e., the influence of the interaction of different influencing factors is greater than the sum of the influence of two factors acting individually. The marine industry structure level (Z2), the marine consumption capacity level (Z5), and the other interaction factors have an explanatory kinetic energy greater than 0.900, and the combination of these groups of driving factors strongly explains the role of marine ecosystems. The degree of synergy influences the MCC and MEHD. In 2010, the synergy of fifteen pairs of two interaction factors in the driving factor interaction effect were stronger explanatory kinetic energies, and this stage needs to focus on the marine industry structure level's (X2) impact effect to strengthen the innovation environment, support measure construction, and focus on regional science and technology innovation capacity cultivation. In 2015–2020, the factor interactions produce a two-factor enhancement effect that is not as significant as the non-linear enhancement type. The interaction factor effects of land-based economic development capacity (Z1), marine industry structure level (Z2), and marine economic development capacity (Z4) have stronger explanatory kinetic energies and explain the synergistic spatial differences between the MCC and MEHD, indicating that the land-based economic development capacity, marine economic development capacity, and marine level of the industrial structure play a driving role in increasing the synergy between the MCC and MEHD, and the important influence of the land-based economy on high-quality development should be emphasised.

5. Discussion

The MCC and MEHD are systematic, dynamic, and regional projects and are based on the construction of a multi-dimensional evaluation index system with good operability. Combined with the geodetector model, they are used to explore the various influencing factors, provide a development direction for China's marine economy and coastal areas to enhance the MCC, and provide a scientific basis for the proposal of policy recommendations for the various regions of the marine economy and the MCC.

(1) Academics pay more attention to theoretical research on the connotation and mechanism of the MCC and are limited to quantitative analysis and measurement in specific areas, and the research on the synergistic relationship between the MCC and MEHD is still relatively weak and lacks theoretical discussion and empirical analysis. This paper is based on the connotation and mechanism of China's MCC. It explores the synergistic relationship, constructs a comprehensive evaluation index system, and analyses the main influence mechanisms of China's marine economic development and the MCC in China and coastal areas by clarifying the evolution trends of the indexes, orderliness, and synergism of China's MEHD and MCC, which will be useful for promoting the development of the marine economy and the MCC in accordance with local conditions. It can provide some ideas for promoting the development of the marine economy and the enhancement of the MCC according to local conditions.
(2) The Fourteenth Five-Year Plan period is a critical period for the reshaping of the international economic order and the MEHD. Enhancing the MCC is of great significance in promoting the sustained and stable growth of the marine economy and realising the MEHD. At present, there is an urgent need to deepen the understanding of the connotation of the MCC and the research mechanism, accurately grasp the key difficulties and focuses of the development of the marine economy and the MCC, build a number of marine strategic emerging industries that are the leaders in enhancing the MCC, transform the old kinetic energies on the basis of sorting out the deficiencies in the development of the marine economy, and achieve the goal of optimising the layout of the industry through scientific and technological marine innovations, fostering new industries, transforming the development mode, and optimising the layout of the industry.
(3) Due to the difficulty of obtaining marine data, the indicator system of the MCC index in this study still needs to be further improved, such as the institutional mechanism and the development mode, which can be further deepened in subsequent studies; this study only involves the national scale, and it is not yet possible to spatially analyse the various regions of China's coasts, so future studies can explore the characteristics of the spatial evolution of the MCC at a more microscopic level. In addition, in terms of influencing factors, factors such as human capital level and government policy support have not yet been included. More in-depth research is needed on these aspects of China's MCC and MEHD.

6. Conclusions

(1) During the study period, China's MCC index and the MEHD index both showed a growing trend, in which the marine environment carrying capacity was at a high level. There were fluctuating trends in the marine resource carrying capacity, the marine economy carrying capacity, the marine society carrying capacity, and the marine science and technology carrying capacity, which were basically the same and reflected, to a certain extent, that technology, industry, knowledge, and finance were the important factors influencing the enhancement of the MCC. The protection of marine ecology, the use of marine resources, and the management of pollution have yet to be strengthened, and it is necessary to continuously enhance the protection of marine ecology and the environment, reduce the discharge of industrial and domestic wastewater and solid waste, and improve the efficiency of the management of marine ecology and the environment.
(2) The synergistic development relationship, along with the carrying capacity of the sea area and the marine economy quality development subsystem, shows a gradual upward trend, and the system composite index also shows a slow upward trend. The MCC and MEHD of the subsystem of the order of the overall trend of the rising.

Degree of the order of the rising degree of the MEHD of the degree of order of the whole is higher than the MCC, resulting in the overall synergistic degree of the two being lower and a synergistic process of the existence of volatility.

(3) Geodetector analysis found that the spatial differentiation of the synergistic influence factors of the MCC and the MEHD are mainly the level of marine consumption capacity, the capacity to open up to the outside world, and the level of the structures of the marine industry, and the interaction of the factors is mostly a two-factor enhancement relationship.

Author Contributions: Validation, Q.D., C.L. and X.C.; formal analysis, C.L. and Z.Y.; data curation, X.C.; writing—original draft preparation, X.C. and Z.Y.; writing—review and editing, X.C.; visualisation, X.C.; supervision, C.L. and Z.Y.; project administration, Q.D.; funding acquisition, Q.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 42076222.

Data Availability Statement: Data are contained within the article. We have use the data from Ministry of Ecology and Environment of the People's republic of China, Ministry of Natural Resources of the People's Republic of China, China Oceanic Information Network (http://www.nmdis.org.cn) and National Science & Technology Infrastructure (http://mds.nmdis.org.cn).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Zhang, K.; Tian, S.-Z.; Wu, Y.; Wu, J.; Liu, N.; Wang, D. Evaluation of China's maritime power construction index and policy textual analysis. *Mar. Econ. Manag.* **2023**, *6*, 2116–2150. [CrossRef]
2. Zou, W.; Yang, Y.; Yang, M.; Zhang, X.; Lai, S.; Chen, H. Analyzing efficiency measurement and influencing factors of China's marine green economy: Based on a two-stage network DEA mode. *Front. Mar. Sci.* **2023**, *10*, 1020373. [CrossRef]
3. Barry, J.; Maxwell, D.; Jennings, S.; Walker, D.; Murray, J. Emon: An R-package to support the design of marine ecological and environmental studies, surveys and monitoring programmes. *Methods Ecol. Evol.* **2017**, *8*, 1342–1346. [CrossRef]
4. Shao, W.; Xiong, Y.; Shi, D.; Xu, X.; Yue, W.; Soomro, M.A. Time dependent analysis of lateral bearing capacity of reinforced concrete piles combined with corrosion and scour. *Ocean Eng.* **2023**, *282*, 115065. [CrossRef]
5. Casimiro, D.; Ventura, M.A.; Botelho, A.Z.; Guerreiro, J. Ecotourism in Marine Protected Areas as a tool to valuate natural capital and enhance good marine governance: A review. *Front. Mar. Sci.* **2023**, *9*, 1002677. [CrossRef]
6. Xiao, J.; Hu, D. Construction and empirical study of the evaluation index system for high-quality development of marine economy in Guangdong Province based on five new development concepts. *J. Phys. Conf. Ser. IOP Publ.* **2020**, *1629*, 012030. [CrossRef]
7. Di, Q.B.; Lv, D.H. Exploration of the relationship between the marine carrying capacity and the measurement of marine economic benefits and its response. *Ecol. Econ.* **2019**, *35*, 126–133+169.
8. Han, L.M.; Luan, X.Z. A review of research on the marine carrying capacity. *Mar. Dev. Manag.* **2008**, *25*, 32–36.
9. Kaeriyama, M.; Seo, H.; Kudo, H.; Nagata, M. Perspectives on wild and hatchery salmon interactions at sea, potential climate effects on Japanese chum salmon, and the need for sustainable salmon fishery management reform in Japan. *Environ. Biol. Fish.* **2012**, *94*, 165–177. [CrossRef]
10. Chen, X.L.; Yu, Z.; Di, Q.B. Assessing the marine ecological welfare performance of coastal regions in China and analysing its determining factors. *Ecol. Ind.* **2023**, *147*, 109942. [CrossRef]
11. Levrel, H.; Pioch, S.; Spieler, R. Compensatory mitigation in marine ecosystems: Which indicators for assessing the "no net loss" goal of ecosystem services and ecological functions? *Mar. Policy* **2012**, *36*, 1202–1210. [CrossRef]
12. Li, W.; Yue, Q.; Hu, H.; Liu, L. Current status of ecological compensation for Bohai Sea reclamation and management countermeasures. *Mar. Policy* **2023**, *155*, 105778. [CrossRef]
13. Alfosail, F.K.; Nayfeh, A.H.; Younis, M.I. A state space approach for the eigenvalue problem of marine risers. *Meccanica* **2018**, *53*, 747–757. [CrossRef]
14. Bui, L.T.; Tran, D.L.T. Assessing marine environmental carrying capacity in semi-enclosed coastal areas—Models and related databases. *Sci. Total Environ.* **2022**, *838*, 156043. [CrossRef]
15. Wang, L.; Kerr, L.A.; Record, N.R.; Bridger, E.; Tupper, B.; Mills, K.E.; Armstrong, E.M.; Pershing, A.J. Modeling marine pelagic fish species spatiotemporal distributions utilizing a maximum entropy approach. *Fish. Oceanogr.* **2018**, *27*, 571–586. [CrossRef]
16. Sadiq, R.; Husain, T.; Veitch, B.; Bose, N. Risk-based decision-making for drilling waste discharges using a fuzzy synthetic evaluation technique. *Ocean Eng.* **2004**, *31*, 1929–1953. [CrossRef]
17. Shao, W.; Sun, Q.; Xu, X.; Yue, W.; Shi, D. Durability life prediction and horizontal bearing characteristics of CFRP composite piles in marine environments. *Constr. Build. Mater.* **2023**, *367*, 130116. [CrossRef]

18. Yu, Z.K.; Kong, H.Z. Evaluation of the rationality of spatial layout of marine fishery based on the marine carrying capacity: An example from the Blue Zone of Shandong Peninsula. *Econ. Geogr.* **2014**, *34*, 112–117.
19. Shan, C.H.; Cui, S.S. Study on the development strategy selection of China's coastal tourism under the perspective of marine carrying capacity. *J. Ocean Univ. China (Soc. Sci. Ed.)* **2016**, 14–19. [CrossRef]
20. Adams, C.M.; Hernandez, E.; Cato, J.C. The economic significance of the Gulf of Mexico related to population, income, employment, minerals, fisheries and ship. *Ocean Coast. Manag.* **2004**, *47*, 565–580. [CrossRef]
21. Yu, Z.; Chen, X.L.; Di, Q.B. Integration of marine and terrestrial ecological economies in the cities of the Bohai rim, China, based on the concept of viscosity. *Water* **2023**, *15*, 749. [CrossRef]
22. Chen, X.; Di, Q.; Hou, Z.; Yu, Z. Measurement of carbon emissions from marine fisheries and system dynamics simulation analysis: China's northern marine economic zone case. *Mar. Policy* **2022**, *145*, 105279. [CrossRef]
23. Bennett, N.J.; Dearden, P. From measuring outcomes to providing inputs: Governance, management, and local development for more effective marine protected areas. *Mar. Policy* **2014**, *50*, 96–110. [CrossRef]
24. Nong, T.N.M. Performance efficiency assessment of Vietnamese ports: An application of Delphi with Kamet principles and DEA model. *Asian J. Shipp. Logist.* **2023**, *39*, 1–12. [CrossRef]
25. Wang, S.; Lu, B.; Yin, K. Financial development, productivity, and high-quality development of the marine economy. *Mar. Policy* **2021**, *130*, 104553. [CrossRef]
26. Chen, X.; Di, Q.; Jia, W.; Hou, Z. Spatial correlation network of pollution and carbon emission reductions coupled with high-quality economic development in three Chinese urban agglomerations. *Sustain. Cities Soc.* **2023**, *94*, 104552. [CrossRef]
27. Chen, X.; Sun, Z.; Di, Q.; Liang, C. Marine fishery carbon emission reduction and changing factors behind marine fishery eco-efficiency growth in China. *Ecol. Inform.* **2024**, *80*, 102478. [CrossRef]
28. Cavallo, M.; Bugeja Said, A.; Pérez Agúndez, J.A. Who is in and who is out in ocean economies development? *Sustainability* **2023**, *15*, 3253. [CrossRef]
29. Wei, X.; Hu, Q.; Shen, W.; Ma, J. Influence of the evolution of marine industry structure on the green total factor productivity of marine economy. *Water* **2021**, *13*, 1108. [CrossRef]
30. Blasiak, R.; Jouffray, J.B.; Amon, D.J.; Claudet, J.; Dunshirn, P.; Søgaard Jørgensen, P.; Pranindita, A.; Wabnitz, C.C.C.; Zhivkoplias, E.; Österblom, H. Making marine biotechnology work for people and nature. *Nat. Ecol. Evol.* **2023**, *7*, 482–485. [CrossRef]
31. Zheng, J.H.; Di, Q.B. Coupling analysis of marine economic development level and sea-shore carrying capacity in Round-the-Bohai Region. *Mar. Econ.* **2017**, *7*, 37–46.
32. Uddin, M.G.; Nash, S.; Rahman, A.; Dabrowski, T.; Olbert, A.I. Data-driven modelling for assessing trophic status in marine ecosystems using machine learning approaches. *Environ. Res.* **2023**, *242*, 117755. [CrossRef]
33. Cheng, J.; Zhang, X.; Gao, Q. Analysis of the spatio-temporal changes and driving factors of the marine economic–ecological–social coupling coordination: A case study of 11 coastal regions in China. *Ecol. Ind.* **2023**, *153*, 110392. [CrossRef]
34. Cao, Q.; Sun, C.; Zhao, L.; Cao, W.; Yan, X. Marine resource congestion in China: Identifying, measuring, and assessing its impact on sustainable development of the marine economy. *PLoS ONE* **2020**, *15*, e0227211. [CrossRef]
35. Xin, Z. Study on the evaluation of the carrying capacity of marine resources and Environment in Weihai City in China. *Popul. Res. Environ. Econ.* **2023**, *4*, 1–14.
36. Ma, R.; Ji, S.; Ma, J.; Shao, Z.; Zhu, B.; Ren, L.; Li, J.; Liu, L. Exploring resource and environmental carrying capacity and suitability for use in marine spatial planning: A case study of Wenzhou, China. *Ocean Coast. Manag.* **2022**, *226*, 106258. [CrossRef]
37. Gao, J.; An, T.; Shen, J.; Zhang, K.; Yin, Y.; Zhao, R.; He, G.; Hynes, S.; Jattak, Z.U. Development of a land-sea coordination degree index for coastal regions of China. *Ocean Coast. Manag.* **2022**, *230*, 106370. [CrossRef]
38. Oldenburg, M.; Jensen, H.J. Maritime welfare facilities—Utilization and relevance for the compensation of shipboard stress. *J. Occup. Med. Toxicol.* **2019**, *14*, 11. [CrossRef]
39. Sedghiyan, D.; Ashouri, A.; Maftouni, N.; Xiong, Q.; Rezaee, E.; Sadeghi, S. RETRACTED: Prioritization of renewable energy resources in five climate zones in Iran using AHP, hybrid AHP-TOPSIS and AHP-SAW methods. *Sustain. Energy Technol. Assess.* **2021**, *44*, 101045. [CrossRef]
40. Wang, S.; Chen, S.; Zhang, H.; Song, M. The model of early warning for China's marine ecology-economy symbiosis security. *Mar. Policy* **2021**, *128*, 104476. [CrossRef]
41. Possamai, B.; Vollrath, S.R.; Vieira, J.P.; Garcia, A.M. Synergistic climatic and anthropogenic effects on marine species turnover in estuarine waters. *Sci. Total Environ.* **2024**, *908*, 168324. [CrossRef]
42. Kosmopoulos, J.C.; Campbell, D.E.; Whitaker, R.J.; Wilbanks, E.G. Horizontal gene transfer and CRISPR targeting drive phage-bacterial host interactions and co-evolution in pink berry marine microbial aggregates. *bioRxiv* **2023**, 2. [CrossRef]
43. Hao, Y.; Sun, C.; Wei, J.; Gu, S. Study on measuring and evaluating the synergy effect of regional coal mine emergency management in China based on the composite system synergy model. *Geofluids* **2022**, *2022*, 1845795. [CrossRef]
44. Sun, Z.; Guan, H.; Zhao, A. Research on the synergistic effect of the composite system for high-quality development of the marine economy in China. *Systems* **2023**, *11*, 282. [CrossRef]
45. Wang, J.F.; Xu, C.D. Geodetector: Principles and Prospects. *Acta Geogr. Sin.* **2017**, *72*, 116–134.
46. Glein, C.R.; Shock, E.L. Sodium chloride as a geophysical probe of a subsurface ocean on Enceladus. *Geophys. Res. Lett.* **2010**, *37*. [CrossRef]

47. Zhang, C.; Wang, M. Assessing the conjugal of the marine economy-ecology-society composite system: China's Case. *Front. Mar. Sci.* **2022**, *9*, 963468. [CrossRef]
48. Lin, Y.; Yang, Y.; Li, P.; Feng, C.; Ding, J.; Zhou, J.; Jiang, Q.; Ye, G. Spatial-temporal evaluation of marine ecological civilization of Zhejiang province, China. *Mar. Policy* **2022**, *135*, 104835. [CrossRef]
49. Lv, P.; Li, X.; Zhang, H.; Liu, X.; Kong, L. Research on the spatial and temporal distribution of logistics enterprises in Xinjiang and the influencing factors based on POI data. *Sustainability* **2022**, *14*, 14845. [CrossRef]

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How Does the Government Guide Marine Resource Enterprises in China to Improve Their Business Performance? A Path Analysis Based on DEA-fsQCA

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Abstract: Policy guidance is a key driving force for improving the business performance of marine resource enterprises. This study establishes a DEA-fsQCA model, selects 42 listed marine resource enterprises as samples, analyzes the business performance improvement paths of marine resource enterprises, and proposes relevant policy recommendations for the government to guide marine resource enterprises to improve their business performance. The result shows that there are three different path models for the high business performance of marine resource enterprises based on their scale and property-right attributes: the "private green innovation" type, the "private green concentration" type, and the "state-owned incentive decentralized" type. According to the research results, this study suggests that, in the process of promoting the improvement of the business performance of marine resource enterprises, the Chinese government should promote the green development of enterprises, stimulate the technological innovation vitality of private marine resource enterprises, optimize enterprise executive incentive policies, and deepen the reform of mixed ownership in state-owned enterprises. Compared with previous studies, this article presents a fresh perspective on researching marine resource enterprises from a macro perspective and constructs a policy system for improving the business performance of different types of marine resource enterprises, providing valuable reference and guidance for the high-quality development of marine resource enterprises and the overall marine economy.

Keywords: marine resource enterprises; business performance; data envelopment analysis; qualitative comparative analysis of fuzzy sets

1. Introduction

Marine economic activities have been recognized as the key driving force for global economic growth in recent years [1]. The development level of the marine economy represents a country's overall national strength [2,3]. As the micro-carriers of the marine industry, marine resource enterprises have a net expansionary effect on the marine economy [4]. Marine resource enterprises are involved in various sea-related activities and services, such as aquaculture, fisheries, marine transportation, and marine chemical engineering [5]. Improving the input–output efficiency and business performance of marine enterprises is of great significance for promoting the development of the marine economy [6]. However, due to the limitations of market regulation and the complexity of the marine economy, relying solely on the efforts of individual companies cannot effectively promote the sustainable development of marine resource enterprises. It is necessary for the government to play a guiding role by formulating relevant policies that encourage marine resource enterprises to improve their business performance and total factor productivity [7].

The 20th National Congress of the Communist Party of China proposed the strategic requirement of "building a maritime power", which must promote the stable development of marine resource enterprises and unleash the blue vitality of our ocean. The 21st century Maritime Silk Road provides important opportunities and platforms for Chinese marine resource enterprises to strengthen their cooperation with other countries along the route [8]. The Chinese government has taken multiple proactive measures to promote the sustainable development of marine resource enterprises. However, the overall framework of China's marine policy still needs further improvement to ensure a synergistic effect between environmental protection policy, research and development policy, talent policy, and equity policy, in order to adapt to the development of different types of marine resource enterprises. Therefore, regarding the government, how to identify the key factors that affect the improvement of business performance of marine resource enterprises, clarify the specific mechanisms behind these factors, and construct a comprehensive policy system that can improve the business performance of marine resource enterprises are the core issues that this study needs to address.

Currently, numerous scholars have confirmed the positive impact of government policy guidance on improving the performance of marine resource enterprises at a macro level [9,10], but there are still some research gaps. Firstly, existing research tends to analyze the economic performance, social performance, innovation performance, and environmental performance of marine resource enterprises separately, lacking exploration of the overall business performance of these enterprises [6,11,12]. In addition, in terms of research methods, existing studies often use multiple regression and fuzzy comprehensive evaluation methods to evaluate the performance of marine resource enterprises [6,13], which cannot objectively evaluate the performance of marine resource enterprises from the perspective of input–output. Secondly, previous research has focused on the impact of a single indicator on the performance of marine resource enterprises [14], without considering the interaction between indicators in terms of performance impact and policy formulation, making the research conclusions unconvincing. Finally, there are differences in business objectives, available resources, management values, and stakeholder participation among enterprises of different sizes and property-right attributes [15–17], and government policies can have varying degrees of impact on their operations [18–20]. However, current policy research is relatively general and does not classify marine resource enterprises based on their specific characteristics, resulting in a lack of targeted and differentiated policy recommendations.

Given the research gaps discussed above, this study establishes a DEA-fsQCA model, selects 42 listed marine resource companies as samples, analyzes the business performance improvement paths of marine resource companies, and proposes relevant policy recommendations for the government to guide marine resource companies to improve their business performance. This study aims to answer two key research questions: (1) What is the business efficiency level of marine resource enterprises? (2) What are the variables and configurations that affect the improvement of the business performance of marine resource enterprises? By answering the above questions, this article can not only help the government understand the current business performance status of marine resource enterprises, but also provide reference for the government to formulate relevant policies from the perspectives of environmental protection, R&D intensity, talent incentives, and equity structure. This is highly significant for propelling the steady and high-quality development of China's marine economy and realizing the strategy of becoming a maritime power.

2. Materials and Methods

This study takes data of Chinese A-share-listed marine resource companies from 2019 to 2022 as samples. After eliminating ST (special treatment) companies, as well as those with missing data, extreme values, and abnormal values, the data of 42 companies were obtained.

ST refers to a company that has suffered losses for two consecutive years [21], and the extreme and abnormal value refers to a data point that significantly deviates from the rest of the observations in a dataset [22]. The operating data were obtained from the annual reports of listed marine resource companies. Due to the high volatility in the growth of

A-share-listed companies, in order to improve the stability of the data, we use the average of the company's four-year data to measure each variable.

2.1. Construction of DEA Model for Performance Evaluation of Marine Resource Enterprises

2.1.1. DEA Model

DEA is a mature, non-parametric (linear programming) method [23] that has been widely used in marine industry research to estimate a series of productivity indicators, such as marine green economy efficiency [24], the ecological efficiency (EF) of marine ranching [25], and the sustainable efficiency of the marine supply chain [26]. The basic principle of this method is mainly to determine the relatively effective production frontier through mathematical programming methods, while keeping the input or output of the decision-making unit (DMU) unchanged. Then, each decision unit is projected onto the production frontier of the DEA and evaluate its efficiency by comparing the degree to which the decision units deviate from the DEA frontier [27]. This method is suitable for evaluating the efficiency of decision-making units with multiple inputs and multiple outputs, providing information for decision-making subjects [28]. In this study, each sampled marine company is regarded as a production decision-making unit that transforms multiple inputs into multiple outputs. DEA's rationale is to make a hypothesis that there are n decision-making units, each DMU has K inputs $(X_i = (x_{i1}, x_{i2}, x_{i3}, \ldots, x_{in})$, $i = 1, 2, \ldots, k)$ and ω outputs $(Y_r = (y_{r1}, y_{r2}, y_{r3}, \ldots, y_{rn})$, $\gamma = 1, 2, \ldots, \omega)$, and the comprehensive business efficiency of the company is θ. The formula is as follows:

$$\begin{gathered}
\min[\theta - \varepsilon(\textstyle\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+)] \\
\textstyle\sum_{j=1}^{n} \lambda_j x_{ij} + s_i^- = \theta x_{ip},\ i = 1, 2, \ldots, k \\
S.t \textstyle\sum_{j=1}^{n} \lambda_j y_{rj} - s_r^+ = x_{rp},\ r = 1, 2, \ldots, s \\
\sum_{j=1}^{n} \lambda_j = 1,\ j = 1, 2, \ldots, n \\
\lambda_j,\ \theta,\ s_i^-,\ s_r^+ \geq 0,\ j - 1, 2, \ldots, n
\end{gathered} \tag{1}$$

where λ_j is the weight of j decision variables, s_i^- is the relaxation variable of the ith input, s_r^+ is the remaining variable of the rth output, and ε is the non-Archimedes infinitesimal quantity.

The DEA-BCC model was initially introduced by Banker et al. (1984) [29]. In this study, we chose the DEA-BCC model to measure the business efficiency of marine resource enterprises for the following reasons: Firstly, the operational activities of enterprises involve various input and output factors, encompassing multiple variables and dimensions. The DEA-BCC method has unique advantages in relative effectiveness evaluation, as it does not require dimensionless data processing before model setup. Secondly, the DEA-BCC method does not require any weight assumptions, but instead obtains the optimal weights from the actual data inputs and outputs of the decision-making unit, eliminating many subjective factors. Thirdly, considering the research objectives and the operational characteristics of the marine industry, we assume that returns to scale are not fixed, allowing for variations in the scale of operations. Lastly, the core explanatory variable of this study is the business efficiency of marine resource enterprises. Drawing on the research conducted by Li et al. [30], the comprehensive efficiency derived from DEA-BCC analysis can serve as the outcome variable for subsequent model analysis. Therefore, the DEA-BCC method is the most suitable approach for measuring the business efficiency of marine resource enterprises [31,32].

2.1.2. Input and Output Indicators of DEA Model

When selecting input–output indicators for the business performance of marine resource enterprises, this study not only considers the correlation of input–output variables and the relationship between their diversity and validity, but also considers whether the selected indicators can achieve an objective and comprehensive evaluation of performance. Therefore, two principles should be followed when selecting input–output variables. Firstly, the selected variables should meet the requirements of performance evaluation for marine resource enterprises and can reflect their performance level scientifically. Secondly, from the management level, variables that can be controlled by management should be selected.

Through reviewing the literature, we found that scholars generally set input variables from three categories: manpower, financial resources, and physical resources [33]. And the selection of output variables is based on income and profit perspectives [34]. Considering the availability of data on marine resource enterprises, we selected five indicators to comprehensively evaluate enterprise business performance (Table 1).

Table 1. Evaluation index system of marine resource enterprise business performance.

First-Level Index	Second-Level Index	Indicator Code	Literature Source	Data Source
Input index	Cost of main business	X1	Gong et al., 2018 [35]	Annual Report
	Net fixed assets	X2	Gong et al., 2018 [35]; Nguyen and Simioni, 2015 [36]	Annual Report
	Number of employees	X3	Gong et al., 2018 [35]; Cui et al., 2016 [37]	Annual Report
Output index	Revenue from main business	Y1	Du et al., 2022 [38]; Cui et al., 2016 [37]	Annual Report
	Earnings before interest and tax	Y2	Horvat et al., 2023 [39]	Annual Report

(1) Input indicators

Enterprise operation is inseparable from considerable financial and labor investments [33]. Therefore, drawing on the research of Gong et al. (2018) [35], Nguyen and Simioni (2015) [36], and Cui et al. (2016) [37], we set the input indicators as the main business cost, net fixed assets, and the total number of employees. The main business cost refers to the cost of business activities such as selling products or providing services to the outside world, which reflects the cost of input to obtain the main business income of the enterprise. Fixed assets are the basis for the production and operation of marine resource enterprises, and the use and depreciation of fixed assets can play a significant role in the business performance of marine resource enterprises. The total number of employees reflects the investment of human resources in the business process of marine resource enterprises, and the employees are the most direct contactors and achievers of enterprise value.

(2) Output indicators

Drawing on the research of Du et al. (2022) [38], Cui et al. (2016) [37], and Horvat et al. (2023) [39], we set the output indicators as the main business revenue and earnings before interest and tax. The main business revenue refers to the business income generated by the production and operation activities of the enterprise, which can effectively measure the competitiveness of the marine resource enterprises and is the support of the profit of the marine resource enterprises with development potential. Enterprise profit reflects the results of business operations and is a key factor in the high-quality development of enterprises. It plays an important role in the quality and sustainability of business operations, which is also an important indicator of enterprise performance.

2.2. Construction of QCA Model for Performance Improvement Path of Marine Resource Enterprises

2.2.1. Qualitative Comparison Method of Fuzzy Sets

This study uses the qualitative comparative analysis (QCA) method developed by Ragin (2008) [40] to explore the multivariate combination paths that affect the high business performance of marine resource enterprises. QCA is essentially a method based on set theory, which uses Boolean algebra for data minimization. This feature enables QCA to handle causal ambiguity situations. The business performance of marine resource enterprises is usually causal with multiple factors, and QCA focuses on the reasons that lead to the results [41], providing methodological guidance for exploring ways to promote high business performance within marine resource enterprises. Fuzzy set QCA (fsQCA) is a method of QCA that allows conditions to be scaled along the 0–1 interval and can handle continuous data and assign values. The business performance or influencing factor data of marine resource enterprises are basically continuous. Using fuzzy set QCA can more accurately describe the actual state of variables, making the research results more convincing.

2.2.2. Variable Design

(1) Conditional variable design

In the QCA method, the number of conditional variables should be well balanced with the number of case samples [42]. If the research sample itself is a small sample and a large number of conditional variables are selected, there may be a situation where the combination of condition variables is larger than the sample size, which is difficult to explain in research. To avoid this situation, we selected 6 conditional variables in combination with actual cases in the marine resource enterprises.

(1.1) Property-right attribute (PRA): The type of ownership is a distinct form in China [43]. SOEs are essential policy tools in China, with resource advantages and important strategic positions [44]. POEs are relatively young and market-oriented, and differ from state-owned enterprises in terms of resources, capabilities, and the degree of institutional pressure [45]. We assign a value of 1 to SOEs and 0 to POEs.

(1.2) Enterprise size: Considering the basic characteristics of enterprises, the scale of enterprises affects their innovation activities and business activities to a certain extent [46]. We measure the size of enterprises using the total assets at the end of the year from 2019 to 2022. Due to the skewed distribution of total asset data, all data are logarithmically transformed.

(1.3) R&D Intensity: R&D investment is the foundation for enterprises to create new products, processes, designs, and technologies, and plays an important role in improving the technological level and performance of the enterprises [47]. We measure the level of R&D investment of a company based on the average ratio of R&D investment to operating revenue from 2019 to 2022.

(1.4) Executive incentive (EI): Executives are in a dominant position in corporate operations. Executive incentives are a key focus of internal governance. From the perspective of domestic practice, the main incentive method for executives is salary incentives. There are two competitive hypotheses about executive motivation: the convergence of interest hypothesis and the management defense hypothesis. We measure the executive incentive level of a company based on the average of the total remuneration of the top three executives from 2019 to 2022.

(1.5) Equity concentration (EC): Ownership concentration has a statistically significant positive impact on enterprise performance [48]. The background and shareholding proportion of major shareholders, to a certain extent, determine the control power of the actual controllers over the company. We measure equity concentration based on the shareholding ratio of the largest shareholder.

(1.6) Environmental investment (ENV): Referring to the study by Lei and Wei (2023) [49], we conducted binary valuation based on whether the enterprise has invested in projects to treat exhaust gas, wastewater, and solid waste. If the enterprise conducts environmental governance and incurs related costs, the value is assigned as 1; otherwise, we assign a value of 0.

(2) Result variable design

Business performance (BP): This study is based on the perspective of input and output, using overall efficiency to measure the business performance of marine resource enterprises, and using the BCC model in the DEA method to measure the comprehensive efficiency of sample enterprises. Table 2 shows the specific variable designs.

Table 2. Selection of variables for fsQCA.

Nature of Variables	Variable Name	Metrics	Variable Code
Conditional Variables	Property-Right Attribute	1 for state-owned enterprises; 0 for private-owned enterprises	PRA
	Enterprise Size	Natural logarithm of total assets at the end of the year	SIZE
	R&D Intensity	R&D investment as a percentage of operating revenue	R&D
	Executive Incentive	Total remuneration of top three executives	EI
	Equity Concentration	Percentage of shareholding of the largest shareholder	EC
	Environmental Investment	1 for environmental costs; 0 for no environmental costs	ENV
Outcome Variable	Business Performance	DEA comprehensive efficiency	BP

2.3. Construction of DEA-fsQCA Theoretical Model

This paper explores the performance improvement path of marine resource enterprises by constructing a DEA-fsQCA theoretical model (Figure 1). There are two following stages: (1) The DEA model is applied to evaluate the business performance of the marine resource enterprises. The input indicators are set as the main business cost, the total number of employees, and the net fixed assets, and the output indicators are set as the main business revenue and earnings before interest and tax. The comprehensive efficiency of marine resource enterprises can be obtained through calculation. (2) Referring to the research of Li et al. (2022) [30], the comprehensive efficiency of the marine resource enterprises obtained from the DEA is used as the outcome variable of the fsQCA. Subsequently, the property-right attribute, R&D intensity, executive incentives, enterprise size, equity concentration, and environmental investment are taken as the conditional variables. Through the fsQCA, the paths that can improve the business performance of marine resource enterprises are obtained. The DEA-fsQCA model is an analytical framework that integrates multiple factors and perspectives to evaluate and improve the business performance of marine resource enterprises. By analyzing the different factors and mechanisms that contribute to the high business performance of marine resource enterprises, this model can provide valuable insights for policymakers seeking to improve the overall performance of marine resource enterprises.

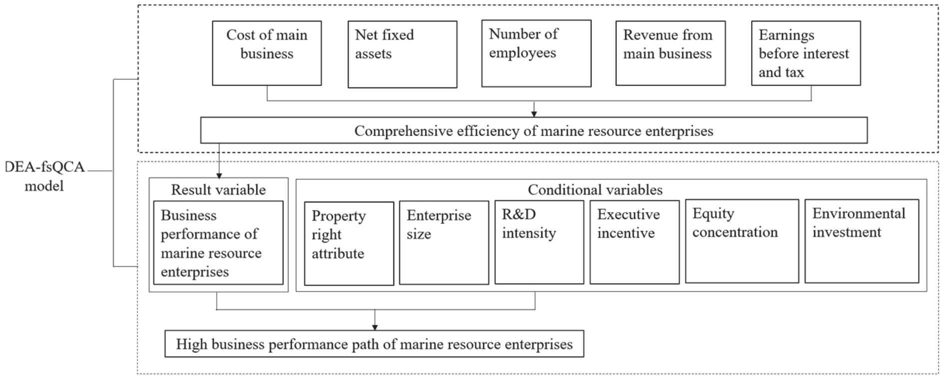

Figure 1. DEA-fsQCA model.

3. Results

3.1. DEA Results

When determining the input and output indicator data of the DEA model, we used sample data from 42 listed marine resource companies in China from 2019 to 2022. Due to the fact that these raw data have different measurement units or measure the same phenomenon at different scales, we have standardized the data to eliminate these unit measurements. Through processing, the data are standardized as values with an interval of [0, 1]. The processing formula is as follows:

$$\max Z_{jg} = a_g,\ (1 \le j \le \mathrm{n}),$$
$$\min Z_{jg} = b_g,\ (1 \le j \le \mathrm{n}),$$
$$Z'_{jg} = 0.1 + \left[\left(Z_{jg} - b_g\right) / \left(Z_{jg} - a_g\right)\right] \times 0.9,\ Z'_{jg} \in [0\ ,1].$$

Among them, Z'_{jg} is the value after data processing, $Z'_{jg} \in [0, 1]$; Z_{jg} is the original data. a_g is the maximum value of the gth indicator; b_g is the minimum value of the gth indicator. Then, the standardized data were imported into Deap 2.1 for analysis. The results of the comprehensive efficiency are shown in Table 3.

Table 3. Comprehensive evaluation results of business performance in 2019–2022.

Enterprise	Comprehensive Efficiency	Enterprise	Comprehensive Efficiency
1	0.904	22	0.906
2	0.931	23	0.944
3	0.945	24	0.895
4	0.936	25	0.962
5	1.000	26	0.853
6	0.955	27	0.959
7	0.923	28	0.906
8	1.000	29	0.893
9	0.935	30	0.937
10	0.952	31	0.984
11	1.000	32	0.940
12	0.973	33	0.925
13	0.958	34	0.925
14	0.919	35	0.981
15	0.963	36	0.860
16	0.962	37	0.923
17	0.962	38	0.928
18	1.000	39	0.984
19	0.967	40	1.000
20	0.847	41	0.991
21	0.858	42	0.946

3.2. fsQCA Results

3.2.1. Calibration

Before conducting the path analysis, the variables needed to be calibrated first. In the fuzzy set analysis, the results and conditions were expressed using fuzzy sets, while antecedent conditions can also be expressed using clear sets. As one of the main calibration methods, the direct calibration method is suitable for variables that lack theoretical and empirical basis. This method is based on statistical models and is relatively formal, making it the most commonly used calibration method in existing research [50]. For the five variables of business performance, enterprise size, R&D intensity, executive incentives, and equity concentration, their data characteristics are relatively complex, and their theoretical and empirical basis is relatively lacking. To avoid subjective bias caused by the absence of theoretical basis in the calibration process, we drew on the research of Fan et al. (2017) [51] and Qin et al. (2021) [42] and set full membership, full non-membership, and the crossover point as 95%, 5%, and 50% of the variable values, respectively. For the property-right attribute and environmental investment variables, we adopted the binary clear set calibration method, assigning state-owned enterprises a value of 1 and private enterprises a value of 0. Similarly, we assigned a value of 1 for environmental investment and 0 for no environmental investment. Table 4 summarizes the calibration information for each conditional and outcome variable in this article.

Table 4. Calibration of conditional and outcome variables.

Variables	Full Membership	Crossover Point	Full Non-Membership
BP	1.000	0.944	0.858
SIZE	25.812	23.757	21.200
R&D	5.649	1.181	0.196
EI	8,654,841.250	3,233,875.000	1,389,635.000
EC	59.194	36.536	17.428
PRA	1	/	0
ENV	1	/	0

3.2.2. Necessity and Sufficiency Analysis

Before calculating the truth table, it is necessary to first test whether a single condition constitutes a necessary condition for the high business performance of an enterprise. According to Ragin (2008) and Schneider (2013), when the consistency level is above 0.9, the variable can be considered a necessary condition for the result [52,53]. We conducted a necessity test on the calibrated variable data, and the results are shown in Table 5. The consistency of all conditional variables in this study is below 0.9, indicating that none of them are necessary conditions for the occurrence of the results. Therefore, there is no need to exclude them in the subsequent truth table calculations. In summary, all conditional variables pass the necessity tests.

Unlike necessary condition analysis, adequacy analysis aims to reveal the adequacy of different configurations formed of multiple antecedent conditions on the results. Through fsQCA, three solutions can be obtained: a complex solution, a parsimonious solution, and an intermediate solution. We consider factors that appear simultaneously in the intermediate solution and parsimonious solution as core elements, and factors that only appear in the intermediate solution but not in the parsimonious solution as edge elements. In order to effectively reveal the core and edge elements of the high business performance configuration path of marine resource enterprises, we draw on the research of Ragin (2006) [54] and sets the consistency threshold for the high business performance of marine resource enterprises to 0.8. Furthermore, due to the small sample size of the study, the sample frequency threshold is set to 1. After conducting a standardized analysis, we obtained a total of six configuration paths, as shown in Table 6.

Table 5. Necessity analysis for business performance.

Variables	Consistency	Coverage
SIZE	0.518228	0.572709
~SIZE	0.742688	0.751870
R&D	0.545266	0.577015
~R&D	0.633185	0.668141
EI	0.597089	0.708897
~EI	0.707089	0.673173
EC	0.584516	0.601903
~EC	0.676400	0.733985
PRA	0.565545	0.448214
~PRA	0.434455	0.688643
ENV	0.798973	0.506571
~ENV	0.201027	0.637286

Note: In the QCA method, "~" means that the element does not exist.

Table 6. Configurations for high business performance in fsQCA results.

Configurations for High Business Performance	Solution					
	C1a	C1b	C1c	C2a	C3a	C3b
SIZE	⊕	⊕	⊕	•	⊕	•
R&D	•	•	•	⊕	⊕	⊕
EI	⊕		⊕	•	●	●
EC	⊕	⊕		•	⊕	⊕
PRA	⊕	⊕	⊕	⊕	•	•
ENV	●	●	●	●	⊕	•
consistency	0.888268	0.841772	0.830508	1.000000	1.000000	0.879093
raw coverage	0.214952	0.239737	0.220810	0.059484	0.067595	0.157271
unique coverage	0.015772	0.040106	0.021631	0.025686	0.067595	0.157271
solution coverage	0.527691					
solution consistency	0.857875					

Notes: • denotes the presence of a condition; ⊕ denotes the absence of a condition; a space means the factor has no effect on the outcome. Moreover, large circles indicate core conditions, and small circles refer to peripheral conditions.

Overall, the consistency level values of the individual solutions and overall solutions for the six configurations of the high business performance of marine resource enterprises are higher than the acceptable minimum standard of 0.75 suggested by Ragin (2008) [40], indicating the high effectiveness of the results. Among them, the consistency of the overall solution is 0.86, indicating that 86% of the marine resource enterprises that meet the following six configuration conditions have achieved high business performance. The coverage of the overall solution is 0.53, indicating that these paths have a high degree of explanation for the high business performance of marine resource enterprises. To further test the robustness of the results, we adjusted the consistency level and reduced the sample size. The results obtained are basically consistent with existing results and meet the two criteria for the robustness of QCA results proposed by Schneider and Wagemann (2012) [55].

4. Discussion

All configurations for high business performance were divided into three types of C1, C2, and C3. Among them, the three paths that can lead to high business performance for small private enterprises take environmental investment as the core condition, with high R&D intensity as a marginal condition. This is the "private green innovation" type, led by environmental protection and coordinated with research and development. The path that leads to high business performance for large private enterprises is based on environmental protection investment as the core condition, with executive incentives and equity concentration as marginal conditions. This is the "private green concentration" type, led by environmental protection, with equity concentration and executive incentives coordinating. The path of high business performance in state-owned enterprises is based on executive incentives and non-equity concentration as the core conditions. This is the "state-owned incentive decentralized" type, dominated by executive incentives and equity concentration. The following analysis explains the logic of the different configuration types.

4.1. Private Green Innovation Type

Configuration paths C1a, C1b, and C1c indicate that increasing environmental investment is the key to achieving high business performance for small private marine resource enterprises. Small private marine resource enterprises are more cautious with using their funds. Investing funds in green production can provide financial support for green technology innovation in enterprises. At the same time, introducing environmentally friendly equipment can significantly reduce the cost of raw materials, thereby bringing higher profits to enterprises [56]. Moreover, according to the resource-based perspective, environmental protection activities are beneficial for enhancing the "heterogeneous" resource of enterprises, which can help marine resource enterprises improve their resource utilization efficiency, win more market and social resources, establish a good social image, and achieve sustainable development [57]. Therefore, executives will be more supportive of enterprises' green strategic investments at present, which can help them achieve higher income in the future.

In addition, for small private marine resource enterprises, increasing their R&D intensity can help them to achieve high business performance. According to the theory of endogenous growth, increasing R&D investment is beneficial for providing support for technological innovation and improving the innovation performance of enterprises [58]. The mechanism of R&D investment on the growth of the business performance of small private marine resource enterprises can be explained based on two aspects: Firstly, R&D investment is conducive to the introduction of new products and processes by marine resource enterprises, ensuring the vitality of their development. Secondly, increasing R&D investment by enterprises is beneficial for attracting more innovative talents, and thus helping marine resource enterprises achieve significant progress in their technological performance. For private enterprises, the core business goal is to maximize profits and achieve long-term development. Executives and shareholders are not eager to immediately receive cash returns or stock dividends from the enterprise, but instead choose to invest more funds into R&D activities to seek future development. When a company's R&D activities succeed, this can positively promote the improvement of the company's business performance. Meanwhile, due to the uncertainty of innovation activities, limiting the excessive concentration of equity is also beneficial for avoiding the inhibitory behavior of major shareholders on R&D investment.

4.2. Private Green Concentration Type

Configuration C2 shows that for large private marine resource enterprises, developing green production is a key measure to achieve high business performance when they form a certain scale and have relatively concentrated equity. Large marine resource enterprises usually have more resources and technology, which can effectively carry out environmental governance and pollution control, thereby reducing the negative impact on the marine environment. Meanwhile, it is worth noting that equity concentration is an effective management mechanism. In large private marine resource enterprises, due to their large scale and high business complexity, a more specialized management team is needed for operation and management. In this case, an increase in equity concentration may provide more funding and resource support for the enterprise, thereby helping to improve its business performance. In addition, large private marine resource enterprises often face more market risks and competitive pressures. The increase in equity concentration can promote the efficiency and flexibility of enterprise decision making, enabling enterprises to better respond to market changes and challenges and thus achieve long-term stable development. Furthermore, improving equity concentration can also enable shareholders to effectively supervise the senior management of the company, thereby enabling them to work diligently to improve the company's business performance.

According to the principal–agent theory, the ultimate goal of business owners and actual managers is not the same. Business owners aim to maximize residual value, while managers always set their goal to obtain the highest reward. Therefore, when equity is relatively concentrated, in order to align the goals of executives and company owners, corporate shareholders need to link the personal benefits of executives with company business performance and incentivize them to restrain their behavior and serve for the benefit of business owners through higher salaries.

4.3. State-Owned Incentive Decentralized Type

Configuration C3a and C3b indicate that for state-owned enterprises, improving the compensation level of company executives and reducing equity concentration is beneficial for improving business performance. Relatively speaking, large state-owned marine resource enterprises have stronger financial strength. Therefore, large state-owned marine resource enterprises should actively assume environmental responsibility, promote green production, and promote the sustainable development of enterprises.

According to the theory of incentive expectations, the internal incentive mechanism of a company determines the level of work effort of executives [59]. Compensation is a good stimulus factor that can increase executives' recognition of the company, motivate them to work harder, and bring more positive returns to the company. According to the resource-based view (RBV), higher levels of compensation will motivate company executives to use resources related to operations, investment, and financing activities more effectively to achieve better economic results, thereby improving the company's business performance. On the other hand, as the personal benefits of executives are directly related to company performance, compensation incentives can also affect their risk preference. Higher compensation will inhibit executives from making high-risk financial decisions and reduce the probability of the company falling into financial difficulties [60].

For state-owned marine resource enterprises, appropriately reducing equity concentration has a positive impact on enterprise business performance. State-owned marine resource enterprises are often controlled by the government or state institutions, and their equity concentration is usually high, which may lead to some problems, such as a lack of effective supervision mechanisms and low market operating efficiency. Therefore, reducing the concentration of equity in state-owned marine resource enterprises can not only ensure effective regulation through equity diversification, but also introduce other strategic investors to improve the level of enterprise management. This will encourage enterprises to focus more on market orientation and customer needs, thereby enhancing their market competitiveness.

5. Conclusions

5.1. Main Findings

Based on the DEA-fsQCA model, we evaluated the business performance of marine resource enterprises and analyzed the path to achieve high business performance by taking their property-right attribute, enterprise size, R&D intensity, executive incentive, equity concentration, and environmental investment as conditional variables. Through an analysis of 42 listed marine resource enterprises, we found the following:

(1) The improvement of the business performance of marine resource enterprises is the result of the synergistic effect of multiple factors. The research results show that there are six different combinations of mechanisms that can achieve high business performance for marine resource enterprises, indicating that any single factor cannot

constitute a sufficient or necessary condition for high business performance. High business performance is the result of the synergistic effect of multiple factors. Marine resource enterprises must choose a suitable combination of conditional factors to improve their business performance.

(2) Enterprises with different characteristics have different paths to achieve high business performance. In the exploration of the path of high performance for private marine resource enterprises, there are two paths, the "green & innovation" type and the "green & concentration" type, that can achieve high performance in business operation. In the exploration of the path to high performance for state-owned marine resource enterprises, only the path of the "incentive & dispersion" type can achieve high performance in business development. The ways to improve the business performance of marine resource enterprises are diversified, and enterprises should formulate corresponding strategies based on their property-right attribute and own asset size.

5.2. Theoretical Implications

Specifically, this article makes two contributions to the existing literature. Firstly, this research has contributed to the literature on business performance by studying how the Chinese government guides marine resource enterprises to improve their business performance. Previous studies mainly focused on the management performance, ecological innovation performance, and economic and social performance of marine enterprises [6,11,61], while few studies have paid attention to the overall business performance of these enterprises. We use the DEA method to measure the business performance of marine resource enterprises from the perspectives of input and output, using the main business costs, net fixed assets, and number of employees as input variables and the main business revenue and earnings before interest and tax as output variables. This not only expands the application scope of the DEA model, but also provides important theoretical references for the research on enterprise business performance.

Secondly, this study provides new insight into the influence mechanism of business performance from the perspective of configuration. Although the existing literature acknowledges the mechanisms that affect business performance, most studies have focused on the role of a single identified factor, neglecting the key and complex mechanisms that drive the improvement of business performance [61,62]. As suggested by Rihoux and Ragin (2009) [63], the "configurational perspective" effectively comprehends complex causality. By combining the DEA and fsQCA approaches, this study adds to existing knowledge on business performance, enterprise size, property-right attributes, R&D intensity, executive incentives, equity concentration, and environmental investment from a methodological perspective, emphasizing how different antecedent configurations affect business performance. Specifically, we have contributed to the research of marine resource enterprises by identifying six configuration paths that lead to high business performance. These findings are a novel attempt to explain the business performance improvement paths from an integrated perspective using configurational analysis [64].

5.3. Research Insights

(1) When formulating environmental policies, relevant departments should promote marine resource enterprises to fulfill their environmental responsibilities and support their green and low-carbon development. We found that increasing environmental investment is the key to promoting the improvement of business performance within private marine resource enterprises. It is generally believed that state-owned enterprises play a leading role in the green development of society and bear the primary responsibility for protecting the environment. However, as the main body of the market economy, private enterprises are also important participants in environmental protection. The "Green Development Report of Chinese Private Enterprises (2022)" systematically demonstrates that Chinese private enterprises have always maintained a high awareness of green and low-carbon development. They are an important force

in promoting the green development of the Chinese economy, and their environmental investment has achieved positive results. Under the ecological protection concept that "Lucid waters and lush mountains are invaluable assets" in China, relevant departments should continue to strengthen the top-level design of environmental protection policies for marine resource enterprises, improve relevant laws and regulations, and stimulate the green development awareness of marine resource enterprises from the source.

(2) When formulating research and development policies, relevant departments should fully stimulate the technological innovation vitality of private marine resource enterprises and promote the high-quality development of the private economy. Stable R&D investment is the key to the innovative development of marine resource enterprises. Enterprises also need to increase their R&D investment to achieve green production transformation. In order to promote the innovative development of private marine resource enterprises, the government should accelerate the formulation of supporting service policies to promote innovation in local marine resource enterprises, and provide corresponding support to marine resource enterprises from tax incentives, government subsidies, and other aspects. At the same time, the government should also promote the implementation of inclusive innovation policies such as procurement policies and technology finance policies, and guide marine resource enterprises to truly become the main organizations for the transformation of scientific research achievements. Furthermore, the government should also guide private marine resource enterprises to strengthen the cultivation of innovative talents and improve the welfare subsidies for marine high-tech talents.

(3) When formulating talent incentive policies, relevant departments should deepen the reform of the incentive system for executives in state-owned marine resource enterprises. At present, the executive equity incentive system of state-owned enterprises has not been deeply implemented, and the executive compensation incentive based on the annual salary system is still the main incentive method of state-owned enterprise executives. In order to further optimize the executive compensation incentive mechanism, relevant departments should classify state-owned marine resource enterprises according to their functional positioning, and implement differentiated executive compensation incentives according to their categories and marketization degrees. For example, for state-owned marine resource enterprises with a high degree of marketization, executive incentives should be linked to market economic benefits, and the government's salary restrictions should be gradually lifted. For public-welfare state-owned marine resource enterprises with a low degree of marketization, the government should continue to implement salary restrictions for executives and implement relatively tight regulations. In addition, the executive equity incentive of state-owned marine resource enterprises in China is relatively weak at present. The government should gradually break the current single-executive-compensation incentive mechanism and promote the reform of the executive equity incentive system of state-owned enterprises.

(4) When formulating equity policies, relevant departments should further optimize the equity structure of marine resource enterprises and enhance their vitality and competitiveness. Path C3 reveals that dispersing the equity of state-owned marine resource enterprises is beneficial for improving their business performance, which implies that equity can be dispersed to more shareholders, and the control of state-owned shareholders over company decisions can be reduced. In recent years, China has actively promoted the mixed ownership reform of state-owned enterprises. As an important means to reduce the concentration of equity in state-owned enterprises, the mixed ownership reform of state-owned enterprises improves their efficiency by introducing private capital and foreign capital and increasing the number of shareholders. Meanwhile, through the mixed ownership reform of state-owned enterprises, state-owned marine resource enterprises can also fully utilize the advantages of the

private economy in terms of funds, technology, management, and improving their profitability. Therefore, in order to improve the business performance of state-owned marine resource enterprises, the government should increase its support for the mixed reform of state-owned enterprises, guide social capital to enter state-owned marine resource enterprises through policy incentives such as financial support and tax benefits, and adjust the proportion of state-owned equity.

Author Contributions: Conceptualization, J.W. and J.C.; methodology, J.W.; software, J.C.; validation, J.W. and J.C.; formal analysis, J.W.; investigation, J.C.; resources, J.C.; data curation, J.C.; writing—original draft preparation, J.C.; writing—review and editing, J.W.; visualization, J.W.; supervision, J.W.; project administration, J.W.; funding acquisition, J.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Social Science Foundation of China, grant number 23BJY260.

Data Availability Statement: Data are contained within the article. Further requests can made to the corresponding author.

Acknowledgments: The authors would like to thank the College of Management for its support during this project.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Ding, L.; Zhao, Z.; Wang, L. Exploring the role of technical and financial support in upgrading the marine industrial structure in the Bohai Rim region: Evidence from coastal cities. *Ocean Coast. Manag.* **2023**, *243*, 106659. [CrossRef]
2. Clifton, J.; Osman, E.O.; Suggett, D.J.; Smith, D.J. Resolving conservation and development tensions in a small island state: A governance analysis of Curieuse Marine National Park, Seychelles. *Mar. Policy* **2021**, *127*, 103617. [CrossRef]
3. Wu, D. Study on the Construction of New Port Area under the Background of National Marine Economic Development Demonstration Zone. *J. Coast. Res.* **2019**, *98*, 159–162. [CrossRef]
4. Carpitella, S.; Mzougui, I.; Benitez, J.; Carpitella, F.; Certa, A.; Izquierdo, J.; Cascia, M.L. A risk evaluation framework for the best maintenance strategy: The case of a marine salt manufacture firm. *Reliab. Eng. Syst. Saf.* **2021**, *205*, 107265. [CrossRef] [PubMed]
5. Liu, B.; Zhang, S.; Xu, M.; Wang, J.; Wang, Z. Spatial differences in the marine industry based on marine-related enterprises: A case study of Jiangsu Province, China. *Reg. Stud. Mar. Sci.* **2023**, *62*, 102954. [CrossRef]
6. Xu, Z.; Ren, Y.; Zhao, P.; Zhang, Z. The Factors Affecting the Performance of Marine Environmental Protection Enterprises. *J. Coast. Res.* **2019**, *94*, 40–49. [CrossRef]
7. Ma, W.; Li, Y.; Ding, L. Does marine financial policy affect total factor productivity of marine enterprises? An empirical evidence based on Chinese first guidance on strengthening finance for marine economy. *Mar. Pollut. Bull.* **2023**, *195*, 115493. [CrossRef]
8. Ma, Y.; Zhang, H. The Structural Features and Centrality Optimization of a Firm Interlocking Network of the Nodal Cities on the South Route of the 21st-Century Maritime Silk Road: The Case of Fujian Province. *Sustainability* **2022**, *14*, 15389. [CrossRef]
9. Li, X.; Wang, M.; Chi, J.; Yang, X. Policy Effects and Suggestions on Green Technology Innovation of Marine Enterprises in China. *J. Coast. Res.* **2020**, *110*, 76–79. [CrossRef]
10. Li, J.; Jiang, S. How can governance strategies be developed for marine ecological environment pollution caused by sea-using enterprises?—A study based on evolutionary game theory. *Ocean Coast. Manag.* **2023**, *232*, 106447. [CrossRef]
11. Tao, L.; Li, R.; Tian, M. Effects of Government Subsidies on the Economic and Social Performance of Marine Enterprises-Taking Chinese Listed Enterprises as Examples. *J. Coast. Res.* **2020**, *110*, 71–75. [CrossRef]
12. Wan, X.; Li, Q.; Zhang, G.; Zhang, K.; Wang, Z. Sustainable collaborative innovation capability enhancement paths of marine ranching: Supernetwork analysis perspective. *Ocean Coast. Manag.* **2023**, *231*, 106387. [CrossRef]
13. Liu, L.; Wen, X.; Ba, J.; Wu, S. Comprehensive Evaluation of Environmental Performance Based on Offshore Oil Drilling. *J. Coast. Res.* **2020**, *112*, 19–21. [CrossRef]
14. Zhou, Y.; Yuen, K.F.; Tan, B. The effect of maritime knowledge clusters on maritime firms' performance: An organizational learning perspective. *Mar. Policy* **2021**, *128*, 104472. [CrossRef]
15. Gupta, A.; Kumar, S. Comparing the performance of public and private enterprises: Case for a reappraisal-evidence from India. *Int. J. Public Sect. Manag.* **2021**, *34*, 87–100. [CrossRef]
16. Cantele, S.; Vernizzi, S.; Campedelli, B. Untangling the Origins of Sustainable Commitment: New Insights on the Small vs. Large Firms' Debate. *Sustainability* **2020**, *12*, 671. [CrossRef]
17. Coppa, M.; Sriramesh, K. Corporate social responsibility among SMEs in Italy. *Public. Relat. Rev.* **2013**, *39*, 30–39. [CrossRef]
18. Liang, J.; Ma, L. Ownership, Affiliation, and Organizational Performance: Evidence from China's Results-Oriented Energy Policy. *Int. Public Manag. J.* **2020**, *23*, 57–83. [CrossRef]

19. Elouaourti, Z.; Ezzahid, E. Financial services and firm performance, are there any differences by size? Worldwide evidence using firm-level data. *J. Econ. Stud.* **2023**, *50*, 858–880. [CrossRef]
20. Kumar, A.S.; Babu, R.V.; Paranitharan, K.P. S-SMILE model: A leveraging mechanism to polarise performance in small and medium enterprises—An empirical study. *Int. J. Value Chain Manag.* **2021**, *12*, 309–335. [CrossRef]
21. Luo, Y.; Xiong, G.; Mardani, A. Environmental information disclosure and corporate innovation: The "Inverted U-shaped" regulating effect of media attention. *J. Bus. Res.* **2022**, *146*, 453–463. [CrossRef]
22. Chang, A.; Wang, M.; Allen, G.I. Sparse regression for extreme values. *Electron. J. Statist.* **2021**, *15*, 5995–6035. [CrossRef]
23. Färe, R.; Grosskopf, S. Theory and Application of Directional Distance Functions. *J. Prod. Anal.* **2000**, *13*, 93–103. [CrossRef]
24. Zou, W.; Yang, Y.; Yang, M. Analyzing efficiency measurement and influencing factors of China's marine green economy: Based on a two-stage network DEA model. *Front. Mar. Sci.* **2021**, *10*, 1020373. [CrossRef]
25. Zhang, X.; Sun, D.; Zhang, X.; Yang, H. Regional ecological efficiency and future sustainable development of marine ranch in China: An empirical research using DEA and system dynamics. *Aquaculture* **2021**, *534*, 736339. [CrossRef]
26. Chi, E.; Jiang, B.; Peng, L.; Zhong, Y. Uncertain Network DEA Models with Imprecise Data for Sustainable Efficiency Evaluation of Decentralized Marine Supply Chain. *Energies* **2022**, *15*, 5313. [CrossRef]
27. Su, L.; Jia, J. New-type urbanization efficiency measurement in Shanghai under the background of industry city integration. *Environ. Sci. Pollut. Res.* **2023**, *30*, 80224–80233. [CrossRef] [PubMed]
28. Zhu, J. DEA under big data: Data enabled analytics and network data envelopment analysis. *Ann. Oper. Res.* **2022**, *309*, 761–783. [CrossRef]
29. Banker, R.D.; Charnes, A.; Cooper, W. Some models for estimating technical and scale inefficiency in Data envelopment analysis. *Manag. Sci.* **1984**, *30*, 1078–1092. [CrossRef]
30. Li, T.; Wen, J.; Zeng, D.; Liu, K. Has enterprise digital transformation improved the efficiency of enterprise technological innovation? A case study on Chinese listed companies. *Math. Biosci. Eng.* **2022**, *19*, 12632–12654. [CrossRef] [PubMed]
31. Neykov, N.; Krišťáková, S.; Hajdúchová, I.; Sedliačiková, M.; Antov, P.; Giertliová, B. Economic efficiency of forest enterprises-empirical study based on data envelopment analysis. *Forests* **2021**, *12*, 462. [CrossRef]
32. Cook, W.D.; Tone, K.; Zhu, J. Data envelopment analysis: Prior to choosing a model. *Omega* **2014**, *44*, 1–4. [CrossRef]
33. Zhang, Y.; Wang, S. Influence of marine industrial agglomeration and environmental regulation on marine innovation efficiency—From an innovation value chain perspective. *Mar. Policy* **2021**, *134*, 104807. [CrossRef]
34. Wang, C.N.; Luu, Q.C.; Nguyen, T.K.L.; Day, J.D. Assessing Bank Performance Using Dynamic SBM Model. *Mathematics* **2019**, *7*, 73. [CrossRef]
35. Gong, Y.; Zhu, J.; Chen, Y.; Cook, W.D. DEA as a tool for auditing: Application to Chinese manufacturing industry with parallel network structures. *Ann. Oper. Res.* **2018**, *263*, 247–269. [CrossRef]
36. Nguyen, P.A.; Simioni, M. Productivity and efficiency of Vietnamese banking system: New evidence using Färe-Primont index analysis. *Appl. Econ.* **2015**, *47*, 4395–4407. [CrossRef]
37. Cui, Q.; Li, Y.; Yu, C.; Wei, Y. Evaluating energy efficiency for airlines: An application of Virtual Frontier Dynamic Slacks Based Measure. *Energy* **2016**, *113*, 1231–1240. [CrossRef]
38. Du, X.; Wan, B.; Long, W.; Xue, H. Evaluation of Manufacturing Innovation Performance in Wuhan City Circle Based on DEA-BCC Model and DEA-Malmquist Index Method. *Discrete Dyn. Nat. Soc.* **2022**, *2022*, 2989706. [CrossRef]
39. Horvat, A.M.; Milenković, N.; Dudić, B.; Kalaš, B.; Radovanov, B.; Mittelman, A. Evaluating Bank Efficiency in the West Balkan Countries Using Data Envelopment Analysis. *Mathematics* **2023**, *11*, 15. [CrossRef]
40. Ragin, C.C. *Redesigning Social Inquiry: Fuzzy Sets and Beyond*; University of Chicago Press: Chicago, IL, USA, 2008.
41. Goertz, G.; Mahoney, J. *A Table of Two Cultures: Qualitative and Quantitative Research in the Social Science*; Princeton University Press: Princeton, NJ, USA, 2012.
42. Qin, M.; Tao, Q.; Du, Y. Policy implementation and project performance: A qualitative comparative analysis based on 29 National Marine ranchings in China. *Mar. Policy* **2021**, *129*, 104527. [CrossRef]
43. Hu, C.; Li, J.; Yun, K.H. Re-examining foreign subsidiary survival in a transition economy: Impact of market identity overlap and conflict. *J. World Bus.* **2023**, *58*, 101432. [CrossRef]
44. Ghorbani, M.; Xie, Z.; Jin, J.; Wang, F. Chinese Firms' Acquisition of Innovation Capability from Overseas: Approaches by State-versus Private-Owned Firms. *Manag. Organ. Rev.* **2023**, *19*, 233–255. [CrossRef]
45. Xu, D.; Lu, J.W.; Gu, Q. Organizational forms and multi-population dynamics: Economic transition in China. *Adm. Sci. Q.* **2014**, *59*, 517–547. [CrossRef]
46. Xiao, Z.; Hao, B.; Li, Y. Strategic Emerging Industry Policy on Enterprise Innovation Performance: The Intermediary Role Based on Cost of Debt Financing and Regulatory Role of Business Environment. *J. Syst. Manag.* **2023**, *32*, 355–366.
47. Hao, J.; Li, C.; Yuan, R.; Ahmed, M.; Khan, M.A.; Oláh, J. The Influence of the Knowledge-Based Network Structure Hole on Enterprise Innovation Performance: The Threshold Effect of R&D Investment Intensity. *Sustainability* **2020**, *12*, 6155.
48. Hu, J.; Hu, L.; Hu, M.; Dnes, A. Entrepreneurial human capital, equity concentration and firm performance: Evidence from companies listed on China's Growth Enterprise Market. *MDE Manag. Decis. Econ.* **2023**, *44*, 187–196. [CrossRef]
49. Lei, Z.; Wei, J. Assessing the eco-efficiency of industrial parks recycling transformation: Evidence from data envelopment analysis (DEA) and fuzzy set qualitative comparative analysis (fsQCA). *Front. Environ. Sci.* **2023**, *11*, 1170688. [CrossRef]

50. Zhang, M.; Du, Y.Z. Qualitative comparative analysis (QCA) in management and organizational research: Position, tactics, and directions. *Chin. J. Manag.* **2019**, *16*, 1312–1323.
51. Fan, D.; Li, Y.; Chen, L. Configuring innovative societies: The crossvergent role of cultural and institutional varieties. *Technovation* **2017**, *66–67*, 43–67. [CrossRef]
52. Ragin, C.C. STRAND SI. Using qualitative comparative analysis to study causal order. Comment on Caren and Panofsky (2005). *Sociol. Methods Res.* **2008**, *36*, 431–441. [CrossRef]
53. Schneider, C.Q.; Wagemann, C. Set-theoretic methods for the social sciences: A guide to qualitative comparative analysis. *Int. J. Sci. Res. Manag.* **2013**, *16*, 165–166.
54. Ragin, C.C. Set Relations in Social Research: Evaluating Their Consistency and Coverage. *Polit. Anal.* **2006**, *14*, 291–310. [CrossRef]
55. Schneider, C.Q.; Wagemann, C. *Set-Theoretic Methods for the Social Sciences*; Cambridge University Press: Cambridge, UK, 2012.
56. Hsieh, C.L.; Tsai, W.H.; Chang, Y.C. Green Activity-Based Costing Production Decision Model for Recycled Paper. *Energies* **2020**, *13*, 2413. [CrossRef]
57. Wamba, L.D. The determinants of environmental performance and its effect on the financial performance of European-listed companies. *J. Gen. Manag.* **2022**, *47*, 97–110. [CrossRef]
58. Sun, Z.; Wang, X.; Liang, C.; Cao, F.; Wang, L. The impact of heterogeneous environmental regulation on innovation of high-tech enterprises in China: Mediating and interaction effect. *Environ. Sci. Pollut. Res.* **2021**, *28*, 8323–8336. [CrossRef] [PubMed]
59. Murphy, K.J. Incentives, Learning, and Compensation: A Theoretical and Empirical Investigation of Managerial Labor Contracts. RAND. *J. Econ.* **1986**, *17*, 59–76. [CrossRef]
60. Chatterjee, B.; Jia, J.; Nguyen, M.; Taylor, G.; Duong, L. CEO remuneration, financial distress and firm life cycle. *Pac. Basin Financ. J.* **2023**, *80*, 102050. [CrossRef]
61. Li, X.; Cai, Q. Analysis on Green Dynamic Ability of Creating Resources and Eco-Innovation Performance of Marine Industrial Clusters. *J. Coast. Res.* **2019**, *94* (Suppl. S1), 6–10. [CrossRef]
62. Madhavan, M.; Sharafuddin, M.A.; Chaichana, T. Impact of Business Model Innovation on Sustainable Performance of Processed Marine Food Product SMEs in Thailand—A PLS-SEM Approach. *Sustainability* **2022**, *14*, 9673. [CrossRef]
63. Rihoux, B.; Ragin, C. *Configurational Comparative Methods: Qualitative Comparative Analysis (QCA) and Related Techniques*; SAGE Publications, Inc.: Thousand Oaks, CA, USA, 2009.
64. Li, Z.; Li, Y.; Zhang, W. Configuration analysis of influencing factors of operating efficiency based on fsQCA: Evidence from China's property insurance industry. *Chin. Manag. Stud.* **2021**, *15*, 1085–1103. [CrossRef]

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A Cloud Model-Based CRITIC-EDAS Decision-Making Approach with Linguistic Information for Marine Ranching Site Selection

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Abstract: Modern marine ranching construction has drawn growing attention of relevant planning authorities and enterprises with the potential value of oceans becoming apparent. To satisfy the demand for a successful marine ranching construction, site selection is considered as the first and fundamental procedure. This work aims to help planning authorities find the optimal marine ranching site by introducing a methodological evaluation framework for solving this critical problem. Firstly, the advanced CRiteria Importance Through Inter-criteria Correlation (CRITIC) method is extended by using a cloud model to determine the relative importance of attributes in marine ranching site selection problems. Secondly, the Evaluation based on Distance from Average Solution (EDAS) method is developed by integration with the cloud model to obtain the ranks of alternative sites for marine ranching construction. The proposed cloud model-based CRITIC-EDAS method considers the fuzziness and randomness of the linguistic terms given by experts simultaneously to ensure the scientificity and rationality of decision making. Finally, a real-world marine ranching site selection problem is solved by using the proposed model, where the efficiency and reliability of the proposed model are verified according to the comparison with other traditional multi-attribute decision-making methods.

Keywords: marine ranching site selection; cloud model; CRITIC method; EDAS method

1. Introduction

With the potential value of oceans becoming apparent, coastal countries attach great importance to the conservation, protection and sustainable utilization of marine resources [1]. As an effective measure for fishery resource enhancement and ecological restoration, marine ranching has received increasing attention all over the world [2–4]. Marine ranching has experienced two versions: the version 1.0 was characterized by the placement of artificial reefs and the proliferation and release of fishery resources based on farming, ranching and engineering techniques; the version 2.0 was characterized by ecologicalization and informatization with the purpose of protecting the environment and enhancing fishery resources. Nowadays, with the development of digitalization and systematization, China pays great effort to establish modern marine ranching, a novel pattern which can be considered as marine ranching version 3.0. In November 2021, China officially released the first national standard for marine ranching building, the 'Technical Guidelines for Marine Ranching construction', indicating that marine ranching 3.0, a type of whole-area aquatic pasture covering both fresh water and sea water, is coming.

On the premise of ensuring the safety of the environment and fishery resources, modern marine ranching promotes coordinated development of marine ranching, energy exploitation, tourism, facility-based breeding and other industries. It has been suggested to implement a development pattern conducive to the entire industrial chain covering site selection, layout, habitat restoration, resource conservation, safety assurance and integrated development, thus boosting global aquatic ecological ranching [5]. It is clear that in the industrial chain of modern marine ranching construction, site selection is the first and fundamental step, which is directly related to the success of the project [6]. A poorly executed site selection for marine ranching may affect ecosystem functions and services with negative environmental, social and economic consequences [7]. Therefore, the main aim of this research study is to evaluate alternative sites for marine ranching and select an optimal site by using a multi-attribute decision-making technique.

1.1. Aims of This Study

This study intends to address the modern marine ranching site selection problem from the MADM perspective. Marine ranching 3.0 is a new fussiness pattern, which integrates environmental protection, resource conservation and sustainable production of fishery resources to supply high-quality protein and ensure the security of the offshore ecosystem. Although a few research studies are devoted to the site selection problem of artificial reefs, they are not applicable for modern marine ranching, so both a practical and a methodological evaluation framework for solving modern marine ranching site selecting problems is still missing. Therefore, an index system for marine ranching evaluation with five primary indices and sixteen secondary indices has been identified, which aims to provide a practical framework for relevant planning authorities to be used when evaluating feasible sites for modern marine ranching. Also, this study aims to introduce an advanced multi-attribute decision-making approach for determining the optimal marine ranching site. The approach is based on the integration of the CRiteria Importance Through Inter-criteria Correlation (CRITIC) method and the Evaluation based on Distance from Average Solution (EDAS) method with linguistic information by introducing a cloud model theory. The proposed cloud model-based CRITIC-EDAS approach can also be used to solve other complex multi-attribute decision-making problems in reality. In addition, this research proposes real-world guidelines for selecting the optimal site for modern marine ranching by using a case study of the city of Yantai in China. In the real case, Yantai intends to construct a novel marine ranching complex with the functions of marine culture, sea sightseeing, leisure fishing, ocean science, and supplying seafood as well as sea accommodation. The rendering for the main building of the marine ranching complex is depicted in Figure 1, the Chinese character identification of the image is the project name. and six marine areas have been selected as alternative sites for the marine ranching construction as shown in Figure 2.

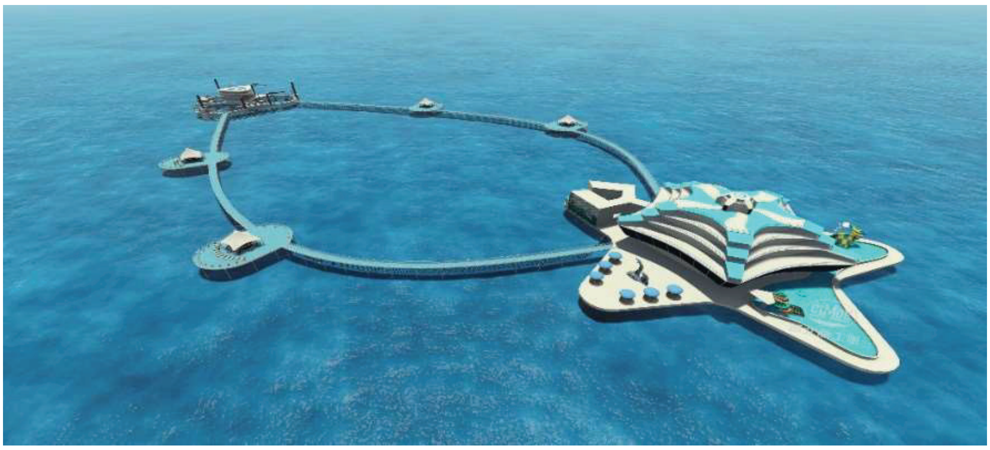

Figure 1. A rendering of the marine ranching complex.

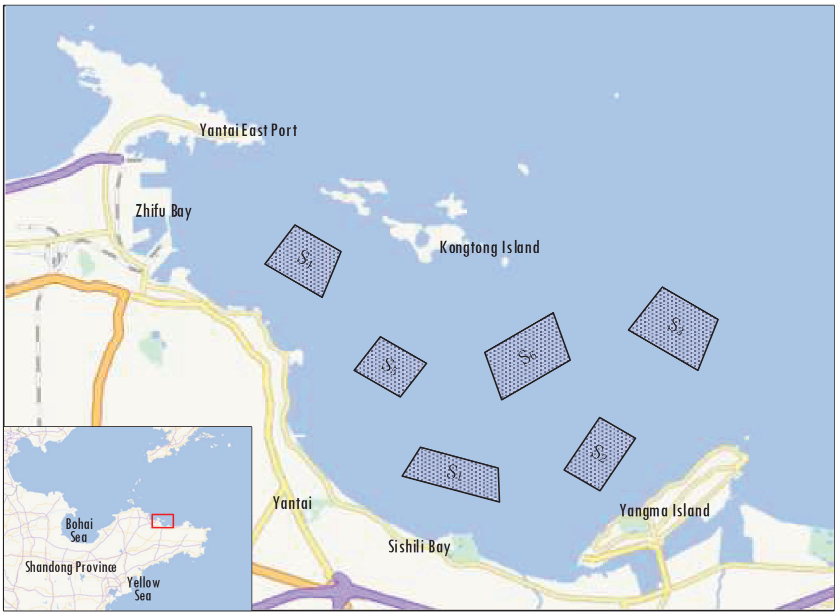

Figure 2. The geographical positions of six alternative marine ranching sites.

1.2. Motivation for Developing a Cloud Model-Based CRITIC-EDAS

Owing to the external environment's variability and complexity and to human cognition incompleteness, it is difficult for experts to quantify their cognition with a precise number. For example, a precise number of plant plankton biomass of a marine ranching site can only be obtained at some fixed monitoring points, and it may lose some critical information such as the dynamics and variance of the index. Therefore, linguistic terms have become popular tools in modeling various decision-making problems in reality, as people tend to rely on language to express their opinion rather than exact numbers. For example, natural language such as 'extremely low' or 'too high' can be used by decision makers to deliver their cognition about the plant plankton biomass of marine ranching sites with fuzziness and uncertainty. Linguistic decision-making problems can be divided into three main types of research: linguistic computational models based on membership functions [8,9], linguistic symbolic models based on ordinal scales [10,11] and two-tuple linguistic models [12,13]. Another character of marine ranching site selection problems is the randomness of data. The first linguistic model can only describe fuzziness but not randomness, and the last two linguistic models cannot produce a clear description of either fuzziness or randomness. Therefore, the cloud model theory is introduced to solve linguistic MADM problems [14].

The cloud model theory, a description of the qualitative concept, is developed on the fundamentals of the probability theory and the fuzzy set theory and manipulates the issue that membership degrees are accurate in the fuzzy set theory through allowing a stochastic disturbance of the membership degree encircling a determined central value [15]. More specifically, the cloud model employs a large number of discrete points to depict the vagueness and randomness of experts' uncertain preferences, and then uses three quantitative numerical characteristics to describe the distribution of elements, in which the objective and interchangeable transformation between qualitative concepts and quantitative values becomes possible. Due to the advantage of the cloud model in reflecting fuzziness and randomness simultaneously, it has been successfully employed to construct extended MADM methods such as cloud AHP [16], cloud TOPSIS [17], cloud VIKOR [18] and cloud CoCoSo [19], and applied in solving realistic practices such as sustainable supplier selection, informatization project evaluation, online education satisfaction assessment, vulnerability assessment for urban road network traffic systems and so on [20–23]. Some typical MADM methods combined with the cloud model are summarized in Table 1.

Table 1. Related studies combining the cloud model with MADM methods.

MADM Methods	Evaluations	Applications	Reference
AHP	Intervals	Select a house by home buyers	[16]
TOPSIS	Linguistic terms	Online education satisfaction assessment	[20]
VIKOR	Linguistic terms	Evaluate the risk of an informatization project	[18]
CoCoSo	Linguistic terms	Select a trusted cloud service provider	[21]
Complex network	Crisp numbers	Vulnerability assessment for traffic systems	[22]
TOPSIS	Rough numbers	Sustainable supplier selection	[23]

The CRITIC method, a well-known multi-attribute decision-making technique proposed by Diakoulaki, was developed to calculate the relative importance of attributes and alternatives in decision-making processes [24]. CRITIC takes into account the standard deviation (S.D.) and correlation coefficient (C.C.) to determine the significance and impact of each attribute on the overall decision outcome, which considers the fluctuation of data to synthesize the weight values of attributes, and helps to reduce the negative impact of the extreme values of weights of individual data within the evaluation system [25]. Recently, CRITIC has been extensively extended to interval-valued intuitionistic fuzzy [26], linguistic Pythagorean fuzzy [23], probabilistic uncertain linguistic [27], Fermatean fuzzy [28], picture fuzzy [29] and type-2 fuzzy [30] environments, as listed in Table 2. Hence, an extension of the CRITIC method with the cloud model is still missing. A combination of CRITIC and the cloud model can be valuable for researchers and practitioners as the existing CRITIC methods are unable to handle fuzziness and randomness of realistic decision-making problems [31–33]. To fill this significant research gap, this study introduces a cloud model-based CRITIC method to determine the importance of evaluation attributes for marine ranching site selection [34,35].

Table 2. Studies related to the CRITIC method.

Environments	Applications	Reference
Interval-valued intuitionistic fuzzy sets	Transportation mode selection	[16]
Linguistic Pythagorean fuzzy sets	Industrial waste management technique selection	[20]
Probabilistic uncertain linguistic sets	Site selection for hospital constructions	[27]
Fermatean fuzzy sets	-	[21]
Picture fuzzy sets	Wearable health technology selection	[29]
Type-2 fuzzy sets	Site selection for nursing homes	[30]

EDAS is one of the recently developed methods for alternative prioritization in various complicated multi-attribute decision-making problems [36]. In traditional distance-based methods such as TOPSIS and VIKOR, the best alternative is determined by using the distances to positive ideal solutions (PIS) and negative ideal solutions (NIS). However, in many realistic MADM problems, lower distance to PIS and higher distance to NIS would not guarantee to get the optimal solution [37]. Therefore, EDAS utilizes two distance measures named positive distance from average value and negative distance from average value to determine the ranking order. As it provides a robust ranking of alternatives, a simple algorithm and calculation swiftness, EDAS has turned into one of the popular and frequently used method to efficiently tackle realistic complex decision-making problems, and been extended by implementing different uncertainty sets, such as fuzzy sets [38], probabilistic hesitant fuzzy sets [19], q-rung orthopair fuzzy sets [39], linguistic intuitionistic fuzzy sets [40], picture fuzzy soft sets [24], and interval-type 2 fuzzy sets [41], as listed in Table 3. However, all the extended EDAS models only represent uncertainties such as fuzziness, imprecision and vagueness, and they cannot handle decision-making problems with fuzziness as well as randomness. To fill this important research gap, this study introduces a cloud model-based EDAS method to rank alternatives and reveal the optimal marine ranching site.

Table 3. Studies related to the EDAS method.

Environments	Applications	Reference
Fuzzy sets	Supplier selection	[16]
Probabilistic hesitant fuzzy sets	Selection of commercial vehicles and green suppliers	[20]
Q-rung orthopair fuzzy sets	Supplier selection in the defense industry	[24]
Linguistic intuitionistic fuzzy sets	Selection of houses and travel destinations	[21]
Picture fuzzy soft sets	Robotic agrifarming	[24]
Interval-type 2 fuzzy sets	Route selection of petroleum transportation	[30]

1.3. Contribution of This Study

The main objective of this study is to construct a multi-attribute group decision-making technique that can assist governments and enterprises in evaluating and selecting optimal marine ranching sites. The main contributions of this research, which might also be viewed as its distinctive strengths or benefits, can be depicted as follows:

- This study constructs a methodology for marine ranching site selection by considering fuzziness and randomness simultaneously. Existing decision-making approaches for marine ranching site selection only take into account the fuzziness of data, while the data collected by detectors and the linguistic terms given by experts are random due to the dynamics and volatility of sample points and human cognition. Therefore, a cloud model is first introduced to reveal the fuzziness and randomness of data in marine ranching site selection problems.
- A new method for determining the relative importance of attributes in marine ranching site selection problems is proposed by integrating CRITIC and the cloud model. The collected evaluation values are transferred from linguistic terms into corresponding clouds, and then the CRITIC approach is extended to handle these clouds in order to obtain the weights of attributes.
- A novel model, named cloud model-based EDAS, is developed to determine the ranks of alternatives in marine ranching site selection problems. The proposed model obtains the final evaluation scores of alternative sites in the form of clouds, which reserve the fuzziness and randomness of evaluation results in order to determine the optimal alternative for marine ranching site selection in a scientific way.
- A real-world marine ranching site selection problem in the city of Yantai is solved by using the cloud model-based CRITIC-EDAS model. Firstly, an evaluation attribute system for modern marine ranching site selection problems is determined from a comprehensive perspective, and then, by transforming linguistic evaluation values into clouds, the proposed model is utilized to obtain the optimal site for marine ranching in Yantai city.
- A comparison of the proposed model with the existing approaches is conducted in the same case to demonstrate its superiority and consistency.

1.4. Organization of This Study

This research is structured as follows: Section 2 presents the preliminaries. Section 3 explores a comprehensive framework of the cloud model-based CRITIC-EDAS model for marine ranching site selection. In Section 4, a real-world case study of the city of Yantai is explored, with an extensive comparative analysis with other methods. Section 5 presents the conclusions and implications.

2. Preliminaries

In this section, the definitions and some of the operations and measures of the cloud are illustrated, and then the concept and properties of linguistic variables are outlined.

2.1. Cloud Model

The cloud model theory, derived from the probability theory and the fuzzy set theory, is an artificial intelligence approach that can reflect the fuzziness and randomness of concepts in human knowledge. It allows a stochastic disturbance of the membership degree encircling a determined central value rather than a fixed number.

Definition 1 [14]**.** *Let U be the universe of discourse and T be a qualitative concept in U. If $x \in U$ is a random instantiation of concept T, which satisfies $x \sim N(Ex,\ En'^2)$ and $En' \sim N(En,\ He^2)$, and if the certainty degree of x belonging to concept T satisfies*

$$y = e^{-\frac{(x-Ex)^2}{2(En')^2}} \quad (1)$$

then the distribution of x in the universe U is called a normal cloud (given as 'cloud' in the remainder of the paper), which can be generally denoted as $(Ex,\ En,\ He)$, and the cloud drop can be denoted as (x, y).

Figure 3 illustrates the cloud $(10, 10, 1)$ with 600 cloud drops. It can be seen that the thickness of the cloud is uneven, which reflects the randomness and fuzziness of the normal cloud. The overall quantitative properties of a concept are described by the cloud using three numerical characteristics: (1) expectation (Ex), the mathematical expectation that the cloud drops belong to a concept in the universe; (2) entropy (En), which illustrates the uncertainty measurements of a qualitative concept, specifically randomness and fuzziness [37]; and (3) hyper entropy (He), the degree of uncertainty of En, i.e., the second-order entropy of the entropy. Additionally, the coverage and discrete degree of clouds have obvious differences: the larger the entropy, the larger the distribution range; the larger the hyper entropy, the bigger the discrete degree [38].

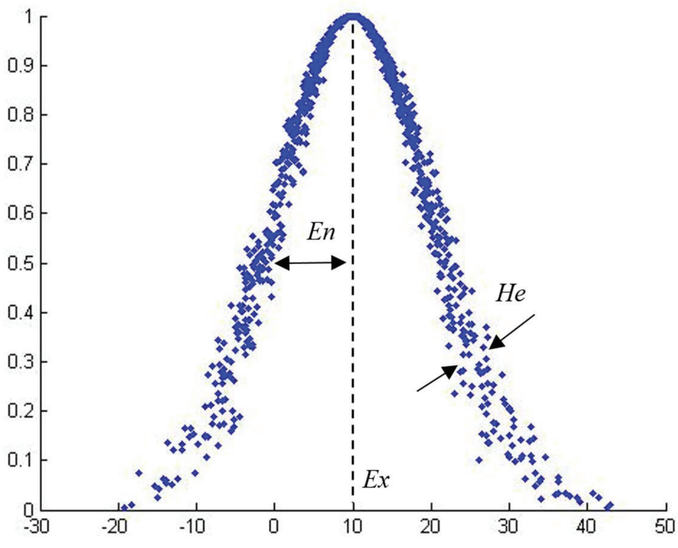

Figure 3. A cloud $(10, 10, 1)$ with 600 cloud drops and its numerical characters.

Definition 2 [39]. *Let $A(Ex_1, En_1, He_1)$ and $B(Ex_2, En_2, He_2)$ be two arbitrary clouds in the domain U. Some basic operations between cloud A and cloud B are defined as follows:*

(1) $A + B = \left(Ex_1 + Ex_2, \sqrt{En_1^2 + En_2^2}, \sqrt{He_1^2 + He_2^2}\right)$

(2) $A - B = \left(Ex_1 - Ex_2, \sqrt{En_1^2 + En_2^2}, \sqrt{He_1^2 + He_2^2}\right)$

(3) $A \times B = \left(Ex_1 Ex_2, \sqrt{(En_1 Ex_2)^2 + (En_2 Ex_1)^2}, \sqrt{(He_1 Ex_2)^2 + (He_2 Ex_1)^2}\right)$

(4) $\lambda A = \left(\lambda Ex_1, \sqrt{\lambda} En_1, \sqrt{\lambda} He_1\right)$

(5) $A^\lambda = \left(Ex_1^\lambda, \sqrt{\lambda} Ex_1^{\lambda-1} En_1, \sqrt{\lambda} Ex_1^{\lambda-1} He_1\right)$

Especially when $En = He = 0$, a cloud $(Ex,\ En,\ He)$ degenerates to a numerical number. In other words, a numerical number a can be expressed as a cloud $(a,\ 0,\ 0)$. Therefore, the operations between a cloud $A(Ex, En, He)$ and a numerical number a can be obtained by using $(a,\ 0,\ 0)$ according to Definition 2.

Definition 3 [40]. *Assume that Ω is the set of all clouds and $w_i(Ex_i, En_i, He_i)$ $(i = 1, 2, \cdots, n)$ is a subset of Ω, a mapping of CWAA: $\Omega^n \to \Omega$ is defined as the cloud-weighted arithmetic averaging (CWAA) operator by*

$$CWAA(A_1, A_2, \cdots, A_n) = \left(\sum_{i=1}^{n} w_i Ex_i, \sqrt{\sum_{i=1}^{n} w_i {En_i}^2}, \sqrt{\sum_{i=1}^{n} w_i {He_i}^2}\right) \tag{2}$$

where $w = (w_1, w_2, \cdots, w_n)$ is the associated weight vector of $A_i(Ex_i, En_i, He_i)$, satisfying $w_i \in [0, 1]$ and $\sum_{i=1}^{n} w_i = 1$.

In particular if $w = \left(\frac{1}{n}, \frac{1}{n}, \cdots, \frac{1}{n}\right)$, then the *CWAA* operator degenerates to the *CAA* operator as

$$CAA(A_1, A_2, \cdots, A_n) = \left(\frac{1}{n}\sum_{i=1}^{n} Ex_i, \frac{1}{\sqrt{n}}\sqrt{\sum_{i=1}^{n} {En_i}^2}, \frac{1}{\sqrt{n}}\sqrt{\sum_{i=1}^{n} {He_i}^2}\right) \tag{3}$$

Definition 4 [41]. *Given a cloud drop (x, y), its contribution to concept T can be measured by the score function $s = xy$. Regarding a cloud $A(Ex,\ En, He)$ with n cloud drops (x_i, y_i), we denote the expected value $\hat{s}(A)$ as the overall score for cloud A to concept T as follows:*

$$\hat{s}(A) = \frac{1}{n}\sum_{i=1}^{n} x_i y_i \tag{4}$$

Wang et al. proposed a method based on Monte Carlo simulation by using the forward generator of the cloud to obtain the expected value $\hat{s}$. And using Definition 4, the comparison method between clouds can be obtained as the following: with regard to two clouds A and B, if $\hat{s}(A) \geq \hat{s}(B)$, then $A \geq B$.

Definition 5 [42]. *Let $A(Ex_1, En_1, He_1)$ and $B(Ex_2, En_2, He_2)$ be two arbitrary clouds in the domain U. The Hamming distance between the two clouds can be defined as follows:*

$$D^H(A, B) = \left|\left(1 - \frac{En_1 + He_1}{Ex_1}\right)Ex_1 - \left(1 - \frac{En_2 + He_2}{Ex_2}\right)Ex_2\right| \tag{5}$$

2.2. Linguistic Variables

The concept of linguistic variables is used to deal with the cases which are too complex or too ill-defined to be reasonably represented by quantitative expressions [17].

Definition 6 [43]. *Let* $L = \{L_i | i = -g, \ldots, 0, \ldots, g,\ g \in N^*\}$ *be a finite and totally ordered discrete linguistic term set, where* L_i *represents a possible value for a linguistic variable. Then, the linguistic term set L has the following characteristics:*

(1) *The set is ordered:* $L_i > L_j$ *if and only if* $i > j$*;*
(2) *There is the negation operator:* $neg(L_i) = L_{-i}$*.*

For example, a set of seven terms L can be defined as follows:

$$L = \{L_{-3} = \text{very poor},\ L_{-2} = \text{poor},\ L_{-1} = \text{moderately poor},\ L_0 = \text{moderate},$$

$$L_1 = \text{moderately good},\ L_2 = \text{good},\ L_3 = \text{very good}.\}$$

So far, there are two perspectives to transform linguistic variables into clouds. One is using the golden ratio to generate the values of expectation, entropy and hyper entropy [18], the other is obtaining the characters by use of a linguistic scale function [18]. In this paper, we improve the former one by using the linguistic term sets with symmetric subscripts.

Definition 7. [44]. *Assume that the effective domain* $U = [Xmax_{min}]$ *and let* $L = \{L_i | i = -g, \ldots, 0, \ldots, g,\ g \in N^*\}$ *be a linguistic term set. Then, the* $2g+1$ *basic clouds can be generated based on the golden segmentation method as follows:*

$$A_{-g}(Ex_{-g}, En_{-g}, He_{-g}),\ A_{-(g-1)}\left(Ex_{-(g-1)}, En_{-(g-1)}, He_{-(g-1)}\right),\ A_0(Ex_0, En_0, He_0), \ldots$$
$$, A_g(Ex_g, En_g, He_g),$$

where

$$Ex_i = X\frac{i+g}{2g}min_{\,max\,min};$$
$$En_0 = 0.382(Xmin_{max};\ En_i = En_0/\left(0.618^{|i|}\right),\ i = -g, \cdots, 0, \cdots, g;$$
$$He_i = He_0/\left(0.618^{|i|}\right),\ i = -g, \cdots, 0, \cdots, g.$$

Note that the effective domain $U = [Xmax_{min}]$ and He_0 need to be designated in advance.

Example 1. *Given the universe* $U = [10,\ 20]$ *and* $He_0 = 0.02$*, then a 5-label linguistic term set* $L = \{L_{-2} = poor,\ L_{-1} = moderately\ poor,\ L_0 = moderate, L_1 = moderately\ good,\ L_2 = good\}$ *can be transformed into five clouds as*

$$A_{-2}(10, 0.667, 0.052),\ A_{-1}(12.5, 0.412, 0.032),\ A_0(15, 0.255, 0.02),$$
$$A_1(17.5, 0.412, 0.032) \text{ and } A_2(20, 0.667, 0.052).$$

And the depictions of the five clouds are given in Figure 4.

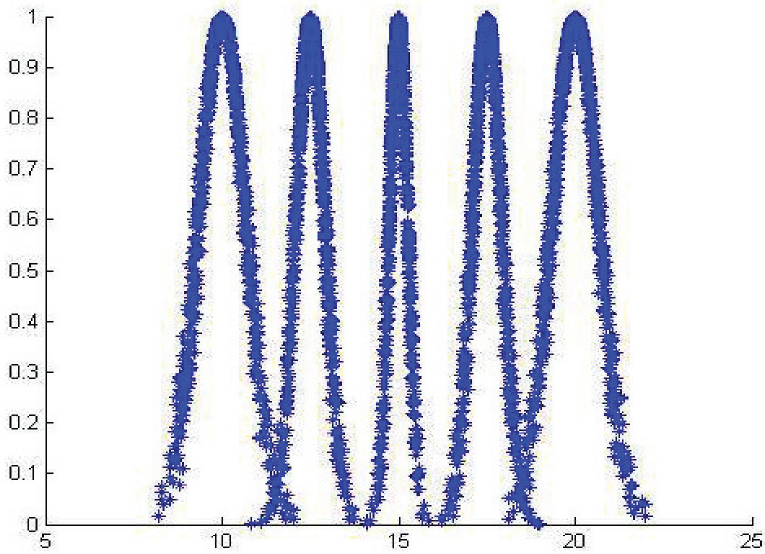

Figure 4. Clouds derived from a 5-label linguistic term set (where $U = [10, 20]$ and $He_0 = 0.02$).

3. An Innovative CRITIC-EDAS Approach Based on the Cloud Model

In this section, we focus on discussing a novel MAGDM approach for site selection for marine ranching. Firstly, the framework of the proposed model is depicted; then, a cloud model-based CRITIC method for weighting attributes and a cloud model-based EDAS method for ranking alternatives are illustrated.

3.1. Framework of the Proposed Model

The proposed model in this section is divided into two phases. The first one is a cloud model-based CRITIC method for calculating the weight of attributes for marine ranching site selection, and the second one is a cloud model-based EDAS method for evaluating and ranking alternative marine ranching sites. The specific procedure of the proposed model is depicted in Figure 5.

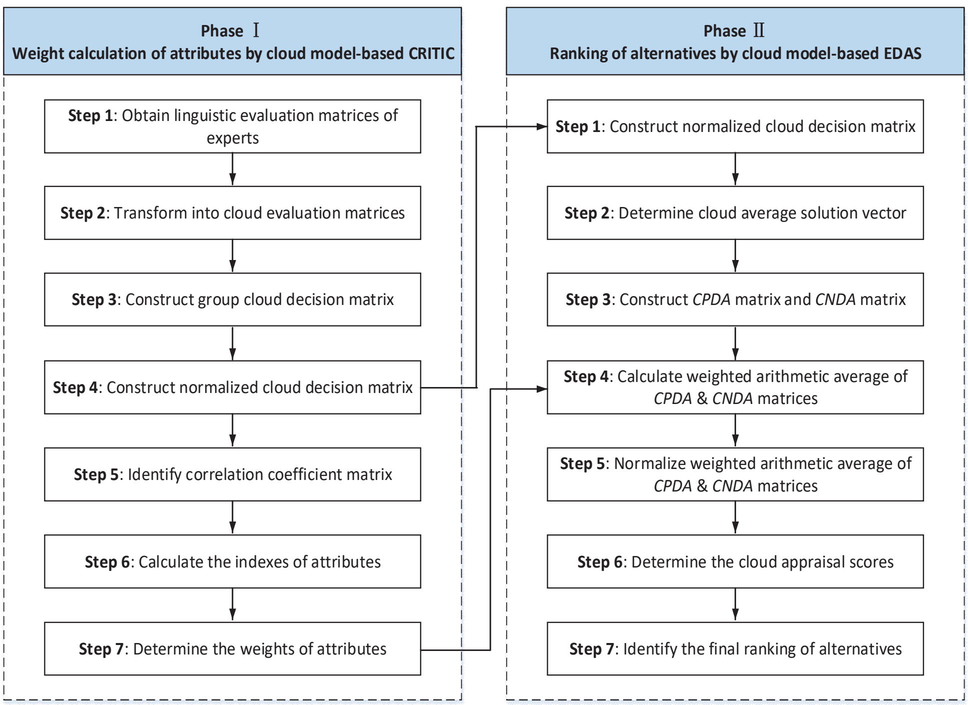

Figure 5. The framework of cloud model-based CRITIC-EDAS approach.

3.2. Cloud Model-Based CRITIC Methodology

The CRITIC method, an objective weighting method, was first proposed by Diakoulak in 1995 [45]. In this section, an extension to the classical CRITIC method is presented by using the cloud model. The procedure of the cloud CRITIC is illustrated as follows.

Step 1. Obtain the linguistic evaluation matrix of expert e_k.

Gather the information from experts in the form of linguistic variables and form decision matrices for each expert. For the kth decision maker e_k $(k = 1, 2, \cdots, s)$ we have the linguistic evaluation matrix as

$$D_k = \begin{pmatrix} L_{11}^k & L_{12}^k & \cdots & L_{1n}^k \\ L_{21}^k & L_{22}^k & \cdots & L_{2n}^k \\ \vdots & \vdots & \vdots & \vdots \\ L_{m1}^k & L_{m2}^k & \cdots & L_{mn}^k \end{pmatrix} \tag{6}$$

where L_{ij}^k is an assessment value for the ith alternative with respect to the jth attribute, a linguistic variable assigned by the kth expert.

Step 2. Transform to cloud evaluation matrices.

Determine the label of a linguistic term set and transform linguistic variables into clouds by using Definition 7. Then, the linguistic evaluation matrix D^k of expert e_k can be transformed into a cloud evaluation matrix as

$$D_k' = \begin{pmatrix} \left(Ex_{11}^k, En_{11}^k, He_{11}^k\right) & \left(Ex_{12}^k, En_{12}^k, He_{12}^k\right) & \cdots & \left(Ex_{1n}^k, En_{1n}^k, He_{1n}^k\right) \\ \left(Ex_{21}^k, En_{21}^k, He_{21}^k\right) & \left(Ex_{22}^k, En_{22}^k, He_{22}^k\right) & \cdots & \left(Ex_{2n}^k, En_{2n}^k, He_{2n}^k\right) \\ \vdots & \vdots & \vdots & \vdots \\ \left(Ex_{m1}^k, En_{m1}^k, He_{m1}^k\right) & \left(Ex_{m2}^k, En_{m2}^k, He_{m2}^k\right) & \cdots & \left(Ex_{mn}^k, En_{mn}^k, He_{mn}^k\right) \end{pmatrix} \tag{7}$$

where $\left(Ex_{ij}^k, En_{ij}^k, He_{ij}^k\right)$ is the transformed cloud used to assess the ith alternative with respect to the jth attribute by the kth expert.

Step 3. Construct a group cloud decision matrix.

Denote the weights of experts as $\omega = (\omega_1, \omega_2, \cdots, \omega_s)$. By using the cloud-weighted arithmetic averaging ($CWAA$) operator as Equation (2), we can aggregate s cloud evaluation matrices D_k' $(k = 1, 2, \cdots, s)$ and generate an integrated group cloud decision matrix as

$$A = \left[A_{ij}\left(Ex_{ij}, En_{ij}, He_{ij}\right)\right]_{m\times n} = \begin{pmatrix} A_{11}(Ex_{11}, En_{11}, He_{11}) & A_{12}(Ex_{12}, En_{12}, He_{12}) & \cdots & A_{1n}(Ex_{1n}, En_{1n}, He_{1n}) \\ A_{21}(Ex_{21}, En_{21}, He_{21}) & A_{22}(Ex_{21}, En_{21}, He_{21}) & \cdots & A_{2n}(Ex_{21}, En_{21}, He_{21}) \\ \vdots & \vdots & \vdots & \vdots \\ A_{m1}(Ex_{m1}, En_{m1}, He_{m1}) & A_{m2}(Ex_{m2}, En_{m2}, He_{m2}) & \cdots & A_{mn}(Ex_{mn}, En_{mn}, He_{mn}) \end{pmatrix} \tag{8}$$

where

$$A_{ij}(Ex_{ij}, En_{ij}, He_{ij}) = CWAA(A_{ij}^1, A_{ij}^2, \cdots, A_{ij}^s) = \left(\sum_{k=1}^{s} \omega_k Ex_{ij}^k, \sqrt{\sum_{i=1}^{n}\left(\omega_k En_{ij}^k\right)^2}, \sqrt{\sum_{i=1}^{n}\left(\omega_k He_{ij}^k\right)^2}\right) \tag{9}$$

Step 4. Construct a normalized cloud decision matrix.

The group cloud decision matrix given in Equation (8) is normalized, both for benefit type attributes and cost type attributes, by using Equation (10):

$$B_{ij} = \begin{cases} \dfrac{A_{ij} - \underset{i}{min}(Ex_{ij})}{\underset{i}{max}(Ex_{ij}) - \underset{i}{min}(Ex_{ij})}, & \text{for beneficial attributes} \\ \dfrac{\underset{i}{max}(Ex_{ij}) - A_{ij}}{\underset{i}{max}(Ex_{ij}) - \underset{i}{min}(Ex_{ij})}, & \text{for cost attributes} \end{cases} \tag{10}$$

where B_{ij} denotes the normalized cloud for the ith alternative with respect to the jth attribute. $\underset{i}{max}(Ex_{ij})$ and $\underset{i}{min}(Ex_{ij})$ represent, respectively, the maximal expectation and the minimal expectation among the clouds under the jth attribute.

Then, we can obtain the normalized cloud decision matrix as

$$\begin{aligned} B &= \left[B_{ij}\left(Ex_{ij}, En_{ij}, He_{ij}\right)\right]_{m \times n} \\ &= \begin{pmatrix} B_{11}(Ex_{11}, En_{11}, He_{11}) & B_{12}(Ex_{12}, En_{12}, He_{12}) & \cdots & B_{1n}(Ex_{1n}, En_{1n}, He_{1n}) \\ B_{21}(Ex_{21}, En_{21}, He_{21}) & B_{22}(Ex_{21}, En_{21}, He_{21}) & \cdots & B_{2n}(Ex_{21}, En_{21}, He_{21}) \\ \vdots & \vdots & \vdots & \vdots \\ B_{m1}(Ex_{m1}, En_{m1}, He_{m1}) & B_{m2}(Ex_{m2}, En_{m2}, He_{m2}) & \cdots & B_{mn}(Ex_{mn}, En_{mn}, He_{mn}) \end{pmatrix} \end{aligned} \tag{11}$$

Step 5. Identify the correlation coefficient.

In traditional CRITIC, the conflicting relationships between attributes are captured with the help of the Pearson correlation. Székely et al. introduced a distance-based correlation measure [46], and then many research studies developed a D-CRITIC method from the perspective of distance correlation [47]. Therefore, by using Hamming distance measures between clouds in Definition 5, a distance-based correlation coefficient, ρ_{jk}, among all attributes is introduced as follows

$$\rho_{jk} = \frac{\sum_{i=1}^{m} D^H\left(B_{ij}, \overline{B}_j\right) D^H\left(B_{ik}, \overline{B}_k\right)}{\sqrt{\sum_{i=1}^{m} D^H\left(B_{ij}, \overline{B}_j\right)^2 \sum_{i=1}^{m} D^H\left(B_{ik}, \overline{B}_k\right)^2}} \tag{12}$$

where $\overline{B}_j$ and $\overline{B}_k$ denote the mean values of the jth and kth attributes by using the CAA operator in Equation (3) as $\overline{B}_j = CAA\left(B_{1j}, B_{2j}, \cdots, B_{mj}\right)$ and $\overline{B}_k = CAA(B_{1k}, B_{2k}, \cdots, B_{mk})$.

The distance-based correlation coefficient ρ_{jk} provides a numerical value that indicates the degree of association of the jth attribute with the kth attribute. The value satisfies $\rho_{jk} \in [0, 1]$, providing a scale for measuring the relationship among attributes. In this step, the symmetrical distance-based correlation coefficient matrix is formed as $\left[\rho_{jk}\right]_{n \times n}$.

Step 6. Calculate the index of each attribute.

Compute the information content represented in the index of the jth attribute as follows:

$$I_j = \sigma_j \sum_{k=1}^{n} \left(1 - \rho_{jk}\right) \tag{13}$$

where σ_j indicates the standard deviation of the jth attribute, which is defined as

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^{m} D^H\left(B_{ij}, \overline{B}_j\right)^2}{m-1}} \tag{14}$$

Step 7. Determine the weights of attributes.

The weight of the jth attribute can be calculated as

$$w_j = \frac{I_j}{\sum_{j=1}^{n} I_j} \tag{15}$$

3.3. Cloud Model-Based EDAS Methodology

Ranking alternatives and selecting the best one is another critical process in MADM problems. In this section, an extension to the classical EDAS method is presented, where the cloud model is incorporated. The procedure of the cloud EDAS is depicted as follows.

Step 1. Construct a normalized cloud decision matrix.

Gather the information from experts in the form of linguistic variables, and, by using the procedure of Step 1–4 in Section 3.2, the normalized group cloud decision matrix B can be constructed as follows:

$$B = \left[B_{ij}\left(Ex_{ij}, En_{ij}, He_{ij}\right)\right]_{m\times n} = \begin{pmatrix} B_{11}(Ex_{11}, En_{11}, He_{11}) & B_{12}(Ex_{12}, En_{12}, He_{12}) & \cdots & B_{1n}(Ex_{1n}, En_{1n}, He_{1n}) \\ B_{21}(Ex_{21}, En_{21}, He_{21}) & B_{22}(Ex_{21}, En_{21}, He_{21}) & \cdots & B_{2n}(Ex_{21}, En_{21}, He_{21}) \\ \vdots & \vdots & \vdots & \vdots \\ B_{m1}(Ex_{m1}, En_{m1}, He_{m1}) & B_{m2}(Ex_{m2}, En_{m2}, He_{m2}) & \cdots & B_{mn}(Ex_{mn}, En_{mn}, He_{mn}) \end{pmatrix} \tag{16}$$

Step 2. Determine the cloud average solution vector.

The cloud average solution vector can be expressed as

$$CAV = [CAV_1, CAV_2, \cdots, CAV_n]_{1\times n} \tag{17}$$

where CAV_j indicates the cloud average solution of the jth attribute, which is denoted as

$$CAV_j = CAA\left(B_{1j}, B_{2j}, \cdots, B_{mj}\right) \tag{18}$$

Actually, CAV_j is the mean value $\overline{B}_j$ in the cloud CRITIC method. In order to keep consistent with the traditional EDAS, we still use CAV_j in the proposed approach to indicate the cloud average solution of the jth attribute.

Step 3. Construct the cloud positive distance from the average matrix and the cloud negative distance from the average matrix.

Calculate two important distance measures, the cloud positive distance from average ($CPDA$) and the cloud negative distance from average ($CNDA$), both for benefit type attributes and cost type attributes as follows:

$$CPDA_{ij} = \begin{cases} \dfrac{max\left(0, \left(B_{ij} - CAV_j\right)\right)}{Ex_{CAV_j}} & \text{for benefit attributes} \\ \dfrac{max\left(0, \left(CAV_j - B_{ij}\right)\right)}{Ex_{CAV_j}} & \text{for cost attributes} \end{cases} \tag{19}$$

$$CNDA_{ij} = \begin{cases} \dfrac{max\left(0, \left(CAV_j - B_{ij}\right)\right)}{Ex_{CAV_j}} & \text{for benefit attributes} \\ \dfrac{max\left(0, \left(B_{ij} - CAV_j\right)\right)}{Ex_{CAV_j}} & \text{for cost attributes} \end{cases} \tag{20}$$

where Ex_{CAV_j} is the expectation of the cloud CAV_j.

After obtaining the two cloud distance measures from the average of all the evaluation information in B, the $CPDA$ matrix and the $CNDA$ matrix can be determined as follows:

$$CPDA = \begin{pmatrix} CPDA_{11} & CPDA_{12} & \cdots & CPDA_{1n} \\ CPDA_{21} & CPDA_{22} & \cdots & CPDA_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ CPDA_{m1} & CPDA_{m2} & \cdots & CPDA_{mn} \end{pmatrix} \tag{21}$$

$$CNDA = \begin{pmatrix} CNDA_{11} & CNDA_{12} & \cdots & CNDA_{1n} \\ CNDA_{21} & CNDA_{22} & \cdots & CNDA_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ CNDA_{m1} & CNDA_{m2} & \cdots & CNDA_{mn} \end{pmatrix} \tag{22}$$

Step 4. Calculate the weighted arithmetic average of $CPDA$ and $CNDA$.

The weighted sums of $CPDA$ and $CNDA$ for each alternative can be calculated by using the $CWAA$ operator shown in Equation (2), respectively, as follows:

$$SCP_i = CWAA(CPDA_{i1}, CPDA_{i2}, \cdots, CPDA_{in}) \tag{23}$$

$$SCN_i = CWAA(CNDA_{i1}, CNDA_{i2}, \cdots, CNDA_{in}) \tag{24}$$

SCP_i represents the weighted sum of the positive distance of the ith alternative from the average solution, SCN_i represents the weighted sum of the negative distance of the ith alternative from the average solution. And the weights of attributes can be obtained by cloud CRITIC.

Step 5. Normalize the values of SCP_i and SCN_i.

The normalized weighted sum values of $CPDA$ and $CNDA$ can be obtained as follows:

$$NSCP_i = \frac{SCP_i}{\max_i(Ex_{SCP_i})} \tag{25}$$

$$NSCN_i = 1 - \frac{SCN_i}{\max_i(Ex_{SCN_i})} \tag{26}$$

where $\max_i(Ex_{SCP_i})$ represents the maximal expectation of the clouds among the weighted sum of $CPDA$, and $\max_i(Ex_{SCN_i})$ represents the maximal expectation of the clouds among the weighted sum of $CNDA$.

Step 6. Determine the cloud appraisal scores.

The cloud appraisal score for the ith alternative can be calculated as

$$CAS_i = \frac{NSCP_i + NSCN_i}{2} \tag{27}$$

Step 7. Determine the final ranking of alternatives.

Generate cloud drops of CAS_i based on Monte Carlo simulation by using the forward generator of the cloud, and calculate the expected score value $\hat{s}(CAS_i)$ for the ith alternative by using Equation (4) in Definition 4. Arrange expected score values in descending order, and then the alternative with the highest expected score value is chosen as the best choice.

4. Case Study: Marine Ranching Site Selection in Yantai

4.1. Problem Description

In order to protect natural ecosystems and enhance fishery resources, marine ranching has been widely promoted as a novel production pattern of marine economy. China attaches great importance to the development of modern marine ranching from version 1.0 to version 3.0, which is a new business form, by integrating environmental protection, resource conservation, and sustainable production of fishery resources to supply high-quality protein and ensure the security of the offshore ecosystem. Whether marine ranching can play a role or not is intensively related to various factors derived from the ecological environment and the social environment. Therefore, evaluating different areas and selecting an optimal site for establishing marine ranching are the crucial procedures.

In recent years, Shandong province has been regarded as a strategic area for high-quality economic and social development in China. As the central city of Shandong Peninsula approved by the State council, an important port city around the Bohai Sea, and a national historical and cultural city, Yantai is identified as a city vigorously developing marine economy. By December 2022, Yantai had established 46 provincial marine ranching demonstration zones and 20 national marine ranching demonstration zones. With the increasing demand for marine ranching 3.0, Yantai intends to construct a novel marine ranching complex with the functions of marine culture, sea sightseeing, leisure fishing, ocean science, and supplying seafood as well as sea accommodation. According to the preliminary investigation, six marine areas in Yantai have been selected as alternative sites for marine ranching construction. The rendering for the main building of the marine ranching complex and the sea areas of six alternative sites are depicted as shown in Figures 1 and 2, respectively.

The marine ranching site selection problem can be illustrated as the following:

(1) Six marine areas were identified beforehand as alternative sites for further evaluation, which are denoted as $S = \{S_1, S_2, S_3, S_4, S_5, S_6\}$.

(2) A committee composed of five experts was formed, denoted as $E = \{e_1, e_2, e_3, e_4, e_5\}$. All the experts are professionals in marine economy, consisting of two enterprise managers, two governmental staff members and one college professor. In order to reserve their evaluation information impartially, we consider that each expert plays an equally important role, so the relative importance vector of the experts is $\omega = (0.2, 0.2, 0.2, 0.2, 0.2)$.

(3) The decision committee collects the data according to the evaluation index system as shown in Figure 6. The evaluation index system contains 5 primary indices and 16 secondary indices, which can be acquired by corresponding monitors. Table 1 shows the collected data of S_1 among all the secondary indices. In order to reduce complexity and interactivity among different secondary indices, experts evaluate each alternative from five primary indices by using linguistic terms according to the specific data of secondary indices. And the five primary indices are denoted as five attributes in the marine ranching site selection problem:

- Physical environment (C_1);
- Chemical environment (C_2);
- Biological environment (C_3);
- Engineering environment (C_4);
- Social environment (C_5).

(4) Collect the specific data of all the alternatives on 16 secondary indices, and then experts evaluate alternatives on 5 primary attributes by using the following 7-label linguistic terms:

$$L = \{L_{-3} = \textit{extremely poor},\ L_{-2} = \textit{very poor},\ L_{-1} = \textit{poor},\ L_0 = \textit{medium},\\ L_1 = \textit{good},\ L_2 = \textit{very good},\ L_3 = \textit{extremely good}\}.$$

Here, 'good' indicates that alternatives perform well in the attributes and 'poor' indicates that alternatives perform badly in the attributes.

Take S_1 for example. The data of S_1 on 16 indices are detected and collected as shown in Table 1, and then five experts evaluate S_1 from five attributes according to the specific data independently. Then, linguistic evaluating values of five experts are listed in the last five columns of Table 4. At last, we can obtain the group linguistic evaluation information as depicted in Table 5.

Table 4. Attributes for marine ranching site selection.

	Primary Indices	Secondary Indices	Data of Indices	e_1	e_2	e_3	e_4	e_5
S_1	Physical environment	Average depth	14.8 m	G	M	G	VG	M
		Sediment particle size	0.2 mm					
		Dissolved oxygen	5.45 mg/L					
	Chemical environment	Inorganic nitrogen	1.67 mg/L	VG	EG	VG	VG	G
		Sulfide content	63 mg/kg					
		Active phosphate	0.032 mg/L					
	Biological environment	Plant plankton biomass	125×10^4 ind/m^3	G	VG	M	M	G
		Zooplankton biomass	76.3 mg/m^3					
		Benthic biomass	89.7 g/m^2					
		Chlorophyll A	3.78 mg/m^3					
	Engineering environment	Bottom load	1.2 t/m^2	EP	VP	VP	VP	VP
		Silt thickness	0.61 m					
		Seabed slope	4.1 m					
	Social environment	Fishery resource density	48 kg/m^2	M	P	M	G	P
		Distance to scenic spots	7.8 km					
		Distance to submarine pipeline	12.1 km					

Table 5. Linguistic assessment information of marine ranching sites from five experts.

	C_1	C_2	C_3	C_4	C_5
S_1	L_1, L_0, L_1, L_2, L_0	L_2, L_3, L_2, L_2, L_1	L_1, L_2, L_0, L_0, L_1	$L_{-3}, L_{-2}, L_{-2}, L_{-2}, L_{-2}$	$L_0, L_{-1}, L_0, L_1, L_{-1}$
S_2	L_1, L_2, L_0, L_1, L_1	$L_{-1}, L_{-2}, L_{-2}, L_{-2}, L_{-1}$	L_3, L_3, L_3, L_2, L_3	$L_{-2}, L_{-3}, L_{-2}, L_{-2}, L_{-2}$	L_0, L_1, L_1, L_1, L_0
S_3	$L_{-2}, L_{-3}, L_{-2}, L_{-1}, L_{-2}$	L_1, L_1, L_2, L_1, L_1	L_3, L_2, L_3, L_3, L_2	L_2, L_1, L_2, L_2, L_1	L_2, L_1, L_0, L_1, L_1
S_4	L_2, L_1, L_1, L_2, L_2	L_2, L_2, L_3, L_2, L_2	L_2, L_1, L_1, L_0, L_1	L_1, L_1, L_1, L_2, L_1	$L_{-1}, L_{-2}, L_{-2}, L_{-2}, L_{-1}$
S_5	L_2, L_1, L_2, L_2, L_2	$L_0, L_1, L_1, L_{-1}, L_0$	L_2, L_1, L_1, L_2, L_0	$L_{-1}, L_0, L_{-1}, L_1, L_0$	L_3, L_2, L_1, L_2, L_2
S_6	$L_{-1}, L_{-2}, L_{-1}, L_{-1}, L_{-1}$	L_2, L_2, L_1, L_3, L_2	$L_{-1}, L_{-1}, L_{-1}, L_0, L_{-2}$	L_1, L_2, L_1, L_1, L_1	L_1, L_0, L_0, L_0, L_1

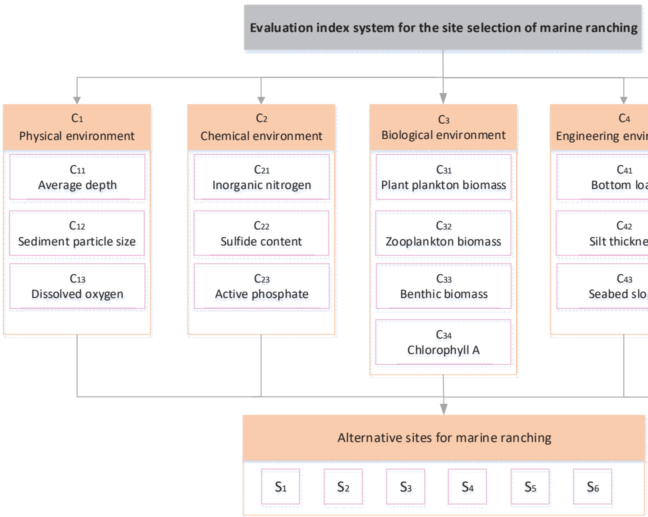

Figure 6. Evaluation index system for marine ranching site selection.

4.2. Assessing the Significance of Attributes Using Cloud CRITIC

Step 1. Collect the linguistic evaluation information of experts as described in Table 2.

Step 2. Transform the linguistic evaluation matrix of each expert into a cloud evaluation matrix. Given the universe $[Xmax_{min} = [0, 10]]$, the 7-label linguistic term set can be transformed to seven clouds by using the transformation rule in Definition 7. Selecting $He_0 = 0.01$, the transformed clouds are depicted in Table 6.

Table 6. Transformation from 7-label linguistic terms to clouds.

Linguistic Terms	Clouds
EP	(0.000, 0.771, 0.042)
VP	(1.667, 0.476, 0.026)
P	(3.333, 0.294, 0.016)
M	(5.000, 0.182, 0.010)
G	(6.667, 0.294, 0.016)
VG	(8.333, 0.476, 0.026)
EG	(10.000, 0.771, 0.042)

Step 3. Compile all decision matrices and create an aggregated cloud decision matrix $A = \left[A_{ij}\left(Ex_{ij}, En_{ij}, He_{ij}\right)\right]_{m\times n}$. In these cases, we consider that the all the experts possess the same significance; therefore, we use the *CAA* operator depicted in Equation (3) to aggregate cloud evaluation information. The group cloud decision matrix is shown in Table 7.

Table 7. Aggregated cloud decision matrix.

	C_1	C_2	C_3	C_4	C_5
S_1	(6.333, 0.305, 0.017)	(8.333, 0.522, 0.028)	(6.333, 0.305, 0.017)	(1.334, 0.548, 0.030)	(4.667, 0.255, 0.014)
S_2	(6.667, 0.322, 0.018)	(2.333, 0.413, 0.023)	(9.667, 0.722, 0.039)	(1.334, 0.548, 0.030)	(6.000, 0.255, 0.014)
S_3	(1.667, 0.522, 0.028)	(7.000, 0.338, 0.018)	(9.333, 0.669, 0.036)	(7.667, 0.413, 0.023)	(6.667, 0.322, 0.018)
S_4	(7.667, 0.413, 0.023)	(8.666, 0.548, 0.030)	(6.667, 0.322, 0.018)	(7.000, 0.338, 0.018)	(2.333, 0.413, 0.023)
S_5	(8.000, 0.446, 0.024)	(5.333, 0.255, 0.014)	(7.000, 0.363, 0.020)	(4.667, 0.255, 0.014)	(8.333, 0.522, 0.028)
S_6	(3.000, 0.338, 0.018)	(8.333, 0.522, 0.028)	(3.333, 0.322, 0.018)	(7.000, 0.338, 0.018)	(6.000, 0.255, 0.014)

Step 4. Normalize the aggregated cloud assessment information by using Equation (10). The normalized cloud decision $B = \left[B_{ij}\left(Ex_{ij}, En_{ij}, He_{ij}\right)\right]_{m\times n}$ is conducted as shown in Table 8.

Table 8. Normalized cloud decision matrix.

	C_1	C_2	C_3	C_4	C_5
S_1	(0.737, 0.211, 0.007)	(0.947, 0.207, 0.011)	(0.474, 0.121, 0.007)	(0.000, 0.218, 0.012)	(0.389, 0.104, 0.006)
S_2	(0.790, 0.223, 0.007)	(0.000, 0.164, 0.009)	(1.000, 0.287, 0.016)	(0.000, 0.218, 0.012)	(0.611, 0.104, 0.006)
S_3	(0.000, 0.361, 0.011)	(0.737, 0.134, 0.007)	(0.947, 0.266, 0.014)	(1.000, 0.164, 0.009)	(0.722, 0.132, 0.007)
S_4	(0.947, 0.285, 0.009)	(1.000, 0.218, 0.012)	(0.526, 0.128, 0.007)	(0.895, 0.134, 0.007)	(0.000, 0.169, 0.009)
S_5	(1.000, 0.308, 0.010)	(0.474, 0.101, 0.006)	(0.579, 0.144, 0.008)	(0.526, 0.101, 0.006)	(1.000, 0.213, 0.012)
S_6	(0.210, 0.234, 0.007)	(0.947, 0.207, 0.011)	(0.000, 0.128, 0.007)	(0.895, 0.134, 0.007)	(0.611, 0.104, 0.006)

To demonstrate the process behind the values in Table 8, we provide a calculation example specifically for B_{11} in the normalized cloud decision matrix. The maximal value and minimal value for C_1 are $A_{51}(8.000, 0.446, 0.024)$ and $A_{31}(1.667, 0.522, 0.028)$, respectively, and then we can transfer A_{11} to a normalized value B_{11} by using Equation (10) as

$$B_{11} = \frac{(6.333, 0.305, 0.017) - (1.667, 0.522, 0.028)}{8.000 - 1.667} = (0.737, 0.211, 0.007)$$

Step 5. Calculate the distance correlation coefficient among all attributes.

The specific procedure of calculating correlation coefficients is shown in Tables 9–11. Firstly, by using the *CAA* operator shown in Equation (3) we can obtain the mean value $\boldsymbol{B_j}$ for attribute $\boldsymbol{C_j}$, as illustrated in Table 9. Then, the Hamming distance between each cloud assessment and the corresponding mean value is depicted by using Equation (5), as shown in Table 10. By using Equation (12), we can obtain the correlation coefficient matrix shown in Table 11.

Table 9. The mean values of attributes.

$\overline{B}_1$	$\overline{B}_2$	$\overline{B}_3$	$\overline{B}_4$	$\overline{B}_5$
(0.614, 0.275, 0.009)	(0.684, 0.177, 0.010)	(0.588, 0.192, 0.010)	(0.553, 0.167, 0.009)	(0.556, 0.144, 0.008)

Table 10. Aggregation of the Hamming distance $\left(B_{ij}, \overline{B}_j\right)$.

	C_1	C_2	C_3	C_4	C_5
S_1	0.1893	0.2315	0.0394	0.6057	0.1252
S_2	0.2299	0.6703	0.3123	0.6057	0.0971
S_3	0.7019	0.0979	0.2818	0.4508	0.1794
S_4	0.3230	0.2732	0.0061	0.3769	0.5820
S_5	0.3523	0.1305	0.0415	0.0433	0.3712
S_6	0.3607	0.2315	0.5203	0.3769	0.0971

Table 11. Correlation coefficient matrix.

	C_1	C_2	C_3	C_4	C_5
C_1	1.0000	0.6160	0.7393	0.7865	0.7357
C_2	0.6160	1.0000	0.6860	0.8766	0.5713
C_3	0.7393	0.6860	1.0000	0.7275	0.3138
C_4	0.7865	0.8766	0.7275	1.0000	0.5981
C_5	0.7357	0.5713	0.3138	0.5981	1.0000

Taking the correlation coefficient ρ_{12} between C_1 and C_2 for example, we have

$$\rho_{12} = \frac{0.1893 \times 0.2315 + 0.2299 \times 0.6703 + \cdots + 0.3607 \times 0.2315}{\sqrt{(0.1893^2 + 0.2299^2 + \cdots + 0.3607^2) \times (0.2315^2 + 0.6703^2 + \cdots + 0.2315^2)}} = 0.6160$$

Step 6. Calculate the index I_j by using Equation (13), which is illustrated in Table 12. To provide a clear understanding of how to obtain the index of each attribute, we use C_1 as an example.

Table 12. The values of indices and weights of attributes.

	σ_j	I_j	w_j
C_1	0.4336	0.4866	0.1956
C_2	0.3627	0.4534	0.1823
C_3	0.3003	0.4605	0.1851
C_4	0.4946	0.5001	0.2010
C_5	0.3296	0.5870	0.2360

Firstly, we calculate the standard deviation of C_1 by using Equation (14) as

$$\sigma_1 = \sqrt{\frac{0.1893^2 + 0.2299^2 + 0.7019^2 + 0.3230^2 + 0.3523^2 + 0.3607^2}{6-1}} = 0.4336$$

Then, the index of attribute C_1 can be determined as

$$I_1 = 0.4336 \times ((1-1.0000) + (1-0.6160) + (1-0.7393) + (1-0.7865) + (1-0.7357)) = 0.4866.$$

Step 7. Calculate the weights of attributes by using Equation (14); the results are described in the last column of Table 12.

For example, the weight of C_1 can be calculated as

$$w_1 = \frac{0.4866}{0.4866 + 0.4534 + 0.4605 + 0.5001 + 0.5870} = 0.1956$$

Therefore, we can determine the weight vector of the marine ranching site selection problem as

$$W = (0.1956, 0.1823, 0.1851, 0.2010, 0.2360).$$

4.3. Evaluating Alternatives Using Cloud EDAS

After obtaining the weights of attributes, a cloud model-based EDAS method is implemented to evaluate the alternative sites for marine ranching.

Step 1. Similar to the procedure depicted in the cloud CRITIC, the normalized group cloud decision matrix can be constructed as shown in Table 8.

Step 2. Calculate the cloud average solution of each attribute, which is equivalent to the mean value in the cloud CRITIC. Therefore, we can obtain the cloud average solution vector as depicted in Table 13.

Table 13. The cloud average solution vector.

CAV_1	CAV_2	CAV_3	CAV_4	CAV_5
(0.614, 0.275, 0.009)	(0.684, 0.177, 0.010)	(0.588, 0.192, 0.010)	(0.553, 0.167, 0.009)	(0.556, 0.144, 0.008)

Step 3. Calculate the cloud positive distance from average (*CPDA*) matrix and the cloud negative distance from average (*CNDA*) matrix as described in Equations (19) and (20) by using the Hamming distance measure shown in Equation (5). The results are depicted in Tables 14 and 15.

Table 14. The cloud positive distance from average (*CPDA*) matrix.

	C_1	C_2	C_3	C_4	C_5
S_1	(0.200, 0.443, 0.014)	(0.385, 0.330, 0.018)	(0.000, 0.000, 0.000)	(0.000, 0.000, 0.000)	(0.000, 0.000, 0.000)
S_2	(0.286, 0.452, 0.014)	(0.000, 0.000, 0.000)	(0.701, 0.450, 0.025)	(0.000, 0.000, 0.000)	(0.100, 0.238, 0.013)
S_3	(0.000, 0.000, 0.000)	(0.077, 0.269, 0.015)	(0.612, 0.428, 0.023)	(0.809, 0.315, 0.017)	(0.300, 0.261, 0.014)
S_4	(0.543, 0.506, 0.016)	(0.461, 0.339, 0.019)	(0.000, 0.000, 0.000)	(0.619, 0.289, 0.016)	(0.000, 0.000, 0.000)
S_5	(0.629, 0.527, 0.017)	(0.000, 0.000, 0.000)	(0.000, 0.000, 0.000)	(0.000, 0.000, 0.000)	(0.800, 0.345, 0.019)
S_6	(0.000, 0.000, 0.000)	(0.385, 0.330, 0.018)	(0.000, 0.000, 0.000)	(0.619, 0.289, 0.016)	(0.100, 0.238, 0.013)

Table 15. The cloud negative distance from average (*CNDA*) matrix.

	C_1	C_2	C_3	C_4	C_5
S_1	(0.000, 0.000, 0.000)	(0.000, 0.000, 0.000)	(0.194, 0.296, 0.016)	(1.000, 0.369, 0.020)	(0.300, 0.238, 0.013)
S_2	(0.000, 0.000, 0.000)	(1.000, 0.292, 0.016)	(0.000, 0.000, 0.000)	(1.000, 0.369, 0.020)	(0.000, 0.000, 0.000)
S_3	(1.000, 0.579, 0.018)	(0.000, 0.000, 0.000)	(0.000, 0.000, 0.000)	(0.000, 0.000, 0.000)	(0.000, 0.000, 0.000)
S_4	(0.000, 0.000, 0.000)	(0.000, 0.000, 0.000)	(0.104, 0.301, 0.016)	(0.000, 0.000, 0.000)	(1.000, 0.297, 0.016)
S_5	(0.000, 0.000, 0.000)	(0.308, 0.247, 0.013)	(0.015, 0.313, 0.017)	(0.048, 0.263, 0.014)	(0.000, 0.000, 0.000)
S_6	(0.657, 0.461, 0.014)	(0.000, 0.000, 0.000)	(1.000, 0.301, 0.016)	(0.000, 0.000, 0.000)	(0.000, 0.000, 0.000)

We still take $CPDA_{11}$ and $CNDA_{11}$ as examples to illustrate the specific calculation procedure. As C_1 is a benefit attribute, the two cloud distances can be calculated as

$$CPDA_{11} = \frac{max(0,(0.737,0.211,0.007)-(0.614,0.275,0.009)))}{0.614} = \frac{(0.123,0.347,0.011)}{0.614} = (0.200,0.443,0.014)$$

$$CNDA_{11} = \frac{max(0,(0.614,0.275,0.009)-(0.737,0.211,0.007))}{0.614} = \frac{(0.000,0.000,0.000)}{0.614} = (0.000,0.000,0.000)$$

Step 4. According to the CWAA operator shown in Equation (2) as well as the weight vector determined by the cloud CRITIC, the weighted arithmetic averages of *CPDA* and *CNDA* for each alternative can be calculated as shown in Table 16.

Table 16. The result of SCP_i and SCN_i for alternatives.

	SCP_i	SCN_i	$NSCP_i$	$NSCN_i$	CAS_i
S_1	(0.109, 0.241, 0.010)	(0.308, 0.239, 0.013)	(0.303, 0.402, 0.016)	(0.197, 0.386, 0.021)	(0.250, 0.394, 0.019)
S_2	(0.209, 0.301, 0.014)	(0.383, 0.207, 0.011)	(0.580, 0.502, 0.023)	(0.000, 0.335, 0.018)	(0.290, 0.427, 0.021)
S_3	(0.361, 0.288, 0.016)	(0.196, 0.256, 0.008)	(1.000, 0.480, 0.026)	(0.490, 0.414, 0.013)	(0.745, 0.448, 0.021)
S_4	(0.315, 0.296, 0.013)	(0.255, 0.194, 0.011)	(0.872, 0.494, 0.021)	(0.334, 0.313, 0.017)	(0.603, 0.413, 0.019)
S_5	(0.312, 0.287, 0.012)	(0.068, 0.208, 0.011)	(0.864, 0.478, 0.019)	(0.821, 0.336, 0.018)	(0.843, 0.413, 0.019)
S_6	(0.218, 0.223, 0.012)	(0.314, 0.242, 0.010)	(0.605, 0.372, 0.020)	(0.182, 0.390, 0.015)	(0.393, 0.381, 0.018)

To demonstrate the process behind the values in Table 16, we calculate SCP_1 and SCN_1, for example, as follows:

$$\begin{aligned} SCP_1 &= CWAA((0.200,0.443,0.014),(0.385,0.330,0.018),\cdots,(0.000,0.000,,0.000)) \\ &= (0.1956\times0.200+0.1823\times0.385+0.1851\times0.000+0.2010\times0.000+0.2360\times0.000, \\ &\sqrt{0.1956\times0.443^2+0.1823\times0.330^2+0.1851\times0.000^2+0.2010\times0.000^2+0.2360\times0.000^2}, \\ &\left.\sqrt{0.1956\times0.014^2+0.1823\times0.018^2+0.1851\times0.000^2+0.2010\times0.000^2+0.2360\times0.000^2}\right) \\ &= (0.109,0.241,0.010) \end{aligned}$$

$$\begin{aligned} SCN_1 &= CWAA((0.000, 0.000, 0.000), (0.000, 0.000, 0.000), \cdots, (0.300, 0.238, 0.013)) \\ &= (0.1956 \times 0.000 + 0.1823 \times 0.000 + 0.1851 \times 0.194 + 0.2010 \times 1.000 + 0.2360 \times 0.300, \\ &\sqrt{0.1956 \times 0.000^2 + 0.1823 \times 0.000^2 + 0.1851 \times 0.296^2 + 0.2010 \times 0.369^2 + 0.2360 \times 0.238^2}, \\ &\sqrt{0.1956 \times 0.000^2 + 0.1823 \times 0.000^2 + 0.1851 \times 0.016^2 + 0.2010 \times 0.020^2 + 0.2360 \times 0.013^2}\Big) \\ &= (0.308, 0.239, 0.013) \end{aligned}$$

Step 5. Normalize the weighted arithmetic averages by using Equations (25) and (26); the results are depicted in the right columns of Table 16.

For example, $NSCP_1$ and $NSCN_1$ can be obtained as follows:

$$NSCP_1 = \frac{(0.109, 0.241, 0.010)}{0.361} = (0.303, 0.402, 0.016),$$

$$NSCN_1 = 1 - \frac{(0.308, 0.239, 0.013)}{0.383} = (0.197, 0.386, 0.021).$$

Step 6. The cloud appraisal scores of the marine ranching sites are depicted in the last column of Table 16 and are obtained with the help of Equation (27) based on the arithmetic average of SCP_i and SCN_i.

We still use CAS_1 as an example:

$$\begin{aligned} CAS_1 &= \tfrac{(0.303,0.402,0.016)+(0.197,0.386,0.021)}{2} \\ &= \left(\tfrac{0.303+0.197}{2}, \sqrt{\tfrac{0.402^2+0.386^2}{2}}, \sqrt{\tfrac{0.016^2+0.021^2}{2}}\right) \\ &= (0.250, 0.394, 0.019). \end{aligned}$$

Step 7. In order to compare the cloud appraisal scores and determine the ranking of marine ranching sites, we generate cloud drops and calculate the expected score value for each alternative. With different numbers of cloud drops, the expected scores and final rankings are depicted as shown in Table 17. The results in Table 17 illustrate that, according to different numbers of cloud drops, the ranking of the alternatives by expected scores can be determined as: $S_5 \succ S_3 \succ S_4 \succ S_6 \succ S_2 \succ S_1$. Thus, S_5 should be selected as the best site to establish marine ranching. The cloud appraisal scores of the six alternatives are plotted as shown in Figure 7.

Table 17. The ranking with different numbers of cloud drops.

	S_1	S_2	S_3	S_4	S_5	S_6	Ranking
n = 5000	0.181	0.204	0.529	0.425	0.599	0.278	$S_5 \succ S_3 \succ S_4 \succ S_6 \succ S_2 \succ S_1$
n = 10,000	0.179	0.203	0.526	0.426	0.597	0.277	$S_5 \succ S_3 \succ S_4 \succ S_6 \succ S_2 \succ S_1$
n = 50,000	0.177	0.205	0.526	0.426	0.595	0.278	$S_5 \succ S_3 \succ S_4 \succ S_6 \succ S_2 \succ S_1$
n = 100,000	0.177	0.205	0.527	0.425	0.597	0.279	$S_5 \succ S_3 \succ S_4 \succ S_6 \succ S_2 \succ S_1$

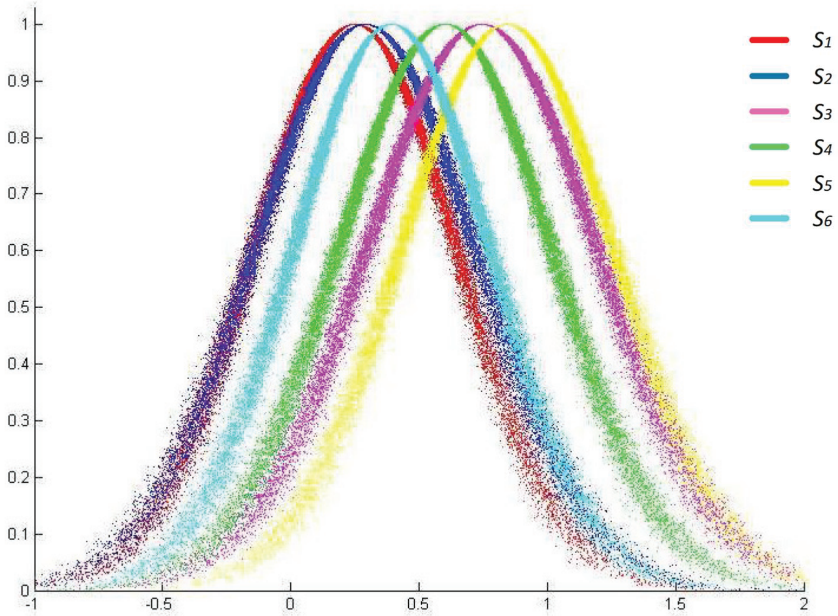

Figure 7. Cloud appraisal scores of six alternatives (with normalized universe $U = [0, 1]$ and $He_0 = 0.01$).

4.4. Comparison and Discussion

To illustrate the effectiveness and superiority of the proposed cloud model-based CRITIC-EDAS approach in this study, it is necessary to compare the proposed approach with some mature methods commonly used in existing studies and some newer methods for verification. In this paper, the same case is applied to the following multi-attribute group decision-making methods: linguistic TOPSIS [48], fuzzy VIKOR [49], probabilistic linguistic EDAS [44] and probabilistic linguistic MABAC [50], cloud TOPSIS [20] and cloud VIKOR [18]. The results obtained from different methods are shown in Table 18 and Figure 8.

Table 18. Comparison of the ranks of the alternatives according to different methods.

Alter.	L-TOPSIS	F-VIKOR	PL-MABAC	PL-EDAS	C-TOPSIS	C-VIKOR	Proposed Method
S_1	6	5	5	6	5	6	6
S_2	5	6	6	4	6	4	5
S_3	3	3	2	3	2	2	2
S_4	2	2	3	2	3	3	3
S_5	1	1	1	1	1	1	1
S_6	4	4	4	5	4	5	4

From Table 18 and Figure 8 we can find an accordant result that the alternative S_5 is always chosen as the optimal alternative in the marine ranching site selection problem, while there are some changes in the ranking of the other alternatives. According to the ranking results in Table 18, it is clear that S_3, S_4 and S_5 occupy the first three positions in the rankings of all the selected methods with S_5 as the optimal one, and S_1, S_2 and S_6 occupy the last three positions in the rankings of all the selected methods. Derived from L-TOPSIS, F-VIKOR and PL-EDAS, S_4 is superior to S_3 in the rankings; while all the cloud model-based models (C-TOPSIS, C-VIKOR and the proposed method) consider S_4 as inferior to S_3 in the rankings. It illustrates that, based on most traditional MADM methods, S_4 performs a little better than S_3 according to the evaluation among attributes, while by using cloud models, the fuzziness and randomness of the evaluation information are both considered. According to the cloud models, the evaluation information of S_3 contains lower fuzziness and randomness than that of S_4. Therefore, from the perspective of a cloud model, S_3 is better than S_4.

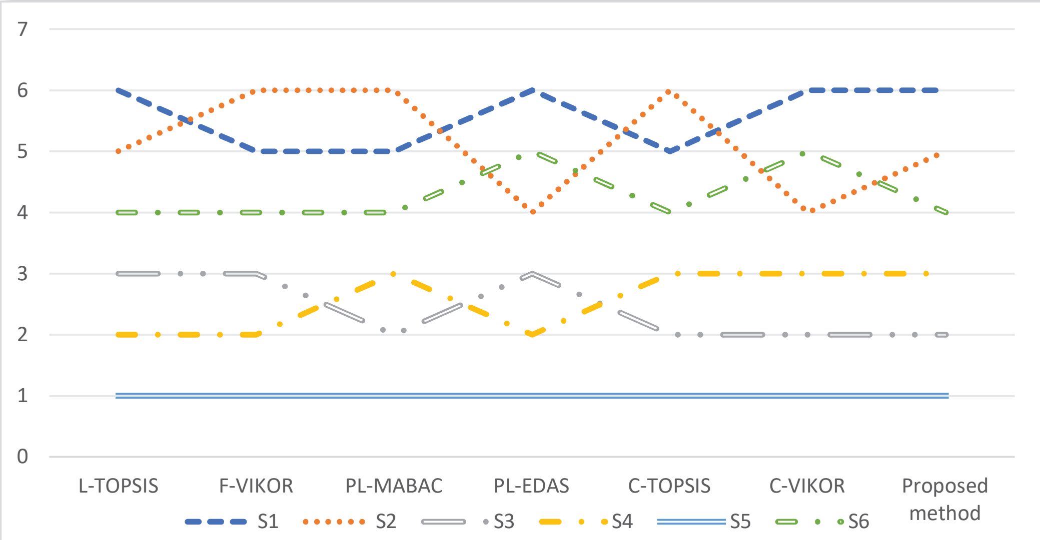

Figure 8. Rankings of alternatives among different methods.

In order to establish the connection between the results derived from different methods, ref. [51] used Spearman's correlation coefficient (SCC) as an indicator to interpret the relationship between two different approaches. So, in this paper, the pairwise comparison method SCC is used to obtain the statistical significance of the results of different methods and to verify the effectiveness of the proposed method. Table 19 represents the SCCs which show the connection between the results of the proposed method and the selected MADM models. There is a consensus that an SCC greater than 0.8 indicates a strong relationship between variables. The results in Table 19 depict that all of the SCCs between the proposed method and other selected MADM models are in the range of [0.886, 1], indicating the effectiveness and credibility of proposed method in this paper.

Table 19. SCCs of the ranks derived from different methods.

MADM Models	L-TOPSIS	F-VIKOR	PL-MABAC	PL-EDAS	C-TOPSIS	C-VIKOR	Proposed Method
L-TOPSIS	1.000	0.943	0.886	0.943	0.886	0.886	0.943
F-VIKOR	-	1.000	0.943	0.829	0.943	0.771	0.886
PL-MABAC	-	-	1.000	0.771	1.000	0.829	0.943
PL-EDAS	-	-	-	1.000	0.771	0.943	0.886
C-TOPSIS	-	-	-	-	1.000	0.829	0.943
C-VIKOR	-	-	-	-	-	1.000	0.943
Proposed method	-	-	-	-	-	-	1.000

5. Conclusions

The evaluation and selection of marine ranching sites has become a significant issue with the rapid develop of marine economy and great importance of marine ecology protection. This study introduces the cloud model to extend multi-attribute decision-making methods in order to help relevant planning authorities and enterprises determine the optimal sites for marine ranching construction.

To handle this issue, an integrated CRITIC-EDAS method based on the cloud model is developed. Firstly, the cloud model-based CRITIC method is formulated to determine the objective importance of the evaluation attributes for marine ranching site selection. Secondly, the cloud model-based EDAS is proposed to evaluate the alternatives and reveal the optimal marine ranching site. Thirdly, the proposed method is employed to solve a real-world practice of marine ranching site selection in the city of Yantai and it considers the fuzziness and randomness of data. Finally, the cloud model-based CRITIC-DEAS is compared with traditional decision-making methods to demonstrate the efficiency, reliability and superiority of the proposed model. The comparison analysis shows that the underlying principle behind the proposed model is acceptable to the managers and decision makers, as it is more suitable to reflect the characteristics of fuzziness and randomness of experts' preferences in the real-world marine ranching site selection process.

There are numerous advantages of this study. First, the cloud model is introduced to describe the fuzziness and randomness of the evaluation information in marine ranching site selection problems, and it proposes a novel manner in dealing with real-world decision-making problems by considering the uncertainty and probability simultaneously. Second, a novel multi-attribute decision-making approach named cloud model-based CRITIC-EDAS is developed, which is the first attempt to integrate CRITIC and EDAS with a cloud model to obtain the relative importance of attributes and the rank of alternatives from the perspective of probability. Thirdly, a real-world marine ranching site selection problem in the city of Yantai is solved by using the proposed model, where the efficiency and reliability are verified according to the comparison with other traditional MAMD methods.

However, there also inevitably exist some limitations of the proposed model. The model only considers the decision-making problems with linguistic terms, and various well-known MADM methods can also be extended with the cloud model. In future research, the study should be extended in several directions: (1) the transformation from many linguistic terms such as probabilistic linguistic terms, multi-granularity linguistic terms and probabilistic uncertain linguistic terms to clouds should be explored to expand the range of applications in real-world decision-making problems; (2) many traditional MADM methods, such as CCSD, ITARA, TODIM and CORPAS should be extended by using the cloud model to demonstrate the randomness of data and obtain more scientific results; (3) a theoretical extension of the cloud model should be taken into account in future studies by considering some classical probability and statistics theories, such as other distribution functions and Bayesian methods [52]. Referring to the application of the proposed model, it is potentially applicable to solve real-word multi-attribute decision-making problems in other research areas such as evaluation of sustainable transportation, renewable energy source selection, green supplier selection, evaluation of medical centers and so on. Another idea is to determine the clouds by using a backward cloud generator mentioned in Ref. [15], where the clouds can be generated directly from big data in real-world problems. For example, after collecting a massive amount of data with fuzziness and randomness during hydrologic monitoring, meteorological monitoring, equipment health monitoring, etc., clouds can be determined and processed by the proposed model to help governments or enterprises making valuable decisions for commercial value.

Author Contributions: Conceptualization, T.L. and M.S.; methodology, T.L. and M.S.; software, T.L.; validation, T.L.; formal analysis, T.L.; investigation, T.L.; resources, T.L.; data curation, T.L.; writing—original draft preparation, M.S.; writing—review and editing, M.S.; visualization, T.L.; supervision, T.L.; project administration, T.L. and M.S.; funding acquisition, T.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: Ming Sun was employed by the company Shandong Modern Fisheries Corporation. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Yu, J.K.; Ma, J.Q.; Liu, D. Historical evolution of marine functional zoning in China since its reform and opening up in 1978. *Ocean Coast. Manag.* **2020**, *189*, 105157. [CrossRef]

2. Yang, H.S. Construction of marine ranching in China: Reviews and prospects. *J. Fish. China* **2016**, *40*, 1133–1140.
3. Morita, K.; Saito, T.; Miyakoshi, Y.; Fukuwaka, M.-A.; Nagasawa, T.; Kaeriyama, M. A review of Pacific salmon hatchery programmes on Hokkaido Island, Japan. *ICES J. Mar. Sci.* **2006**, *63*, 1353–1363.
4. Loneragan, N.R.; Jenkins, G.I.; Taylor, M.D. Marine stock enhancement, restocking, and sea ranching in Australia: Future directions and a synthesis of two decades of research and development. *Rev. Fish. Sci.* **2013**, *21*, 222–236. [CrossRef]
5. Yang, H.; Ding, D. Marine ranching version 3.0: History, status and prospects. *Bull. Chin. Acad. Sci.* **2022**, *37*, 832–839.
6. Zhou, X.; Jie, Z.X.; Zhao Xu, Z.X.; Zhang, S.; Yu, Z.S.; Lin Jun, L.J. Marine ranching construction and management in East China Sea: Programs for sustainable fishery and aquaculture. *Water* **2019**, *11*, 1237. [CrossRef]
7. Valentine, J.F.; Heck, K.L.; Cinkovich, A.M. Impacts of seagrass food webs on marine ecosystems: A need for a broader perspective. *Bull. Mar. Sci.* **2002**, *71*, 1361–1368.
8. Shemshadi, A.; Shirazi, H.; Toreihi, M.; Tarokh, M.J. A fuzzy VIKOR method for supplier selection based on entropy measure for objective weighting. *Expert Syst. Appl.* **2011**, *38*, 12160–12167. [CrossRef]
9. Büyüközkan, G.; Ruan, D. Evaluation of software development projects using a fuzzy multi-criteria decision approach. *Math. Comput. Simul.* **2008**, *77*, 464–475. [CrossRef]
10. Xu, Z. Uncertain linguistic aggregation operators based approach to multiple attribute group decision making under uncertain linguistic environment. *Inf. Sci.* **2004**, *168*, 171–184. [CrossRef]
11. Wei, G.W. Uncertain linguistic hybrid geometric mean operator and its application to group decision making under uncertain linguistic environment. *Int. J. Uncertain. Fuzziness Knowl. Based Syst.* **2009**, *17*, 251–267. [CrossRef]
12. Wei, G.; Zhao, X. Some dependent aggregation operators with 2-tuple linguistic information and their application to multiple attribute group decision making. *Expert Syst. Appl.* **2012**, *39*, 5881–5886. [CrossRef]
13. Wan, S.P. 2-Tuple linguistic hybrid arithmetic aggregation operators and application to multi-attribute group decision making. *Knowl. Based Syst.* **2013**, *45*, 31–40. [CrossRef]
14. Wang, J.Q.; Peng, J.J.; Zhang, H.Y.; Liu, T.; Chen, X.H. An uncertain linguistic multi-criteria group decision-making method based on a cloud model. *Group Decis. Negot.* **2015**, *24*, 171–192. [CrossRef]
15. Li, D.; Liu, C.; Gan, W. A new cognitive model: Cloud model. *Int. J. Intell. Syst.* **2009**, *24*, 357–375. [CrossRef]
16. Yang, X.; Yan, L.; Zeng, L. How to handle uncertainties in AHP: The Cloud Delphi hierarchical analysis. *Inf. Sci.* **2013**, *222*, 384–404. [CrossRef]
17. Zadeh, L.A. The concept of a linguistic variable and its application to approximate reasoning—I. *Inf. Sci.* **1975**, *8*, 199–249. [CrossRef]
18. Li, C.B.; Qi, Z.Q.; Feng, X. A multi-risks group evaluation method for the informatization project under linguistic environment. *J. Intell. Fuzzy Syst.* **2014**, *26*, 1581–1592. [CrossRef]
19. Liao, N.; Gao, H.; Lin, R.; Wei, G.; Chen, X. An extended EDAS approach based on cumulative prospect theory for multiple attributes group decision making with probabilistic hesitant fuzzy information. *Artif. Intell. Rev.* **2023**, *56*, 2971–3003. [CrossRef]
20. Xu, X.; Xie, J.; Wang, H.; Lin, M. Online education satisfaction assessment based on cloud model and fuzzy TOPSIS. *Appl. Intell.* **2022**, *52*, 13659–13674. [CrossRef]
21. Mandal, S.; Khan, D.A. Cloud-CoCoSo: Cloud model-based combined compromised solution model for trusted cloud service provider selection. *Arab. J. Sci. Eng.* **2022**, *47*, 10307–10332. [CrossRef]
22. Deng, Z.; Huang, D.; Liu, J.; Mi, B.; Liu, Y. An assessment method for traffic state vulnerability based on a cloud model for urban road network traffic systems. *IEEE Trans. Intell. Transp. Syst.* **2020**, *22*, 7155–7716. [CrossRef]
23. Li, J.; Fang, H.; Song, W. Sustainable supplier selection based on SSCM practices: A rough cloud TOPSIS approach. *J. Clean. Prod.* **2019**, *222*, 606–621. [CrossRef]
24. Dhumras, H.; Bajaj, R.K. Modified EDAS method for MCDM in robotic agrifarming with picture fuzzy soft Dombi aggregation operators. *Soft Comput.* **2023**, *27*, 5077–5098. [CrossRef]
25. Li, X.; Zhou, S.; Zhao, Y.; Wan, G. A CRITIC-TOPSIS and optimized nonlinear grey prediction model: A comparative convergence analysis of marine economic resilience. *Expert Syst. Appl.* **2024**, *236*, 121356. [CrossRef]
26. Bilişik, Ö.N.; Duman, N.H.; Taş, E. A novel interval-valued intuitionistic fuzzy CRITIC-TOPSIS methodology: An application for transportation mode selection problem for a glass production company. *Expert Syst. Appl.* **2024**, *235*, 121134. [CrossRef]
27. Wang, S.; Wei, G.; Lu, J.; Wu, J.; Wei, C.; Chen, X. GRP and CRITIC method for probabilistic uncertain linguistic MAGDM and its application to site selection of hospital constructions. *Soft Comput.* **2022**, *26*, 237–251. [CrossRef]
28. Mishra, A.R.; Chen, S.M.; Rani, P. Multicriteria decision making based on novel score function of Fermatean fuzzy numbers, the CRITIC method, and the GLDS method. *Inf. Sci.* **2023**, *623*, 915–931. [CrossRef]
29. Kahraman, E.C. A novel picture fuzzy CRITIC & REGIME methodology: Wearable health technology application. *Eng. Appl. Artif. Intell.* **2022**, *113*, 104942.
30. Zhang, H.; Bai, X.; Hong, X. Site selection of nursing homes based on interval type-2 fuzzy AHP, CRITIC and improved TOPSIS methods. *J. Intell. Fuzzy Syst.* **2022**, *42*, 3789–3804. [CrossRef]
31. Keshavarz Ghorabaee, M.; Zavadskas, E.K.; Olfat, L.; Turskis, Z. Multi-criteria inventory classification using a new method of evaluation based on distance from average solution (EDAS). *Informatica* **2015**, *26*, 435–451. [CrossRef]
32. Torkayesh, A.E.; Deveci, M.; Karagoz, S.; Antucheviciene, J. A state-of-the-art survey of evaluation based on distance from average solution (EDAS): Developments and applications. *Expert Syst. Appl.* **2023**, *221*, 119724. [CrossRef]

33. Ghorabaee, M.K.; Zavadskas, E.K.; Amiri, M.; Turskis, Z. Extended EDAS method for fuzzy multi-criteria decision-making: An application to supplier selection. *Int. J. Comput. Commun. Control.* **2016**, *11*, 358–371. [CrossRef]
34. Güneri, B.; Deveci, M. Evaluation of supplier selection in the defense industry using q-rung orthopair fuzzy set based EDAS approach. *Expert Syst. Appl.* **2023**, *222*, 119846. [CrossRef]
35. Li, Q.; Rong, Y.; Pei, Z.; Ren, F. A novel linguistic decision making approach based on attribute correlation and EDAS method. *Soft Comput.* **2023**, *27*, 7751–7771. [CrossRef]
36. Simić, V.; Milovanović, B.; Pantelić, S.; Pamučar, D.; Tirkolaee, E.B. Sustainable route selection of petroleum transportation using a type-2 neutrosophic number based ITARA-EDAS model. *Inf. Sci.* **2023**, *622*, 732–754. [CrossRef]
37. Qin, K.; Xu, K.; Liu, F.; Li, D. Image segmentation based on histogram analysis utilizing the cloud model. *Comput. Math. Appl.* **2011**, *62*, 2824–2833. [CrossRef]
38. Liu, H.C.; Li, Z.; Song, W.; Su, Q. Failure mode and effect analysis using cloud model theory and PROMETHEE method. *IEEE Trans. Reliab.* **2017**, *66*, 1058–1072. [CrossRef]
39. Wang, J.Q.; Peng, L.; Zhang, H.Y.; Chen, X.H. Method of multi-criteria group decision-making based on cloud aggregation operators with linguistic information. *Inf. Sci.* **2014**, *274*, 177–191. [CrossRef]
40. Wu, Y.; Chen, K.; Zeng, B.; Yang, M.; Geng, S. Cloud-based decision framework for waste-to-energy plant site selection—A case study from China. *Waste Manag.* **2016**, *48*, 593–603. [CrossRef]
41. Wang, J.Q.; Yang, W.E. Multiple criteria group decision making method based on intuitionistic normal cloud by Monte Carlo simulation. *Syst. Eng. Theory Pract.* **2013**, *33*, 2859–2865. (In Chinese)
42. Li, J.; Fang, H.; Song, W. Modified failure mode and effects analysis under uncertainty: A rough cloud theory-based approach. *Appl. Soft Comput.* **2019**, *78*, 195–208. [CrossRef]
43. Xu, Z. Deviation measures of linguistic preference relations in group decision making. *Omega* **2005**, *33*, 249–254. [CrossRef]
44. Liu, H.C.; Wang, L.E.; Li, Z.; Hu, Y.P. Improving risk evaluation in FMEA with cloud model and hierarchical TOPSIS method. *IEEE Trans. Fuzzy Syst.* **2018**, *27*, 84–95. [CrossRef]
45. Diakoulaki, D.; Mavrotas, G.; Papayannakis, L. Determining objective weights in multiple criteria problems: The critic method. *Comput. Oper. Res.* **1995**, *22*, 763–770. [CrossRef]
46. Székely, G.J.; Bakirov, R.N.K. Measuring and Testing Dependence by Correlation of Distances. *Ann. Stat.* **2007**, *35*, 2769–2794. [CrossRef]
47. Krishnan, A.R.; Kasim, M.M.; Hamid, R.; Ghazali, M.F. A modified CRITIC method to estimate the objective weights of decision criteria. *Symmetry* **2021**, *13*, 973. [CrossRef]
48. Pei, Z. A note on the TOPSIS method in MADM problems with linguistic evaluations. *Appl. Soft Comput.* **2015**, *36*, 24–35. [CrossRef]
49. Sanayei, A.; Mousavi, S.F.; Yazdankhah, A. Group decision making process for supplier selection with VIKOR under fuzzy environment. *Expert Syst. Appl.* **2010**, *37*, 24–30. [CrossRef]
50. Wei, G.; Wei, C.; Wu, J.; Wang, H. Supplier selection of medical consumption products with a probabilistic linguistic MABAC method. *Int. J. Environ. Res. Public Health* **2019**, *16*, 5082. [CrossRef]
51. Pamučar, D.; Petrović, I.; Ćirović, G. Modification of the Best–Worst and MABAC methods: A novel approach based on interval-valued fuzzy-rough numbers. *Expert Syst. Appl.* **2018**, *91*, 89–106. [CrossRef]
52. Thapa, S.; Lomholt, M.A.; Krog, J.; Cherstvy, A.G.; Metzler, R. Bayesian analysis of single-particle tracking data using the nested-sampling algorithm: Maximum-likelihood model selection applied to stochastic-diffusivity data. *Phys. Chem. Chem. Phys.* **2018**, *20*, 29018–29037. [CrossRef]

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Advancing Marine-Bearing Capacity and Economic Growth: A Comprehensive Analysis of Blue Economy Resilience, Network Evolution, and Technological Influences in China's Coastal Areas

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Abstract: This study presents a groundbreaking approach to evaluating the resilience of China's blue economy, shedding light on its critical role in promoting sustainable development along the nation's coastlines. By employing advanced methodologies such as social network analysis and the time-varying effect random graph model (TERGM), our research meticulously examines the period from 2007 to 2019. It uncovers the complex dynamics of resilience, focusing on the adversities of unbalanced growth and pinpointing pivotal factors which shape this resilience, including the stability of the marine economy, the rigor of environmental regulations, and the impact of technological progress. Through a strategic compilation of indicators, our analysis offers a detailed perspective on the multi-faceted nature of blue economy resilience. The outcomes underscore the necessity of enhancing network effectiveness and implementing specific measures to encourage sustainable expansion in coastal domains. Leveraging these insights, we advocate for targeted strategies to refine the resilience network's framework, aiming to bolster the sustainable evolution of marine economic activities. This study not only deepens the understanding of marine economic resilience but also charts a course for achieving a resilient and sustainable blue economy. It stands as an indispensable guide for policymakers and scholars in the realm of marine economics, offering a blueprint for navigating the challenges and opportunities within this vital sector.

Keywords: blue economy; resilience; social network analysis; TERGM

1. Introduction

With China's strategic emphasis on becoming a maritime power, the marine economy has emerged as a crucial driver of global economic expansion. This strategy advocates for a sustainable blue economy, highlighting the importance of marine ecological preservation alongside economic advancement. Yet, the evolution of globalization presents dual challenges. On one side, reliance on expansive development and the adverse effects of climate change-induced marine disasters have significantly compromised marine ecological integrity, hindering sustainable progress. On the other hand, mounting global uncertainties, including economic trade tensions and geopolitical disputes, have markedly decelerated marine economic growth. Within this global scenario, bolstering the blue economy's resilience and enhancing its network cohesion to effectively navigate and thrive amid crises and volatility are paramount. Achieving this goal necessitates comprehensive policy coordination, innovation in science and technology, and market integration on a global scale. Moreover, it entails a delicate balancing act between marine ecological conservation and economic expansion, aiming to elevate the global marine economy's quality of development and stimulate new momentum and pathways for worldwide economic growth.

The term "blue economy" gained prominence during a 2012 US Senate hearing, symbolizing the United States' commitment to leveraging this strategy as a pivotal element in solidifying their maritime dominance. At its heart, this strategy seeks a harmonious balance between economic advancement and the safeguarding of marine ecosystems, aspiring towards a marine economic framework which fosters both growth and ecological preservation (Griggs et al., 2013) [1]. The World Bank's interpretation of the blue economy underscores the critical role of sustainable marine resource utilization in spurring economic growth, enhancing livelihoods, and securing employment, all while preserving marine ecosystems' health (World Bank, 2017) [2]. Furthermore, Voyer et al. (2018) offer a comprehensive examination of the blue economy through the lenses of marine ecological resources, livelihoods, commerce, and innovation, contributing valuable insights to marine governance [3]. Despite these advancements, there remains a noticeable gap in geospatial research within the blue economy sphere. Doloreux (2017) [4] delves into marine agglomeration perspectives, whereas Garland et al. (2019) review the pertinent literature to delineate the blue economy's geographical dimensions, thereby facilitating further academic exploration in this arena [5].

The scope of blue economy research has broadened significantly in recent years, extending its reach from Europe and North America to embrace East Asia (Ebarvia, 2016 [6]), South Asia (Humayun, 2014 [7]; Sarker, 2018 [8]), and Southeast Asia (Sarker, 2018 [9]). This expansion not only underscores the growing global interest in the blue economy but also highlights the distinct challenges and opportunities that different regions encounter in fostering its growth. In China, the "maritime power strategy" has elevated the blue economy to a pivotal role in the nation's economic reform and pursuit of high-quality development, particularly in coastal regions. The development and refinement of a resilience network for the blue economy is seen as a crucial strategy for enhancing regional economic quality and navigating global adversities. An examination of the development traits of China's coastal blue economy resilience network and its determinants offers valuable insights to other nations and regions aiming to advance the sustainable growth of the global blue economy.

Recent scholarly work has delved deeply into the domain of economic resilience, offering valuable perspectives on mitigating the negative impacts of risk shocks on economic frameworks [10–14]. These investigations encompass a broad spectrum of economic systems, extending beyond terrestrial economies to increasingly encompass maritime domains, underscoring the escalating emphasis on the resilience of marine economies. The resilience of marine economies has emerged as a critical area of inquiry, paralleling the global shift towards sustainable marine resource utilization. Zhu et al. (2021) investigated the interplay between the resilience and efficiency of marine economies, employing a marine economy-specific resilience index derived from the marine GDP. This approach unveils novel insights into the marine economy's adaptive capabilities against external perturbations [15]. Furthermore, Wang & Wang (2019) developed a comprehensive resilience evaluation framework for marine economies, incorporating elements of robustness, recovery, reorganization, and renewal. This framework serves as a tool for assessing the marine economy's overall capacity to navigate diverse challenges [16]. Additionally, Wu & Li (2022) applied the entropy weight method to assess the resilience of China's marine economy, examining its spatial and temporal progression. Their findings not only highlight the regional disparities in China's marine economic resilience but also offer a scientific foundation for informed policymaking [17].

The advancements in these research endeavors underscore that the exploration of marine economic resilience has emerged as a pivotal intersection of environmental transformation, economic progression, and societal welfare. Through the development and application of varied resilience assessment metrics, scholars have been able to pinpoint critical factors influencing marine economic resilience. This includes evaluating the marine economy's resistance, recuperation, and adaptability to external disturbances, thereby offering both theoretical insights and practical guidance to foster the sustainable advancement of the marine economy. Moreover, as global marine economic activities escalate and the exploitation of marine resources intensifies, the study of marine economic resilience is poised to make a significant contribution. It aims to enhance our comprehension and fortification of the marine economic system's stability and sustainability, marking a crucial step towards a balanced integration of ecological conservation and economic development.

The existing scholars on this subject has predominantly concentrated on delineating the conceptual framework and gauging the extent of the blue economy or its resilience, seldom intertwining the two to delve into the determinants impacting the blue economy's resilience. Notably absent are cross-sectional analyses exploring developmental variances within the blue economy across coastal areas, alongside a marked scarcity in discourse adopting a network-centric viewpoint. Thus, the unique contributions of this article are illuminated through three primary dimensions. Firstly, by amalgamating the principles of the blue economy with those of resilience, this investigation meticulously charts the interaction between maritime and land-based dynamics, crafting a layered evaluative framework for the blue economy's resilience which spans systemic, dimensional, and indicator levels. This elaborate framework captures the core elements of the blue economy while thoroughly addressing the complex essence of resilience, thereby enriching the marine economy's appraisal with a more comprehensive and insightful exploration. Secondly, leveraging social network analysis, this study probes the structural nuances of China's blue economy resilience network, conducting both longitudinal and latitudinal assessments of resilience within diverse marine economic zones. This methodological progression furnishes a novel perspective and analytical toolset for unraveling the evolving dynamics within the blue economy's resilience network, enhancing our comprehension and strategic augmentation of sustainable marine economic frameworks. Thirdly, by employing the time-varying effect random graph model (TERGM), this research reveals the structural evolution and driving forces behind China's blue economy resilience network, offering a solid foundation of empirical evidence for subsequent inquiries, grounded in data integrity.

The architecture of this study is meticulously organized, presenting a clear and logical progression. The Section 2 introduces the theoretical foundations. In the Section 3, this paper delineates its research design, elaborating on the methodologies and data sources employed, thereby laying a solid foundation and offering a transparent framework for its readers. The Section 4 employs a statistical analysis to map out the resilience characteristics and distribution patterns of China's blue economy, highlighting regional disparities and specific resilience trends across different locales. The Section 5 delves into a comprehensive analysis of the social network underpinning the blue economy's resilience, crafting a detailed portrait of the network's evolution through the examination of individual, overall, and spatial structural dynamics. In the Section 6, this study leverages the time-varying effect random graph model (TERGM) to intensify the investigation into the drivers influencing the dynamics of China's blue economy resilience network, offering a scientific elucidation of the pivotal factors and mechanisms at play. The concluding Section 6 encapsulates the research findings and, drawing upon these insights, proposes nuanced policy recommendations aimed at fostering the synergistic advancement of blue economy resilience in China's coastal regions alongside the high-quality development of the marine economy. This comprehensive approach not only illuminates the intricacies of marine economic resilience but also charts a path forward for sustainable and robust development within this critical sector. In the Section 7 analyzes China's coastal blue economy's resilience from 2007 to 2019, highlighting fluctuating growth due to technological advancements and regional imbalances, with recommendations for optimizing network structure and enhancing ecological protection for sustainable development.

The distinctive value of this study is rooted in its novel research perspective and methodological approach. It introduces a fresh theoretical framework and analytical instruments for assessing and dissecting the resilience of the blue economy, extending beyond theoretical contributions to offer empirically grounded policy recommendations. These insights are aimed at aiding policymakers in fostering the sustainable progression and holistic management of the marine economy. By delving into the structure and dynamics of the blue economy's resilience network, this paper significantly augments the corpus of marine economics and resilience economics. Its contributions bear substantial theoretical and practical relevance, providing a robust foundation for guiding the high-quality advancement of the global marine economy. This blend of innovative analysis and practical application underscores this study's pivotal role in navigating the complexities of marine economic sustainability and resilience, marking a significant stride toward informed and effective economic policy and management in the marine sector.

2. Theoretical Foundations

2.1. Adaptive Theory

Adaptive theory, emerging from global climate governance [18], offers a nuanced lens for examining economic systems through the prism of resilience and adaptability. This theory is instrumental in dissecting a system's ability to respond to environmental shocks, self-regulate, and undergo innovative transformations. The cyclical model of system evolution—comprising exploitation, conservation, release, and reorganization stages [19]—provides a robust framework for understanding the dynamic interplay between economic activities and marine ecosystems within the blue economy. By situating economic systems as entities subject to adaptive processes and environmental systems as the adaptation's target, this theory underscores the necessity of harmonious co-evolution for sustainable marine development [20–22]. The incorporation of adaptive theory into blue economy research highlights the potential for resilience through adaptive management strategies, emphasizing the importance of responsive governance, regulatory frameworks, and innovation in fostering economic and environmental sustainability.

2.2. Vulnerability Theory

Vulnerability theory has expanded from its roots in natural disaster prevention [23] to become a cornerstone in economic resilience and sustainable science discourse. Within the context of the blue economy, this theory elucidates the dual nature of systems' attributes in terms of vulnerability and resilience. Vulnerability exposes a system's fragilities against external shocks, while resilience encompasses a system's inherent capacity for self-reorganization and controlled transformation post shock [24]. Applying vulnerability theory to the blue economy illuminates the critical need for strategies that mitigate vulnerabilities through enhanced resilience, thus ensuring the marine economy's stability and sustainability in the face of environmental and economic perturbations.

2.3. Theory of Creative Destruction

Schumpeter's theory of creative destruction [25] elucidates the pivotal role of innovation in economic renewal and growth. It posits that economic development is propelled by the cyclical process of innovation, leading to the disruption of old structures and the creation of new growth avenues. This theory's application to the blue economy suggests that external shocks, rather than solely having detrimental effects, can serve as catalysts for innovation and structural transformation, thereby opening new paths for economic development within marine sectors [26]. Creative destruction becomes an essential mechanism for resilience, driving the blue economy towards sustainable practices and innovative solutions which address both economic and environmental challenges.

2.4. Regional Economic Resilience Theory

The concept of regional economic resilience, integral to regional economics, offers valuable insights into the resilience of the blue economy. This theory focuses on the capacity of regional economic systems to resist, recover from, and adjust to external shocks. Resilience, in this context, emerges not as a reaction to external shocks but as a characteristic inherent to a regional economic system, shaped by its internal structure and dynamics [27–29].

Applying regional economic resilience theory to the blue economy emphasizes the significance of understanding regional disparities and strengths in marine economic activities. It advocates for a tailored approach to enhancing the resilience of marine economies by leveraging local advantages, fostering innovation, and strengthening regional cooperation and connectivity. This perspective encourages a nuanced analysis of marine economic systems, highlighting the role of spatial dynamics, regional policies, and community engagement in building a resilient blue economy.

2.5. Integrated Theoretical Analysis of the Blue Economy

(1) Adaptive Theory and the Blue Economy

Adaptive theory highlights the cyclical nature of economic and environmental systems, emphasizing the necessity for the blue economy to continually adapt to changing marine conditions, regulatory frameworks, and technological advancements. This theory underscores the importance of adaptability in ensuring the sustainability of marine economic activities, suggesting that the blue economy's resilience can be enhanced through adaptive management practices which anticipate and respond to environmental and economic shocks. By fostering an environment conducive to innovation and flexibility, the blue economy can evolve in harmony with marine ecosystems, ensuring long-term sustainability.

(2) Vulnerability Theory's Implications for the Blue Economy

Vulnerability theory brings to light the inherent susceptibilities within the blue economy, urging stakeholders to recognize and address these vulnerabilities to prevent systemic collapses in the face of external shocks. It suggests that a deep understanding of these vulnerabilities, combined with proactive resilience-building measures, can transform potential weaknesses into strengths. For the blue economy, this means not only safeguarding against environmental degradation and market fluctuations but also building a robust framework that supports economic stability, environmental conservation, and community well-being.

(3) The Role of Creative Destruction in the Blue Economy

The theory of creative destruction offers an optimistic perspective on the role of innovation and structural transformation within the blue economy. It posits that disruptions, whether from technological breakthroughs, policy shifts, or environmental crises, can serve as catalysts for renewing and strengthening marine economic systems. By embracing innovation and the restructuring of marine industries, the blue economy can generate new growth opportunities that align with sustainable practices, thus fostering a resilient economic structure which is better equipped to handle future challenges.

(4) Regional Economic Resilience and the Blue Economy

Regional economic resilience theory emphasizes the importance of localized strategies in enhancing the overall resilience of the blue economy. It recognizes that regions have unique economic structures, resource endowments, and environmental challenges that require tailored approaches to resilience building. By leveraging regional strengths and fostering inter-regional collaboration, the blue economy can enhance its capacity to withstand and recover from shocks, ensuring equitable growth and sustainability across different marine economic zones. This approach calls for integrated policies that consider the diverse needs and potentials of regions within the blue economy, encouraging innovation and investment in areas most likely to drive sustainable growth.

The integration of these theoretical perspectives offers a comprehensive understanding of the complexities and dynamics of the blue economy. It highlights the importance of adaptability, vulnerability mitigation, innovation, and regionalized strategies in building a resilient and sustainable blue economy. By drawing on insights from these theories, policymakers, researchers, and practitioners can develop more effective frameworks for managing marine resources, fostering economic growth, and ensuring environmental sustainability within the context of global and regional challenges.

3. Research Design

3.1. Study Area

In Figure 1, this study focuses on the expansive maritime economic zones of China, encompassing three principal marine economic circles: the northern marine economic circle, which integrates the Liaoning province, Tianjin city, the Hebei province, and the Shandong province; the eastern marine economic circle, comprising the Jiangsu province, Shanghai city, and the Zhejiang province; and the southern marine economic circle, including the Fujian province, the Guangdong province, the Guangxi Zhuang autonomous region, and the Hainan province. This delineation encapsulates a total of 11 coastal regions, providing a comprehensive geographic framework for our analysis (Figure 1). This geographical scope not only highlights the diversity and strategic importance of China's marine economic sectors but also sets the stage for an in-depth evaluation of marine economic resilience across these pivotal areas, thereby enriching this study's analytical breadth and depth.

Figure 1. Study area.

3.2. Data Sources and Processing

The dataset foundational to this study was meticulously gathered from a range of respected sources, including the China Marine Statistical Yearbook, the China Environmental Statistical Yearbook, and several bulletins on coastal environmental quality, ecological environment, and sea level. To maintain this analysis's integrity and continuity, we first addressed any missing data through interpolation, ensuring the dataset's completeness. We then utilized this comprehensive dataset to calculate critical indices that reflect the dynamics of the marine economy: the location entropy of the marine industry, the marine economy's green efficiency, and the marine industrial structure upgrading index. This rigorous methodology not only bolstered the credibility of our results but also deepened our understanding of the complex aspects of marine economic resilience, green efficiency, and industrial evolution. As a result, it provided a solid framework for assessing the sustainable development of China's marine economy, enhancing the precision and clarity of our findings.

The specific calculation methods for the additional individual indicators required are as follows.

The formula for calculating the locational entropy of marine industries is the following:

$$Q_i = \sum_{j=1}^{3} w_{ij} \frac{x_{ij}/y_i}{X_j/Y} \tag{1}$$

In Equation (1), x_{ij} represents the total output value of the *j*th marine industry in region *i*, X_j represents the national total output value of the *j*th marine industry, y_i represents the total production value of region *i*, Y represents the national total production value, and w_{ij} represents the weight of the *j*th marine industry in region *i* as a proportion of the total marine output value of region *i*.

The green efficiency of the marine economy is calculated based on the DEA model.

The formula for calculating the marine industry structure upgrade index is as follows:

$$SU_j = \sum_{j=1}^{3} w_{ij} j \tag{2}$$

In Equation (2), w_{ij} represents the weight of the *j*th marine industry in region *i* as a proportion of the total marine output value of region *i*, with the value of *j* ranging from 1 to 3.

3.3. Construction of the Indicator Evaluation System for the Resilience of the Blue Economy

The blue economy is a vital component of regional economies, and thus, the dimensions used to evaluate the resilience of regional economies are also applicable to the resilience of the blue economy. Building on the research of numerous scholars such as Martin and Sunley (2015) and Bristow and Healy (2017), this paper will characterize the resilience of the blue economy across four dimensions as follows (in Table 1): (1) Endurance and resistance capacity, which refers to vulnerability and risk resistance when facing external shocks. The marine environment has a certain ecological carrying capacity, but negative externalities from economic and social activities on the marine environment, along with losses from natural marine disasters, can bring external shocks to the complex system of the blue economy, increasing ecological pressure and risks, challenging its endurance and resistance capabilities. (2) Recovery and growth capacity, referring to the speed and extent of recovery after a shock. A rational industrial structure is the intrinsic drive to restore the original economic order, and a solid economic foundation guarantees steady growth of the blue economy. (3) Adaptation and adjustment capacity, the ability to adjust and adapt to the external environment after being impacted. Affected by external shocks, the blue economy system needs to respond through ecological environmental governance and marine environmental protection, reallocating blue economy resources to enhance its adaptation and adjustment capabilities. (4) Control and transformation capacity, the ability to create new development pathways. After adapting to a new external environment, the blue economy system will dynamically adjust, unleashing the vitality of the blue economy through strengthening marine science and technology and innovation capabilities, seeking new development pathways. Finally, this paper calculates the comprehensive index of the resilience of the blue economy in China's coastal regions from 2007–2019 based on the TOPSIS entropy weight method.

Table 1. Comprehensive evaluation system of the blue economy's resilience.

System	Dimensions	Indicators	Nature
Ability to withstand and resist	Stress on marine ecology	Proportion of excellent water quality in nearshore waters (%)	+
		Number of pollution sources monitored by direct discharge into the sea (item)	–
	Marine ecological risk	Change in sea level from the same period last year (mm)	–
		Direct economic losses from major marine disasters (100 million yuan)	–

Table 1. *Cont.*

System	Dimensions	Indicators	Nature
Recovery and growth capacity	The ability of the marine economy to increase stability	Per capita marine output (ten thousand CMY/person)	+
		Growth rate of marine economy (%)	+
		Port cargo throughput (million tons)	+
	Marine industry resilience	Location entropy of marine industry	+
		Green efficiency of marine economy	+
		Upgrading index of marine industrial structure	+
Ability to adapt and adjust	Ecological and environmental governance	Investment in pollution control projects (ten thousand CNY)	+
		Intensity of regional environmental regulation	+
	Marine environmental response	Number of marine-type nature reserves (number)	+
		Monitoring points in coastal waters (PCS)	+
Control and transformation ability	Marine science and technology strength	Number of employees in marine research institutions (persons)	+
		Income from marine science and technology funds (thousand CNY)	+
	Marine innovation capability	Number of marine science and technology projects (items)	+
		Number of patents granted by marine research institutions (pieces)	+

3.4. Construction of the Resilience Network of the Blue Economy

Our research employs an enhanced gravity model to quantify the spatial correlation strength among 11 regions regarding blue economy resilience between 2007 and 2019. This approach allows for a clearer depiction of regional interconnectivity in resilience within the blue economy, as illustrated in Equation (1).

$$K_{ij} = \frac{R_i \times R_j}{distance_{ij} / \left| G_i - G_j \right|} \tag{3}$$

where K_{ij} represents the spatial correlation strength of the resilience of the blue economy among the regions; R_i and G_i, respectively, represent the resilience level of the blue economy and the total output value of the marine economy in region i; R_j and G_j, respectively, represent the resilience level of the blue economy and the total output value of the marine economy in region j; $distance_{ij}$ represents the geographical distance between region i and region j; and the denominator is the marine economic distance between region i and region j, which is regarded as the modified distance coefficient in this paper.

Building on this foundation, our study constructs a spatial correlation matrix for blue economy resilience. We calculate the average value of each row in the matrix to establish a threshold. Coastal areas are designated as network nodes, with the strength of the blue economy's resilience among regions serving as the connecting edges. This process creates an initial correlation network for China's blue economy resilience. Utilizing the threshold method, we adjust the original network's edge weights. Values exceeding the threshold are assigned to represent the correlation strength of the blue economy's resilience among nodes, while values below the threshold are set to zero.

3.5. Analysis of Influencing Factors of Blue Economy Resilience Network

To delve deeper into the collaborative development strategies of China's blue economy resilience network, this study adopts a forward-thinking approach, utilizing the time exponential random graph model (TERGM). This model offers a novel way to pinpoint the factors influencing China's blue economy resilience network, overcoming the multicollinearity challenges inherent to conventional analysis methods and yielding more robust empirical results. Guided by the principles of discrete time Markov chains, we hypothesize that the network's configuration in any given period (t) is influenced by its configurations in preceding periods ($t-k$). Consequently, we have constructed a k-order Markov dependency TERG model, as detailed below:

$$P\left(N^t = n^t \middle| N^{t-k}, \ldots, N^{t-1}, \theta\right) = \frac{exp\left(\sum_h \theta_h g\left(N^t, N^{t-1}, \ldots, N^{t-K}\right)\right.}{c\left(\theta, N^{t-K}, \ldots, N^{t-1}\right)} \quad (4)$$

In the above formula, $P(\cdot)$ is the probability of the occurrence of network n observed in the N feasible network set, $c\left(\theta, N^{t-K}, \ldots, N^{t-1}\right)$ is the normalized constant to ensure that the probability is between 0 and 1, h is the factor that may affect the formation of a network relationship, $g(\cdot)$ is the network statistics corresponding to h, and θ_h is the coefficient vector of relevant influencing factors, the coefficient vector of relevant factors meet the test of statistical significance. It indicates that this variable is of great significance to the formation and construction of the resilience network of the blue economy. In this paper, TERGM will be used to test the impact of differences in marine economic stability enhancement capacity (EG), marine industrial structure (IS), environmental regulation intensity (ER), and marine science and technology strength (TEC) on the resilience network of the blue economy (in Tables 2 and 3).

Table 2. Model variable setting and calculation method.

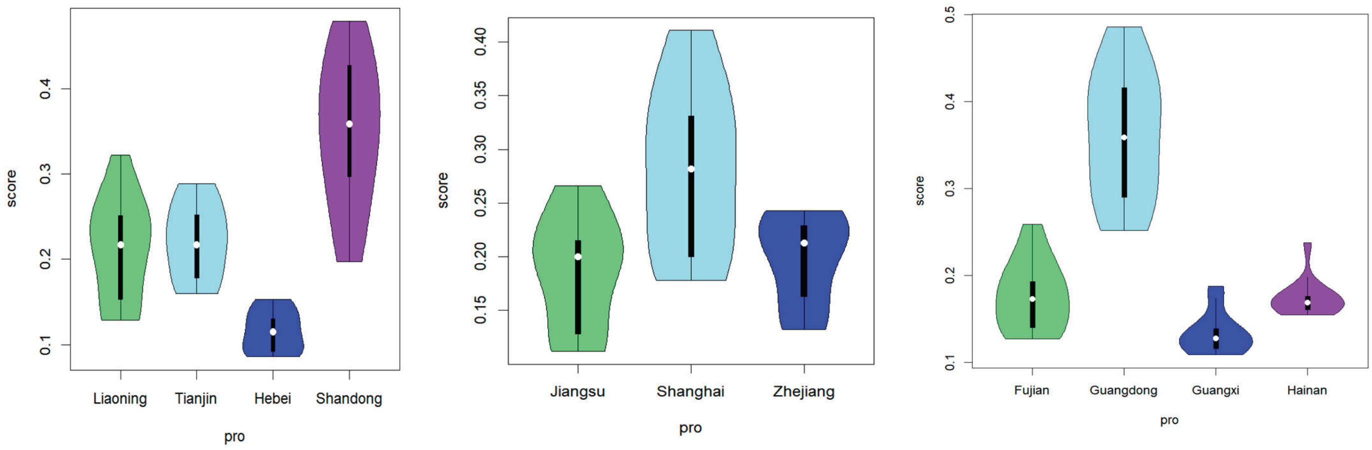
Model Statistics	Calculation Method
EG	Differences in marine economic growth rates between regions
IS	Difference in industrial structure upgrading index among regions
ER	Difference in intensity of environmental regulation between regions
TEC	Change value of the number of employees in marine research institutions between regions

Table 3. TERGM main variables and their meanings.

Category	Variable	Description
Endogenous structural variables	Edges	the edges of the network
	Nsp1	non-edgewise shared partners
	Cycle3	3-Cycle census
Network covariates	EG	Differences in growth rates of marine economy between regions
	IS	Difference in industrial structure upgrading index between regions
	ER	Difference in environmental regulation intensity between regions
	TEC	Change value of the number of employees in marine research institutions between regions

4. Evaluation Results of the Resilience of the Blue Economy

This paper, through constructing violin plots of blue economy resilience in coastal areas from 2007 to 2019 (Figure 2), aims to more intuitively display the statistical characteristics and distribution density of the blue economy's resilience in coastal regions. A violin plot is a combination of a box plot and a kernel density plot. The white dot in the plot represents the median of blue economy resilience, useful for comparing the average level of blue economy resilience across regions. The inner black box's upper and lower sides represent the upper and lower quartiles, respectively; a position higher up indicates an upward trend in resilience for that region. The length of the outer violin shell reflects the range of data fluctuation during the study period, with longer lengths indicating a broader range of fluctuation. The width of the outer violin shell reflects the probability density (i.e., kernel density) of the data distribution, with wider shells indicating a more concentrated distribution.



(**i**) Northern Marine Economic Circle (**ii**) Eastern Marine Economic Circle (**iii**) Southern Ocean Economic Circle

Figure 2. Violin plot of blue economic resilience in coastal areas from 2007 to 2019.

Overall, the resilience of the blue economy in China's coastal regions has grown amidst fluctuations. The continuously expanding scale of the marine economy, the increasingly optimized marine industrial structure, the steadily enhanced marine scientific and technological strength, and more proactive marine environmental responses have strengthened the growth and recovery capabilities, control and transformation capabilities, and adaptability and adjustment abilities of the blue economy. However, due to the imbalance in the development foundation and differences in the development positioning of the marine economy, there is a significant gap in the blue economy's resilience among provinces, with issues of uneven and insufficient growth still present.

Specifically, within the northern marine economic circle, Shandong's blue economy resilience median is higher than 0.3, significantly above other regions, and its violin plot length is longer, with the black box positioned higher up. This indicates that the region has a high level of blue economy resilience and a fast improvement rate. The kernel density curves for Liaoning, Tianjin, and Shandong are all "single-peaked", whereas Hebei's blue economy resilience level is far below that of other regions, with a "double-peaked" kernel density curve, indicating low and unstable resilience levels. The possible reason for this is Hebei's smaller marine economy scale, its marine industry still being in a more extensive development stage, and its insufficient marine innovation capabilities, resulting in lower scores for Hebei in terms of growth and recovery, control, and transformation capabilities. In the eastern marine economic circle, Shanghai's blue economy resilience median ranges between 0.25 and 0.3, slightly higher than in the area of Jiangsu–Zhejiang. Although the outer violin shell length is long, the inner black box is positioned lower, indicating a general downward trend in Shanghai's blue economy resilience. High-intensity socio-economic activities have increased marine ecological pressure, coupled with frequent marine disasters in recent years, leading to reduced scores in terms of resistance and resilience capabilities for regions like Shanghai. In the southern marine economic circle, Guangdong's blue economy resilience median is close to 0.4, significantly higher than Fujian, Guangxi, and Hainan. The latter three have their medians and black boxes positioned very low, with "single-peaked" kernel density distributions. Although the southern marine economic circle is known for its rich marine resources, there is still a significant development space. Apart from Guangdong, the scale of marine economic development in these areas is far lower than that of other regions in the same period, indicating a heavy task in developing the blue economy in the southern marine economic circle.

5. Social Network Analysis

5.1. Characteristics of Individual Network Structure

This study meticulously applies the principle of temporal symmetry to judiciously choose the starting, ending, and intermediate years for the sample period, employing the igraph package within R-4.2.3 software for an in-depth computation and analysis of the centrality within the blue economy resilience network across coastal areas in the years of 2007, 2013, and 2019 in Table 4. This analysis uncovers a pronounced core–periphery status in the network, highlighting the evolving dynamics and the intensity of inter-regional interactions within the coastal blue economy resilience framework. This approach not only delineates the structural nuances of the network but also sheds light on the shifting patterns of resilience and collaboration among coastal regions over time.

Table 4. Centrality characteristics of the blue economy resilience network in coastal areas (2007, 2013, and 2019).

Marine Economic Circle	Node	2007			2013			2019		
		Point Centrality	Betweenness Centrality	Proximity Centrality	Point Centrality	Betweenness Centrality	Proximity Centrality	Point Centrality	Betweenness Centrality	Proximity Centrality
Northern Marine Economic Circle	Liaoning	2	0.033	0.435	2	0.000	0.435	3	0.093	0.588
	Tianjin	2	0.000	0.370	3	0.000	0.435	3	0.000	0.400
	Hebei	2	0.000	0.370	3	0.000	0.435	3	0.000	0.400
	Shandong	7	0.459	0.556	9	0.445	0.667	7	0.370	0.588
Eastern Marine Economic Circle	Jiangsu	3	0.067	0.435	4	0.159	0.588	4	0.120	0.588
	Shanghai	6	0.319	0.500	7	0.169	0.588	5	0.037	0.476
	Zhejiang	2	0.000	0.345	3	0.000	0.435	5	0.209	0.625
Southern Ocean Economic Circle	Fujian	3	0.500	0.588	4	0.241	0.588	2	0.000	0.500
	Guangdong	5	0.378	0.455	7	0.387	0.500	8	0.437	0.625
	Guangxi	2	0.000	0.323	2	0.000	0.345	2	0.000	0.400
	Hainan	2	0.000	0.323	2	0.000	0.345	2	0.000	0.400

The analysis of nodal centrality reveals that Shandong, Shanghai, and Guangdong occupy pivotal roles within their respective marine economic circles, demonstrating significant influence and leadership. This suggests that these regions are central to the network of blue economy resilience, exerting a substantial radiating effect and holding commanding positions. Notably, Shanghai's nodal centrality has seen a decline in recent years, indicating a shift towards a more comparable standing with Zhejiang within the central marine economic circle. This change points to evolving dynamics of competition and collaboration within the network, highlighting the fluid nature of leadership and influence in the blue economy resilience framework.

From the viewpoint of betweenness centrality, there was a noticeable decline from 2007 to 2013 and 2019, suggesting a reduction in the network's polarizing tendencies and a more balanced distribution of influence among its nodes. Specifically, Shandong, Guangdong, and Shanghai maintained high levels of betweenness centrality across these periods, underscoring their significant control and pivotal roles as connecting hubs within the network. Conversely, regions such as Tianjin, Hebei, Guangxi, and Hainan consistently exhibit a betweenness centrality of zero, placing them in comparatively peripheral positions within the network. This dynamic highlights a shift towards a more equitable connectivity and interaction among regions, albeit with certain areas remaining less central in the overall structure.

The analysis of closeness centrality further reveals that, while regions like Liaoning, Zhejiang, Guangdong, Guangxi, and Hainan may not occupy leading positions within the network, they have consistently demonstrated an upward trajectory in this measure. This trend signifies an acceleration in the flow and exchange of blue economy resources across these areas. Notably, in 2019, the closeness centrality across coastal areas saw a general improvement, highlighting a significant enhancement in the mobility and interconnectivity of the entire blue economy resilience network. This advancement indicates a strengthened interaction among the nodes, thereby facilitating a more dynamic and responsive network structure. These insights not only shed light on the structural features and evolving patterns of the blue economy resilience network in coastal regions but also offer critical policy insights and strategic recommendations for further enhancing the network's architecture and elevating the resilience level of the blue economy in these areas.

5.2. Overall Network Structure Characteristics

Utilizing the igraph package within the R-4.2.3 software, this study comprehensively examines the structural characteristics of the blue economy resilience network in coastal regions, focusing on three key dimensions—network scale, density, and connectivity—as illustrated in Figure 3.

(**i**) network density (**ii**) clustering coefficient (**iii**) average path length

Figure 3. Overall network structure characteristics of China's blue economy resilience.

This research meticulously investigates the evolution of the blue economy resilience network within China's coastal regions from 2007 to 2019, crafting a detailed map of structural changes based on pivotal metrics such as network density, clustering coefficient, and average path length. The observed yearly variations and overall growth in network density underscore an intensification of connections within the blue economy's resilience across these coastal areas, particularly between 2013 and 2019. Despite a trend towards stabilization in the network's structure, the average network density remains at a modest 0.397, highlighting significant potential for enhancing collaborative efficiency within the blue economy resilience network.

The network clustering coefficient exhibits an inverted "W"-shaped trend, consistently remaining below that of a similarly scaled random network. This pattern underscores a low degree of clustering within the blue economy resilience network across coastal areas, indicating that the connections between the nodes are relatively sparse. This dispersion suggests that, while certain regions may engage in robust interactions within the blue economy sphere, overall, blue economic activities are predominantly focused around a few central nodes. This concentration prevents the emergence of a broad-based regional synergy, highlighting an area for potential enhancement to foster a more interconnected and collaborative blue economy network.

The analysis of the network's average path length indicates that the efficiency of information and resource dissemination within the coastal areas' blue economy resilience network is generally suboptimal. Notably, a slight upward trend post 2016 suggests a decline in the network's efficiency regarding the flow of resources and information in recent years. This trend may stem from factors such as the geographic distribution of marine economic activities, adjustments in the industrial structure, and shifts in the marine environment. These factors contribute to increased costs associated with emergency responses and resource allocation within the network. Particularly in the context of marine disasters and other urgent situations, the capability for rapid inter-regional response appears constrained.

In conclusion, while the blue economy resilience network in coastal areas has achieved a degree of structural stability, there remains substantial scope for enhancing its coordination, clustering, and transmission efficiency. Future efforts should aim to bolster inter-regional coordination within the blue economy, refine the network's architecture, and augment the efficiency of information and resource flows. By doing so, we can forge a more interconnected and efficient blue economy resilience network, thereby advancing the sustainable development of the blue economy in coastal regions.

5.3. Evolution Characteristics of Cyberspace Structure

To more vividly depict the spatial structure evolution of China's blue economy resilience network, this study employs the ggplot2 package in R to create spatial correlation networks for the years 2007, 2013, and 2019 [22] (in Figure 2). In these visualizations, the size of the network nodes represents the resilience level of the regional blue economy, while the thickness of the edges' connecting nodes indicates the strength of the resilience connections between regions.

While the thickness of the edges' connecting nodes indicates the strength of the resilience connections between regions.Drawing from an in-depth analysis of China's blue economy resilience network, this study uncovers the emergence of a distinctive spatial pattern characterized by "multi-point leadership and tri-regional coordination". This pattern highlights the dynamic development and unique features of the blue economy resilience network across China's coastal regions (in Figure 4).

(**i**) 2007 (**ii**) 2013 (**iii**) 2019

Figure 4. Spatial correlation network of China's blue economy resilience.

Firstly, the network's scale expansion and density increase signify a strengthening of connections within marine economic circles and a notable enhancement of the network's radiative effect. This evolution from sparse to dense connectivity not only bolsters the network's cohesion but also fosters inter-circle resilience in the blue economy, thereby reinforcing the coordinated development across the northern, eastern, and southern marine economic circles.

Secondly, the network's hierarchical structure is manifested through the radial dispersion of core nodes within the spatial layout, transitioning from Shandong–Shanghai–Guangdong to Shandong–Zhejiang–Guangdong. This shift indicates that Shanghai's marine ecological environment faces challenges due to intense socio-economic activities and frequent marine disasters, and, thus, its pivotal role in the blue economy resilience network is under threat. Meanwhile, Zhejiang has emerged as the new cornerstone of the eastern marine economic circle, attributed to its stable marine economic growth and efficient marine resource management.

Thirdly, the enhancement of network connectivity within distinct marine economic zones is evident in the notable performance of both the northern and southern marine economic sectors. Leveraging its robust marine scientific and technological capabilities, the northern marine economic zone consistently deepens integration, fosters the exchange and coordination of marine economic resources, and bolsters the gravitational pull among internal network nodes. Meanwhile, the southern marine economic zone capitalizes on its abundant marine resources, particularly centered around Guangdong, to significantly bolster its capacity for stability enhancement and industrial recovery within the marine economy. This strengthens its control and driving influence within the network, further accentuating the siphoning effect of its core node.

By employing a spatial framework characterized by multi-faceted leadership and coordination across the three regions, China's blue economy resilience network not only demonstrates the dynamic evolution of its internal architecture but also presents a fresh perspective and strategy for advancing high-quality development within coastal blue economies. Moving forward, prioritizing the enhancement and synchronization of inter-regional connections within the blue economy resilience network while optimizing its structural layout holds paramount importance for fostering the sustainable growth of China's marine economy and significantly bolstering the overall resilience of the blue economy.

6. TERGM Analysis

Building upon the preceding analysis, this paper has fundamentally elucidated the spatiotemporal evolution traits and spatial correlation structure of China's blue economy resilience network spanning from 2007 to 2019. Subsequently, this paper will proceed with a TERGM analysis, as per Equation (2), with the ensuing results being presented in Table 5. To ensure the robustness of the model fitting outcomes, MPLE (maximum pseudo-likelihood estimation) methodologies are employed in this study.

Table 5. TERGM analysis of China's blue economy resilience network.

Model Statistics	(1)
Edges	−0.99 *** (0.16)
Nsp1	0.11 ** (0.04)
Cycle3	−0.31 ** (0.11)
EG	0.98 *** (0.20)
IS	−0.47 * (0.21)
ER	0.58 ** (0.02)
TEC	−0.44 * (0.21)
Number of observations	143
AIC	746.91
BIC	778.36

Note: Values in parentheses are standard errors; ***, **, and * indicate significance at the 1%, 5%, and 10% level, respectively.

In this study, both estimation methods are employed to conduct a thorough analysis of the factors influencing the formation of the blue economy resilience network. The model's AIC and BIC values, both below 1000, signify high degrees of fit and explanatory capabilities. This outcome not only validates the chosen model's efficacy but also provides a scientific foundation for comprehending the pivotal factors shaping the construction of the blue economy resilience network.

The estimation outcomes of the model unveil the influence of numerous pivotal factors on the establishment of the blue economy resilience network [30–32].

Firstly, the variance in the stability enhancement capacity of the marine economy profoundly influences the establishment of the blue economy resilience network. This suggests that, within regions marked by substantial differences in their economic development levels, those experiencing swifter economic growth are notably appealing to regions with slower development rates. This "siphon effect" fosters resource flow between regions, hastening the cross-regional exchange and integration of blue economy resources.

Secondly, the coefficient of influence of the variance in marine industrial structure is negative, suggesting that a greater similarity in marine industrial structure between regions correlates with closer ties in the blue economy resilience network. This phenomenon likely stems from the fact that comparable industrial structures foster the convergence of capital, technology, and labor demands, thereby facilitating resource sharing and collaboration among regions.

Thirdly, the positive coefficient of influence regarding the variance in environmental regulation intensity suggests that regional disparities in regulatory stringency may prompt market players to relocate from regions with stricter regulations to those with more lenient ones. This not only affects resource allocation between regions but also influences the formation of the blue economy's resilience network.

Fourthly, the negative coefficient of influence pertaining to the variance in marine scientific and technological prowess underscores the fact that, when marine economic resources are heavily concentrated in certain developed regions, differences in marine scientific and technological capabilities among regions impede scientific and technological exchanges and cooperation. This scenario is detrimental to the construction and advancement of the blue economy's resilience network.

In conclusion, the disparities in the stability enhancement capacity of the marine economy, marine industrial structure, environmental regulation strength, and marine science and technology strength intricately shape the formation and progression of the resilience network within coastal blue economies. These insights not only offer policy directives for fostering the efficient construction of the blue economy's resilience network but also serve as crucial benchmarks for advancing blue economy collaboration and sustainable development within the marine economy [33].

Robustness Test

To ensure the robustness of the model fitting results, this paper will employ the following methods to re-conduct the TERGM analysis: (1) The estimation method of TERGM will be changed to MCMC MLE (Markov Chain Monte Carlo Maximum Likelihood Estimation), with the empirical results presented in column (2) of Table 6. (2) The time interval will be changed from 1 year to 3 years, with the criteria for edge selection remaining unchanged and the empirical results being shown in column (3) of Table 6. Then, (3) a complete binary processing of the dependent variable will be conducted, with the empirical results shown in column (4) of Table 6. It is not difficult to observe that the data in Table 6 and the baseline regression both demonstrate relatively consistent empirical results; hence, it is considered that the research conclusions of this paper are robust.

Table 6. TERGM analysis of China's blue economy resilience network.

Model Statistics	(2)	(3)	(4)
Edges	−0.31 *** (0.22)	−0.88 ** (0.29)	−0.65 *** (0.27)
Nsp1	0.22 ** (0.08)	0.03 (0.07)	0.21 ** (0.06)
Cycle3	0.13 (0.19)	−0.56 * (0.22)	−0.21 * (0.20)
EG	0.84 *** (0.19)	1.45 *** (0.34)	0.96 *** (0.23)
IS	−0.46 * (0.22)	−0.65 (0.38)	−0.54 * (0.26)
ER	0.49 * (0.19)	0.75 * (0.35)	0.50 * (0.22)
TEC	−0.28 (0.21)	−0.40 (0.37)	−0.43 * (0.22)
Number of observations	143	143	143
AIC	756.54	249.83	544.59
BIC	787.99	273.59	576.32

Note: Values in parentheses are standard errors; ***, **, and * indicate significance at the 1%, 5%, and 10% level, respectively.

7. Conclusions and Suggestions

7.1. Conclusions

This study systematically measures and deeply analyzes the resilience of the blue economy in China's coastal regions from 2007 to 2019, employing a comprehensive approach encompassing the entropy weight method, social network analysis, and the time series edge plot regression model (TERGM). Through these methodologies, this paper unveils the dynamic evolutionary process and influencing factors of the blue economy's resilience network, yielding the following key conclusions:

(1) Growth Trend and Challenges

Over the study period, the resilience of the blue economy in China's coastal regions exhibited a fluctuating growth trend, propelled by the expansion of the marine economy scale and advancements in marine scientific and technological capabilities. However, due to the imbalanced foundation of marine economic development and regional disparities in marine economic development strategies, growth within the marine economy remains uneven and insufficient. Particularly, regions such as Hebei and Guangxi display a low resilience, while Shanghai's blue economy resilience demonstrates a downward trajectory, highlighting challenges in marine economic development across certain regions.

(2) Analysis of Network Structure Characteristics

The individual structure of the blue economy's resilience network exhibits prominent core–periphery characteristics, with core regions like Shandong and Guangdong holding high degrees of centrality within the network, while Tianjin and Hebei consistently occupy peripheral positions. In recent years, the strengthening of regional indirect closeness centrality indicates an enhanced regional interconnectedness within the network, signifying a gradual improvement in the integration level of the blue economy's resilience network.

(3) Network Performance and Spatial Pattern

The rise in network density and expansion of the network scale signify the development of the blue economy's resilience network towards a closer and more extensive direction. Nonetheless, network agglomeration and transmission remain lower compared to a random network of a similar scale, indicating the need for enhanced flexibility and adaptability. Furthermore, the increase in network spatial correlation strength contributes to the spatial pattern of "multi-point leading, three-zone coordination", significantly enhancing interactions among diverse marine economic circles.

(4) Analysis of Influencing Factors

Variances in the stability enhancement capacity of the marine economy and marine industrial structure positively impact the formation of the blue economy's resilience network, while disparities in environmental regulation intensity and marine science and technology strength exert negative influences. This finding sheds light on pivotal factors driving the formation and development of the blue economy's resilience network, providing robust support for the formulation of pertinent policies and strategies.

In summary, this study not only offers insights into understanding and fortifying the resilience of the blue economy in China's coastal regions but also provides critical guidance for crafting strategies and policies aimed at promoting sustainable development within the marine economy. Moving forward, optimizing the network structure and enhancing the network performance of the blue economy's resilience network will be pivotal in driving high-quality development within coastal blue economies.

7.2. Suggestions

The aforementioned research findings hold significant implications for fostering resilient and coordinated development within China's coastal blue economy and promoting the high-quality development of the marine economy. Firstly, bolstering the coupling and coordination between marine economic growth and marine scientific and technological prowess stands as a pivotal strategy for enhancing blue economy resilience. Nurturing innovative marine scientific and technological talent, amplifying investments in basic and applied research within the marine domain, and facilitating the transformation and application of marine scientific and technological innovations can provide robust scientific and technological underpinnings for blue economy development [34].

Secondly, leveraging the first-mover advantage of core areas within the blue economy's resilience network and providing effective guidance and assistance to peripheral regions constitute effective approaches to realizing balanced development across coastal blue economies. Through industrial upgrading, innovation cooperation, and other initiatives, the status and role of peripheral regions within the network can be elevated, fostering the overall development and optimization of the blue economy's resilience network in coastal areas [35].

Moreover, safeguarding the marine ecological environment and enhancing the value of marine ecology are pivotal in constructing a healthy and stable blue economy resilience network. Strengthening marine ecological protection and restoration and enhancing the efficiency and efficacy of marine environmental governance can effectively bolster the resilience of the blue economy in coastal regions, ensuring strong support for its sustainable development.

Finally, clarifying the development positioning and comparative advantages of the three marine economic circles and establishing a flexible and diversified blue economy network pattern characterized by competitive disparities and complementary advantages are essential in realizing high-quality development within coastal blue economies. By solidifying the bridging role of regions such as Shandong and Guangdong and fostering communication and collaboration among different marine economic circles, the coordinated development of the blue economy's resilience network can be effectively promoted, ultimately enhancing the overall blue economy across China's coastal regions [36].

Through the implementation of these measures, not only can the internal connectivity and external interaction of the blue economy resilience network in coastal areas be strengthened, but also efficient collaboration and high-quality development of the marine economy can be advanced, laying a robust foundation for achieving the strategic objective of maritime prowess.

Author Contributions: Formal analysis, T.W. and L.Y.; investigation, K.-s.M.; resources, T.W. and K.-s.M.; data curation, D.D. and L.Y.; writing—original draft, T.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the [National social science fund of China], with grant number [23BGJ027].

Data Availability Statement: The data that support the findings of this study are openly available on http://www.stats.gov.cn/sj/ accessed on 1 January 2007.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Griggs, D.; StaffordSmith, M.; Gaffney, O.; Rockstrom, J.M.; Ohman, M.C.; Shyamsundar, P.W.; Steffen; Glaser, G.; Kanie, N.; Noble, I. Sustainable development goals for people and planet. *Nature* **2013**, *495*, 305–307. [CrossRef] [PubMed]
2. World Bank. *The Potential of the Blue Economy: Increasing Long-Term Benefits of the Sustainable Use of Marine Resources for Small Island Developing States and Coastal Least Developed Countries*; World Bank: Washington, DC, USA, 2017.
3. Voyer, M.; Quirk, G.; McIlgrom, A.; Azmi, K. Shades of blue: What do competing interpretations of the blue economy mean for oceans governance? *J. Environ. Policy Plan.* **2018**, *20*, 595–616. [CrossRef]
4. Doloreux, D. What is a maritime cluster? *Mar. Policy* **2017**, *83*, 215–220. [CrossRef]
5. Garland, M.; Axon, S.; Graziano, M.; Morrissey, J.; Heidkamp, C.P. The blue economy: Identifying geographic concepts and sensitivities. *Geogr. Compass* **2019**, *13*, e12445. [CrossRef]
6. Ebarvia, M.C.M. Economic assessment of oceans for sustainable blue economy development. *J. Ocean Coast. Econ.* **2016**, *2*, 2. [CrossRef]
7. Humayun, A.; Zafar, N. Pakistan's 'blue economy': Potential and prospects. *Policy Perspect.* **2014**, *11*, 57–76.

8. Sarker, S.; Bhuyan, M.A.H.; Rahman, M.M.; Islam, M.A.; Hossain, M.S.; Basak, S.C.; Islam, M.M. From science to action: Exploring the potentials of blue economy for enhancing economic sustainability in Bangladesh. *Ocean Coast. Manag.* **2018**, *157*, 180–192. [CrossRef]
9. Gamage, R.N. Blue economy in Southeast Asia: Oceans as the new frontier of economic development. *Marit. Aff. J. Natl. Marit. Found. India* **2016**, *12*, 1–15. [CrossRef]
10. Reggiani, A.; De Graaff, T.; Nijkamp, P. Resilience: An Evolutionary Approach to Spatial Economic Systems. *Netw. Spat. Econ.* **2002**, *2*, 211–229. [CrossRef]
11. Courvisanos, J.; Jain, A.K.; Mardaneh, K. Economic Resilience of regions under Crises: A Study of the Australian Economy. *Reg. Stud.* **2016**, *50*, 629–643. [CrossRef]
12. Gossling, S. Risks, Resilience, and Pathways to Sustainable Aviation: A COVID-19 perspective. *J. Air Transp. Manag.* **2020**, *89*, 101933. (In Chinese) [CrossRef]
13. Ntounis, N.; Parker, C.; Skinner, H.; Steadman, C.; Warnaby, G. Tourism and Hospitality Industry Resilience during the Covid-19 Pandemic: Evidence from England. *Curr. Issues Tour.* **2020**, *25*, 46–59. [CrossRef]
14. Zhu, W.; Li, B.; Han, Z. Synergistic analysis of the resilience and efficiency of China's marine economy and the role of resilience the policy. *Mar. Policy* **2021**, *132*, 104703, ISSN 0308-597-x. [CrossRef]
15. Wang, Z.Y.; Wang, Y.X. Spatial and temporal differentiation and influencing factors of the marine economy resilience in China. *Econ. Geogr.* **2019**, *39*, 139–145.
16. Wu, J.; Li, B. Spatio-temporal evolutionary characteristics and type classification of marine economy resilience in China. *Ocean Coast. Manag.* **2022**, *217*, 106016, ISSN 0964-5691. [CrossRef]
17. Martin, R.; Sunley, P. On the Notion of Regional Economic Resilience: Conceptualization and Explanation. *J. Econ. Geogr.* **2015**, *15*, 1–42. [CrossRef]
18. Smit, B.; Burton, I.; Klein, R.J.T.; Street, R. The science of adaptation: A framework for assessment. *Mitig. Adapt. Strateg. Glob. Change* **1999**, *4*, 199–213. [CrossRef]
19. Holling, C.S.; Gunderson, L.H. *"Resilience and Adaptive Cycles", Panarchy: Understanding Transformations in Human and Natural Systems*; Island Press: Washington, DC, USA, 2001; pp. 25–62.
20. Holbrook, N.J.; Johnson, J.E. Climate change impacts and adaptation of commercial marine fisheries in Australia: A review of the science. *Clim. Change* **2014**, *124*, 703–715. [CrossRef]
21. Mokrech, M.; Kebede, A.S.; Nicholls, R.J.; Wimmer, F.; Feyen, L. An integrated approach for assessing flood impacts due to future climate and socio-economic conditions and the scope of adaptation in Europe. *Clim. Change* **2015**, *128*, 245–260. [CrossRef]
22. Li, B.; Shi, Z.Y.; Tian, C.; Su, F.; Peng, F. Environmental adaptability evolution and early-warning of human-sea economic system in China. *Sci. Geogr. Sin.* **2019**, *39*, 533–540.
23. White, G.F. *Natural Hazards*; Oxford University Press: Oxford, UK, 1974.
24. Zhen, Y.; Qiyan, D.; Nian, W. Distribution characteristics of health vulnerability and its influence factors in China. *Sci. Geogr. Sin.* **2018**, *38*, 135–142.
25. Schumpeter, J.A. *Capitalism, Socialism, and Democracy*; Routledge: London, UK, 2013.
26. McDaniels, T.; Chang, S.; Cole, D.; Mikawoz, J.; Longstaff, H. Fostering resilience to extreme events within infrastructure systems: Characterizing decision contexts for mitigation and adaptation. *Glob. Environ. Change* **2008**, *18*, 310–318. [CrossRef]
27. Martin, R. Regional economic resilience, hysteresis and recessionary shocks. *J. Econ. Geogr.* **2012**, *12*, 1–32. [CrossRef]
28. Martin, R.; Sunley, P.; Gardiner, B.; Tyler, P. How regions react to recessions: Resilience and the role of economic structure. *Reg. Stud.* **2016**, *50*, 561–585. [CrossRef]
29. Martin, R.; Gardiner, B. The resilience of cities to economic shocks: A tale of four recessions (and the challenge of Brexit). *Pap. Reg. Sci.* **2019**, *98*, 1801–1832.
30. Bristow, G.; Healy, A. Innovation and Regional Economic Resilience. *Ann. Reg. Sci.* **2018**, *60*, 265–284. [CrossRef]
31. Shih, H.S.; Shyur, H.J.; Lee, E.S. An Extension of TOPSIS for Group Decision Making. *Math. Comput. Model.* **2007**, *45*, 801–813. [CrossRef]
32. Csardi, G.; Nepusz, T.; Traag, V.; Horvat Sz Zanini, F.; Noom, D.; Muller, K. The Network Analysis and Visualization in R. *arXiv* **2024**, arXiv:2402.18450.
33. Wickham, H. *ggplot2: Elegant Graphics for Data Analysis*; Springer: New York, NY, USA, 2016.
34. Wang, S.; Li, W.; Xing, L. A review on marine economics and management: How to exploit the ocean well. *Water* **2022**, *14*, 2626. [CrossRef]
35. Wang, T.; Wang, S.; Ding, W.; Guo, H. Can Technological Innovation and Financial Agglomeration Promote the Growth of Real Economy? Evidence from China. *Sustainability* **2023**, *15*, 15995. [CrossRef]
36. Yu, L.; Sun, Y.; Liu, X.; Wang, T. Does regional value chain participation affect global value chain positions? Evidence from China. *Econ. Res.-Ekon. Istraživanja* **2023**, *36*, 2108474. [CrossRef]

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Exploring Integrated Ocean Management Policy in China: Evolution, Challenges, and Prospects

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Abstract: Integrated ocean management (IOM) aligns with the United Nations' Sustainable Development Goals (SDGs) and serves as a crucial strategy for promoting the enduring health of marine ecosystems and the sustainable utilization of marine resources. An analysis of the evolution of China's integrated ocean management policy (IOMP) is crucial for providing valuable guidance in achieving sustainable growth in marine management and the marine economy for both China and other coastal nations worldwide. This paper studies the evolution characteristics, challenges, and prospects of IOMP in China since 1978 using content analysis. The findings indicate that the evolution of IOMP can be categorized into four stages: the germination period (1978–1998), the construction period (1999–2009), the systematization period (2010–2017), and the strategization period (2018–present), based on the state of international marine management. The IOMP has transitioned over time from its initial emphasis on resource development during the germination period to a strategization period that prioritizes the full development of all parts of the system. However, the ultimate goal has consistently been to achieve harmonious coexistence between people and the sea. China's IOMP has experienced a progressive development; nevertheless, it continues to encounter obstacles such as the pressing requirement to revise sea-related policies and the absence of policy alignment. The objective of this paper is to explore the evolution, challenges, and prospects of China's IOMP to better improve the land–sea coordination policy, strengthen international judicial cooperation. and provide effective policy reference for other maritime countries.

Keywords: integrated ocean management; management policy; maritime power; evolution; challenge

1. Introduction

The notion of marine territory in contemporary civilization emerged from the domain of international law, mostly as a result of conflicts between independent nations over the sovereignty of sea areas. The United Nations Convention on the Law of the Sea (UNCLOS), which was approved in 1982, established the boundaries of a nation's maritime territory, including internal seas, territorial seas, exclusive economic zones, and continental shelves, each of which grants the nation certain rights of sovereignty. The UNCLOS created a fundamental structure for the management of the world's oceans [1]. During the Roman era, the sea was considered a shared resource, providing citizens with established rights and liberties to utilize it. Initially, due to limited utilization, marine resources held little economic value. Nevertheless, in contemporary times, the ocean's significance as a bountiful ecosystem has increased, coinciding with people's quest for economic gain [2].

Claus et al. (2014) developed an online database of marine areas, cataloguing global marine geographical names and delineating boundaries of marine biogeographic regions and managed marine areas. This initiative aims to facilitate marine data management, research, and area governance [3].

As marine development and use continue to expand, there is a growing trend in various sea-related activities, such as reclamation. Consequently, issues such as the depletion of marine resources and environmental degradation are becoming increasingly prominent, exacerbating the scarcity of marine resources. Therefore, as early as the 1980s, experts and scholars advocated for the integrated management of marine ecosystems and their resources [4]. However, current marine governance still encounters numerous challenges, including the need to enhance the legal framework, address weak management and law enforcement, improve the efficiency of cross-sectoral collaboration, and establish mechanisms to mitigate interdepartmental conflicts [5]. The IOM approach aims to serve the overall maritime interests of a country. It seeks to achieve the sustainable utilization of marine resources, protect the marine environment, and develop the marine economy through comprehensive and coordinated management. This approach promotes the harmonious development of marine areas, balances the interests of all stakeholders, and fosters the growth of an environmentally friendly economy. Therefore, to address these challenges and achieve the goal of balancing short-term economic benefits with long-term ocean health, countries urgently need to adopt an integrated, ecosystem-based, and science-driven approach to ocean management.

The ocean is a vital component of the global ecosystem and a crucial resource for sustainable human development [6]. China's coastline, characterized by its winding nature, stretches for approximately 32,000 km. Among these, the mainland coastline spans about 18,000 km, while the coastal beach area covers roughly 196,000 km^2. Shallow sea regions with depths not exceeding 10 m encompass over 78,500 km^2, boasting abundant marine resources [7]. Within China, the sea area falls under the classification of marine territory, denoting marine blocks endowed with independent economic value, fixed geographical location, and definable coordinates [8]. The sea area serves as a foundational element for China's marine economy development and national rejuvenation. Consequently, efforts have been made to enhance the efficiency of sea area utilization, foster intensive and sustainable use practices, and optimize the economic, social, and ecological benefits derived from these areas. As a result, China's sea area management system has undergone gradual refinement. The law is the cornerstone of any system, and the stability and sustainability of such a system are ensured by law. The interdependent relationship of institutions, laws, and policies reflects the dynamic nature of the national superstructure, necessitating their collaboration to achieve social stability and development. The establishment of IOM laws and policies ensures the gradual improvement and steady advancement of IOM systems. The "Law of the People's Republic of China on the Administration of the Use of Sea Areas", enacted in 2002, delineated the paid use system for China's sea areas and introduced guidelines for asset-based sea area management. The "12th Five-Year Plan for the Development of National Marine Undertakings" in 2013 mandated activities such as conducting sea area value assessments and promoting the transfer of sea area use rights through bidding, auctions, and listing. In 2016, the "Law of the People's Republic of China on the Exploration and Development of Resources in the Deep Seabed Area" mandated contractors to utilize advanced technologies to mitigate the environmental impact of deep-sea development activities. In 2023, the "Notice of the Ministry of Natural Resources on Exploring and Promoting the Three-dimensional Stratification of Sea Areas" advocated for the implementation of three-dimensional stratification in sea areas, aiming to transition the sea area management paradigm from a "two-dimensional" plane to a "three-dimensional" approach. The exploration of the ocean should be anchored in the development and utilization of marine resources and space, with marine management serving as a crucial pillar for maritime development. Innovative approaches to marine management should span various fronts, including the legal framework governing sea area usage rights and the overhaul of marine systems and mechanisms, thereby enhancing the efficacy of marine governance [9].

China is one of the leading countries in promoting the idea of integrated sea area management on a worldwide scale. China has actively and systematically pursued the rational development and usage of marine resources since the concept's formal establishment in 1980, while also effectively protecting the maritime natural environment. This undertaking has involved tackling the overarching challenges in sea management and governance while promoting a comprehensive approach to marine governance. Concurrently, China has established a relatively comprehensive integrated management framework encompassing marine policies, laws, planning, and technical standards. Furthermore, there is a continued emphasis on capacity enhancement at national, provincial, and municipal levels to fortify the sea area's comprehensive management system [4]. This paper outlines the evolutionary characteristics of China's IOMP, delves into the challenges it encounters, and anticipates future policy trends.

The Blue Paper on Integrated Marine Management, commissioned by the High-level Panel on Sustainable Marine Economy, was prepared in Xiamen, China, and released on World Oceans Day 2023. In the fourth section, practical cases of IOM are presented, showcasing the integrated coastal zone management model of Xiamen to the global audience and sharing the challenges and experiences of Xiamen's integrated marine zone management [10]. Additionally, Xiamen International Ocean Week has become an annual international event for exchanging global ocean policies, science, technology, decisions, and actions [11]. The management of Yundang Lake has been incorporated into the "integrated coastal zone management" course as part of the Chinese government's foreign aid projects, providing training and experience sharing for over 100 developing countries worldwide. Furthermore, ecological and environmental agencies from the United States (US), Germany, South Korea, and other countries, as well as the European Union (EU), have visited Yundang Lake [11,12]. It holds pivotal significance in guiding the sustainable development of marine management and the marine economy in both China and coastal nations worldwide. Moreover, it stimulates a heightened worldwide focus on measures for governing the world's oceans, thus assisting in the advancement of sustainable practices for the marine environment. Ultimately, it advocates for the establishment of a global consensus on the shared future of the oceans, thus contributing to the achievement of a cohesive global community committed to the welfare of the oceans.

2. Literature Review

2.1. Research on the Paid Use of Sea Areas

As the global ocean economy continues to grow, the ocean has become a crucial driver of socio-economic growth in coastal regions. The marine domain, being a crucial component of the oceans and seas' natural resources, is considered both a public resource and a valuable asset of the State [13]. Therefore, it should be utilized in accordance with the law and subject to appropriate fees for its usage. With the continuous development of the global ocean economy, the ocean area has become an important vehicle for the socio-economic development of coastal areas. To achieve sustainability and conservation goals as described in Sustainable Development Goal 14 and the Marine Biodiversity of Areas Beyond National Jurisdiction (BBNJ), a combination of management tools is necessary [14]. The main reasons for the collection of marine royalties are to ensure the national ownership of marine resources, to collect the costs of marine development and restoration, and to optimize the area of marine use by increasing and adjusting the cost of marine use [15]. China's compensated use of sea areas dates back to the 1990s, promoting their market-oriented allocation to ameliorate efficiency and to achieve their intensive and economical use [16]. In 1993, the Ministry of Finance and the State Oceanic Administration (SOA) jointly issued the Interim Provisions on the Management of National Sea Area Use, which initially clarified the implementation of the sea area use certificate system and the system of paid use in China. In the same year, China implemented a marine royalty system. Marine royalty systems are considered to be an effective economic tool for securing the remunerative use of maritime areas, with the central feature being the establishment of a system of permits or licenses and fees for maritime use [17]. The Law of the People's Republic of China on the Administration of Sea Area Usage, which was formally implemented in 2002, for the first time clarified in law the property rights of sea areas and resources, the management system of remunerative use, and the system of marine functional zoning [18]. The rate of marine royalties is set at the governmental level. This has led to the beginning of the regularization of the remunerative management of the country's maritime areas.

2.2. Research on the Right to Use Sea Areas

After the establishment of the management system for the right to use the sea, more and more sea users demanded mortgages for the right to use the sea [19]. In 2006, the SOA issued the Provisions on the Administration of the Right to Use Sea Area, which for the first time explicitly referred to a contract for the transfer of the right to use sea areas. In 2007, China's Property Law made it clear that the right to use maritime areas acquired by the law is protected by law, confirming the status of the right to use maritime areas as a usufructuary right [18]. A maritime domain use management system based on maritime domain use rights was established. Li et al. (2019) proposed that the implementation of the management system for the compensated use of maritime areas in China is characterized by the following three features: large-scale compensated use of maritime areas, a rapid increase in the number of payments for the use of levied maritime areas, and an increasing proportion of payments for the right to use maritime areas obtained through market-oriented means [13]. Yu et al. (2023) demonstrated that the transaction system for sea use rights operates as a hierarchical framework within the boundaries of state ownership and the requirement for payment for sea usage and the functioning of the SUR transaction system depend on a combination of government and market mechanisms [20]. Xue et al. (2023) examined the use of IOM to achieve the sustainable development aim by focusing on the marine eco-environment foundation, market mechanism, management support, and space consideration [21]. Wang et al. (2021) investigated ways to enhance the productivity of the marine sector and promote the high-quality development of the marine economy through financial support using the framework of Integrated Land–Sea Management [22]. Wang et al. (2022) conducted a comprehensive review of the historical development and current research frontiers in different marine-related fields. They also identified the challenges in marine economic development and marine management processes. The objective was to find innovative solutions for transforming and upgrading marine development and to enhance the modernization of marine governance capacity [23].

2.3. Research on Reclamation Activities in Sea Areas

Stimulated by large populations and rapid economic growth, coastal areas have developed maritime facilities and coastal industries, thus contributing to the process of urbanization [24]. This growth has led to a shortage of land resources. Frequent outbreaks of marine disasters in the context of global warming pose a serious threat to the sustainable development of coastal areas and the construction of global maritime capitals [25]. The shorelines of beaches undergo dynamic changes due to the processes of coastal erosion, river inputs, and sea level rise [26]. Reclamation—creating new land in the ocean—is a common solution [27]. However, land reclamation can cause the degradation and loss of coastal ecosystems [28], which is also not conducive to the sustainable conservation and management of marine biodiversity [29]. It has been recognized that the integration of marine sciences and coastal management would generate better-formulated marine policies and viable policy implementation strategies which may be utilized to make a significant contribution to coastal management in various aspects [30]. Bai et al. (2024) pointed out that the construction of marine ecological security shelters upholds inter-regional and inter-departmental administrative barriers to the collaborative governance of the marine environment. To establish an effective collaborative governance model, it is essential to improve the structure and mechanism of governance [31]. Jiang and Guo (2023) proposed that the sustainable management of Marine Protected Areas on the high seas requires legal regimes to support them, though relevant regimes are still immature [32]. Li et al. (2023) showed that China is still in the early stages of developing marine ecological compensation mechanisms, and many problems have been exposed stemming from historical issues and from the institutions exerting strict control over sea reclamation [33]. Wang et al. (2023) considered that port reclamation management models, adaptation strategies to rising sea levels, and ecological compensation systems need to be improved [24]. To mitigate the negative impacts of reclamation, since the end of the 20th century, the Chinese government has issued a series of policies, regulations, and directives to regulate reclamation activities [33–36].

2.4. Literature Summary

The majority of the current literature on marine management in China concentrates on three topics: paid usage of marine areas, the right to use maritime zones, and reclamation activities. These works are categorized and summarized in Table 1. Despite extensive research on marine management, there remains a lack of comprehensive and systematic studies on IOMP. An in-depth examination of China's IOMP holds significant implications for national security, economic development, ecological protection, legal infrastructure, international cooperation, promotion of social awareness, and the summation of historical experiences.

Table 1. Summary of the related studies.

Field	Content	Example	Year	Contribution
Research on the paid use of maritime areas	Strengthening management	Joana et al. [14]	2023	Proposed that a combination of management tools is necessary to achieve sustainability goals.
	Marine royalties	Zhang [15]	2015	The main reason for the collection of marine royalties is to ensure the national ownership of marine resources.
	Marine royalty systems	Yue et al. [17]	2018	Considered marine royalty systems an effective economic tool for securing the remunerative use of maritime areas.
Research on the right to use maritime areas	Mortgage demand	Liu et al. [19]	2016	Demand for mortgages for the right to use the sea emerged after the establishment of a marine management system.
	Legal protection	Yang et al. [18]	2020	China's property law made it clear that the right to use maritime areas acquired by law is protected by law.
	Transaction systems	Yu et al. [20]	2023	Showed that the sea use rights transaction system is a tiered structure under the constraints of state ownership and paid use of the sea.
	Land–sea management	Xue et al. [21]	2023	Discussed IOM for meeting sustainable development goals.
	Maritime development	Wang et al. [22]	2021	Explored how to effectively improve the productivity of the marine industry.
	Review of frontiers	Wang et al. [23]	2022	Identified existing problems in the processes of marine economic development and marine management.

Table 1. *Cont.*

Field	Content	Example	Year	Contribution
Research on the reclamation activities in maritime areas	Improving management	Wang et al. [24]	2023	Considered that port reclamation management model, adaptation strategies to rising sea levels, and ecological compensation systems need to be improved.
	Sea threats	Sui et al. [25]	2022	Frequent outbreaks of marine disasters in the context of global warming pose a serious threat to sustainable development.
	Reclamation activities	Duan et al. [27]	2016	Reclamation—creating new land in the ocean—is a common solution.
	Legal regimes	Jiang and Guo [32]	2023	Proposed the sustainable management of Marine Protected Areas on the high seas requires legal regimes to support.
	Issued policies	Li et al. [33]	2023	Chinese government has issued a series of policies, regulations, and directives to regulate reclamation activities.

3. Evolution of Subjects Responsible for IOMP Formulation

Following the establishment of the People's Republic of China, China has placed significant emphasis on ocean development and utilization. The marine industry has undergone rapid growth, accompanied by the gradual enhancement of the maritime management system, which initially had minimal infrastructure. The reform of marine management institutions has progressed alongside advancements in the deepening of marine development and the deepening of the understanding of marine science. The evolution of the main body of China's IOMP can be roughly divided into four stages: (1) the establishment of the SOA in 1964; (2) institutional reform of the SOA in 1998; (3) reorganization of the SOA in 2013; (4) its incorporation into the Ministry of Natural Resources (MNR) in 2018. Pivotal time nodes of the evolution of the subjects responsible for the formulation of IOMP are depicted in Figure 1.

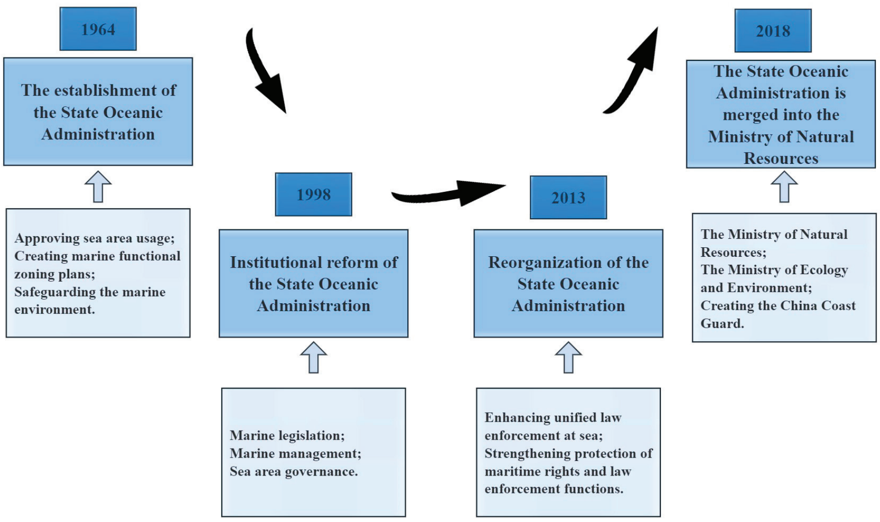

Figure 1. Evolution of the subjects responsible for IOMP formulation.

3.1. Establishment of the SOA

In May 1963, under the leadership of Yelie Yuan, head of the marine professional group of the State Science and Technology Commission, 29 experts convened to discuss and address the challenges facing marine development in China. They identified four critical issues: maritime safety, inefficient utilization of marine aquatic resources, limited understanding of seabed mineral distribution, and inadequate protection of marine rights and interests. As a solution, they proposed the establishment of the SOA. In February 1964, the State Council of the People's Republic of China (SCPRC) established the SOA to oversee marine affairs nationwide. Subsequently, in March 1965, the SCPRC approved the establishment of branches in the North Sea, East China Sea, and South China Sea, located in Qingdao, Ningbo, and Guangzhou, respectively. As the marine administrative body of the SCPRC, the SOA held a deputy ministerial-level position. Its responsibilities included approving sea area usage, creating marine functional zoning plans, and safeguarding the marine environment. The establishment of the SOA signified the initial establishment of China's IOM system.

3.2. Institutional Reform of the SOA

With the goal of streamlining staff structures, cutting down on the number of ministries and commissions, and merging institutions, the SCPRC launched a thorough institutional adjustment and reform in 1998. Aligned with this objective, the SOA was integrated into the State Bureau under the Ministry of Land and Resources. Its core functions encompassed marine legislation, management, and planning. At the time, China's "integrated management" model for sea area governance was further embodied in the SOA's 1998 institutional reform.

3.3. Reorganization of the SOA

The fragmentation and lack of coordinated management of China's many sea-related departments after the 1980s resulted in overlapping functions and powers, impeding the effective utilization of maritime regions [37]. To streamline functions, clarify responsibilities, enhance the system and its mechanisms, and improve administrative efficiency, China initiated institutional reforms of the SCPRC in line with the directives of the 18th National Congress of the Communist Party of China and the Second Plenary Session of the 18th Central Committee. One of these changes was reorganizing the SOA. The purpose of this reorganization was to enhance unified law enforcement at sea and improve enforcement efficiency. It strengthened marine right protection and law enforcement functions by combining several maritime law enforcement teams, including maritime surveillance, fishery administration, border guard, and maritime anti-smuggling teams. The restructured SOA continued to be overseen by the Ministry of Land and Resources.

3.4. SOA Merged into MNR

Attention gradually turned to the disadvantages of the fragmented management of land and sea, unclear division of responsibilities, and low management efficiency in the marine management system since the 18th and 19th National Congresses of the Communist Party of China advocated for the strategy of adhering to integrated land and sea planning and building maritime prowess [38]. In 2018, China underwent another round of reforms in its central-level marine administrative agencies. After the SOA was disbanded, the MNR was created to assume the majority of its previous duties. This involved managing natural resources, strategic planning, and the marine economy. The former SOA's oversight of marine environmental protection was transferred to the newly formed Ministry of Ecology and Environment. The SOA's maritime law enforcement responsibilities were taken over and the coast guard squad was placed under the command and supervision of the newly established China Coast Guard. This reform marks another significant step in China's marine management system.

As a component of the SCPRC, the MNR assumed the responsibilities previously held by the SOA of China, becoming the new national marine administrative department, a role it continues to hold. A new phase in China's sea area management system was marked by the reform of its marine management institutions, which represented a change in the country's marine management strategy from "comprehensive management" to "comprehensive and decentralized integration".

4. Evolution of the IOMP

4.1. Method

A quantitative, methodical, and objective way to describe communication material is content analysis. It was developed in the 1950s by the American researcher Berelson and is a method for quantitatively examining different data contents that are derived from qualitative research [39]. It addresses the subjectivity and uncertainty problems inherent in qualitative research by converting language-described content into data represented by quantities and interpreting the findings through statistical numbers [40]. This study employs content analysis to quantitatively analyze IOMP. Due to the non-quantifiability, complexity, and organization of content, IOMP must undergo systematic analysis through content analysis to avoid uncertainty [41], thus revealing its evolutionary characteristics.

We used keywords such as "integrated ocean management", "sea area use fee", and "reclamation" on various official websites such as those of the SCPRC, MNR, Ministry of Ecology and Environment of the People's Republic of China, etc., to obtain numerous policy samples, which were then downloaded for analysis, ensuring that the policy samples were representative. In the selection of samples, we considered their diversity and analyzed all policies related to ocean management to ensure that the samples reflected various aspects and characteristics of IOMP. To avoid subjectivity, we excluded content unrelated to IOM based on established professional vocabulary pertinent to the field. The retained content was then coded chronologically and classified according to the issuing body. There were numerous essential steps in the subsequent research process: First, after coding, classifying, and screening the policy samples according to the content and focus of the policy documents, the retained content was summarized to establish a database of Chinese IOM policy documents. Second, the policies were sorted chronologically by the year they were issued in and divided into four evolutionary stages based on changes in the status of IOM throughout the evolution process. Third, using word frequency statistics and social semantic network analysis of the text content, we analyzed the evolutionary characteristics and challenges of each stage and attempted to forecast future trends for China's IOMP.

4.2. Data

The policy samples for this study were sourced from official websites, including those of the SCPRC, MNR, Ministry of Ecology and Environment of the People's Republic of China, Ministry of Agriculture and Rural Affairs of the People's Republic of China, and Ministry of Justice of the People's Republic of China. For analysis, 76 national-level policy samples from 1978 onwards were chosen. This paper conducted searches on the official websites of coastal provinces and municipalities. Additionally, field research was carried out in Liaoning (Dalian), Shandong (Qingdao, Weihai, Yantai), Jiangsu (Lianyungang, Nantong), Shanghai, Zhejiang (Ningbo, Zhoushan), Fujian (Xiamen, Putian, Fuzhou), Guangdong (Guangzhou, Zhuhai), Guangxi Zhuang Autonomous Region (Beihai), and other coastal provinces and cities in China. Visits were made to provincial and municipal Marine and Fisheries Bureaus and to the First and Third Institute of Oceanography of the MNR. Investigations were conducted on marine-related enterprises to obtain relevant provincial and municipal IOMPs through engagement with government bodies, universities, research institutes, and enterprises. Due to data availability constraints, this study does not include relevant policies from coastal areas such as Hong Kong, Macao, and Taiwan.

The policy samples were processed in the following ways to enable a comprehensive examination of policy content during the investigation of China's IOMP's evolution. First, word frequency analysis was conducted, gathering and organizing the policy text for keyword frequency data using the ROSTCOM6 (Version 5.8.0.603) analysis software. Second, co-word analysis was performed by tallying the occurrences of each pair of keywords within a policy document, thus generating a policy co-word matrix. Subsequently, utilizing the social network analysis tool ROSTCOM6, a social network diagram depicting the co-word matrix of IOMP at each evolutionary stage was generated.

4.3. IOMP Evolution Stages

To comprehensively illustrate the evolution of sustainable IOMP, this paper categorizes the policy into four stages: the germination period (1978–1998), the construction period (1999–2009), the systematization period (2010–2017), and the strategization period (2018–present), as depicted in Figure 2.

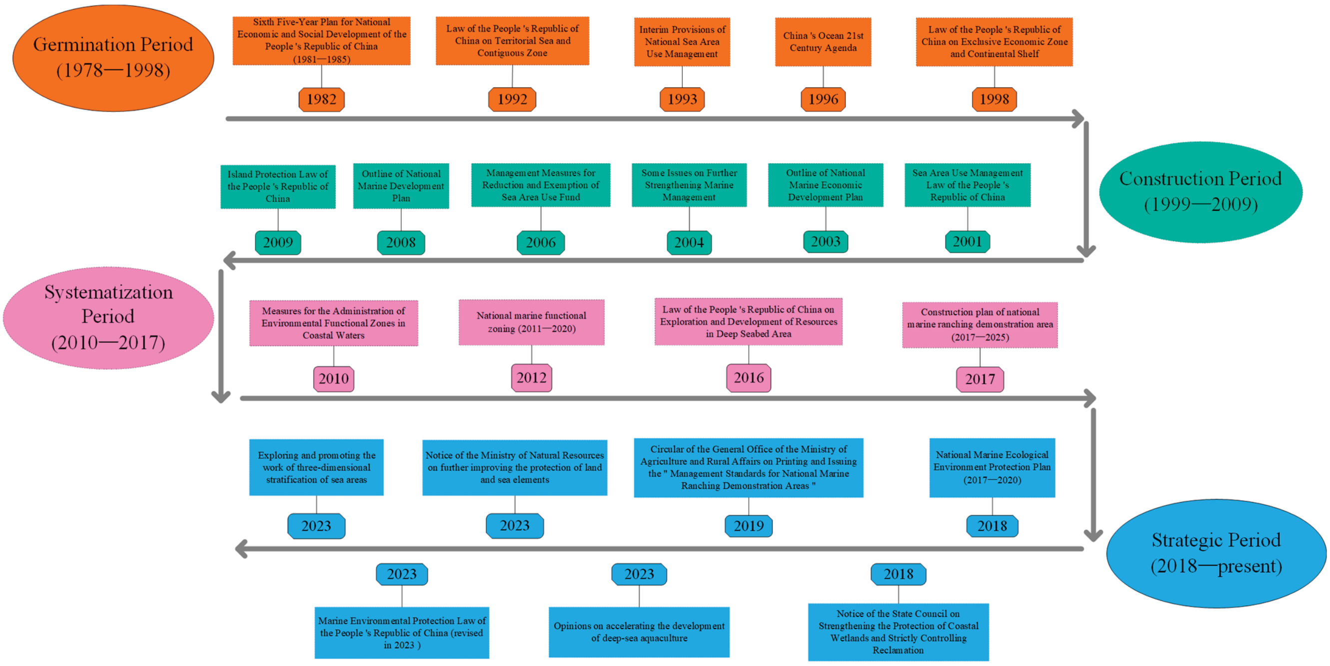

Figure 2. Descriptive statistics.

4.3.1. IOMP Germination Period (1978–1998)

The IOMP germination period can be traced back to the early years of China's reform and opening-up, particularly after 1978. During this period, China began to recognize the significance of its maritime territory and gradually established corresponding management policies and institutions. In the 1980s, China undertook a comprehensive survey of coastal zone and tidal flat resources nationwide, providing crucial data and information for subsequent sea area management policies. In 1982, the Chinese government issued the Sixth Five-Year Plan for the National Economic and Social Development of the People's Republic of China (1981–1985), aimed at conducting investigations and developing marine resources, while also laying the groundwork for marine development and utilization. China has enacted several key laws and regulations to support the implementation of IOMP, including the Law of the People's Republic of China on the Territorial Sea and Contiguous Zone, the Interim Provisions on the Administration of the Use of National Sea Areas, the Measures for the Administration of Marine Nature Reserves, and the Exclusive Economic Zone and Continental Shelf Law of the People's Republic of China. During this period, there were relatively few specific IOMPs, with more focus on the development of legal frameworks. These efforts gradually established a solid legal foundation for IOM, providing the groundwork for the formulation and execution of subsequent policies and regulations.

The ROSTCOM6 software was employed to analyze the titles and content of China's IOPM from 1978 to 1988. The statistical findings of keyword frequency are presented in Table 2. The term "management" was observed 25 times in the policy samples during this period, ranking second only to "ocean". Meanwhile, "development" appeared 17 times in the policy samples. Additionally, professional terms like "continental shelf" and "ships" were also identified, indicating a specialized focus on marine-related topics. Notably, there were minimal mentions of other management-related terms. These findings suggest that during this period, IOPMs were in their nascent stages, with primary attention directed towards resource development and sea area management.

Table 2. Keyword frequency statistics (1978–1998).

Serial	Keywords	Word Frequency	Serial	Keywords	Word Frequency
1	Ocean	63	6	Ships	8
2	Management	25	7	Use sights	5
3	Development	17	8	Fisheries	4
4	Continental shelf	10	9	Exploration	3
5	Demonstration area	10	10	Breeding	2

The social and semantic network analysis of the keyword matrix for this period is illustrated in Figure 3. Each node in the graph denotes a keyword, with connections between nodes indicating the simultaneous appearances of the two keywords in policy texts and their associated relationship. The significance of keywords is inferred from the number of connections they extend or gather; thicker connecting lines signify stronger direct correlations between keywords [42]. In Figure 3, connections between "resources" "management", "resources" "development" appear thicker than others, suggesting closer associations. Moreover, the keywords "management" and "development" exhibit more extensive node radiation. During this period, the governmental focus on the ocean primarily pertained to the rational development, utilization, and management of marine resources. Overall, China's IOM mechanism had not yet been fully established between 1978 and 1998, with policy interests being relatively dispersed.

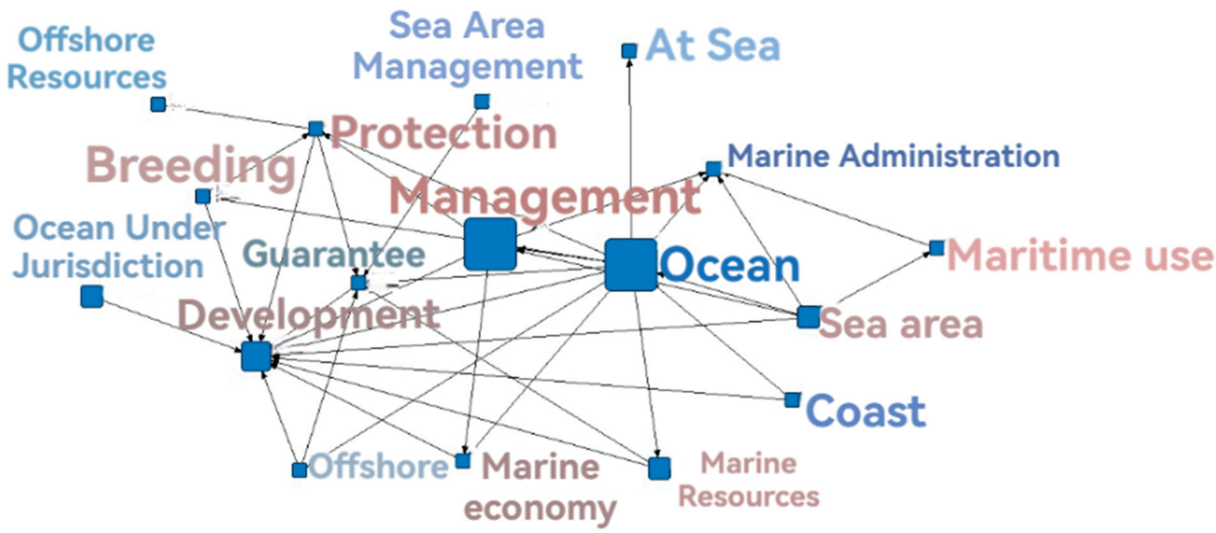

Figure 3. Social network and semantic network analysis (1978–1998).

4.3.2. IOMP Construction Period (1999–2009)

Since the reform of the SOA in 1998, China's IOMP entered a critical phase of rapid development. During this period, significant efforts were made in formulating functional zoning, development planning, supervising and managing the use of sea areas (including coastal zones), and delineating sea areas with neighboring countries. These endeavors yielded fruitful results. The "Marine Environmental Protection Law", revised in 1999, and the "Sea Area Use Management Law", promulgated in 2001, formally established the legal framework for marine functional zoning. In 2002, the "National Marine Functional Zoning" was completed and implemented by the SCPRC. Subsequently, coastal areas systematically undertook the preparation and approval of marine functional zoning at the provincial, municipal, and county levels. This led to further advancements in sea area ownership management and the continual enhancement of the marine functional zoning system. Various normative documents, such as measures for reducing and exempting sea area use fees and notices on strengthening the collection and management of these fees, were successively issued to standardize the collection and management of sea area use fees. Additionally, a unified national standard for the collection of sea area use fees was established, comprehensively standardizing their collection, management, and reduction. This marked a significant breakthrough in the establishment of a system for the paid use of sea areas. Furthermore, the government promulgated several key legal provisions, including the outline of the national marine economic development plan, regulations on the management of the right to use sea areas, and the outline of the national plan for revitalizing the sea through science and technology, along with the island protection law of the People's Republic of China. Through these legal measures, the development and utilization of marine resources were regulated, the protection of the marine environment was strengthened, and the sustainable development of the marine economy was promoted. Consequently, a more comprehensive IOM system was gradually being established. During this period, there was an increase in the number of IOMPs, and policy construction became more standardized and diversified. These policies gradually aligned with international standards for marine management, demonstrating China's commitment to global marine governance.

The titles and contents of China's IOMP texts from 1999 to 2009 were analyzed, and the statistical results of keyword frequency are presented in Table 3. "Sea area use fee" appeared 42 times in the policy samples during this period, representing the highest word frequency. Following closely behind, the terms "marine utilization" and "sea area usage rights" were the next most frequently occurring keywords in the policy sample. Additionally, terms such as "sea area use management" "reclamation", and "marine functional zoning" began to emerge during this stage, indicating a further maturation of IOMPs from the embryonic period. This also signifies a strategic planning and construction phase for key marine resources. The social network and semantic network analysis of the keyword matrix during this period are depicted in Figure 4. The connections between "sea area use" and "marine utilization", "protection", and "management" are notably thicker than other connections, indicating a relatively closer association between them. Furthermore, the keywords "sea use" "sea area management", and "sea area use fee" represent relatively more lines of node radiation, suggesting their significant importance during this stage. During this period, the government's focus on ocean-related matters was centered around the right to use sea areas and the associated usage fees. Overall, China's IOM mechanism underwent initial establishment and gradual maturation from 1999 to 2009, with policy hotspots beginning to emerge and gain focus.

Table 3. Keyword frequency statistics (1999–2009).

Serial	Keywords	Word Frequency	Serial	Keywords	Word Frequency
1	Sea area use fee	42	6	Sea area use management	13
2	Marine utilization	41	7	Reclamation	13
3	Sea area usage rights	26	8	Marine aquaculture	8

Table 3. *Cont.*

Serial	Keywords	Word Frequency	Serial	Keywords	Word Frequency
4	Marine administration	21	9	Marine functional zoning	7
5	Sea area demarcation	14	10	Marine economic development	6

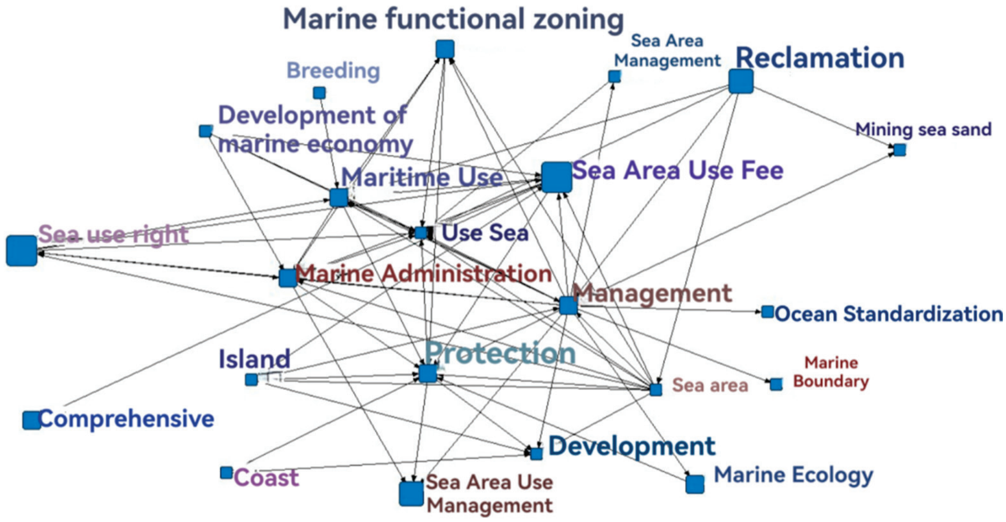

Figure 4. Social network and semantic network analysis (1999–2009).

4.3.3. IOMP Systematization Period (2010–2017)

From 2010 to 2017, China implemented a series of IOMPs aimed at fostering the sustainable development of the marine economy, enhancing the protection and rational utilization of marine resources, and elevating the level of marine ecological environment protection. In 2010, the SOA issued key directives on sea area management, with a focus on revising marine functional zoning and enhancing reclamation management. This initiative comprehensively propelled the advancement of sea area management, marking a transition of China's IOMP into a systematic period. Subsequently, in 2012, national marine functional zoning strategically partitioned the marine space, providing a foundational framework for the balanced development and safeguarding of marine resources. In 2015, the SCPRC issued the national marine main functional area plan, advocating for the strategic planning of marine development and the establishment of a pattern of land–sea coordination and human–sea harmony in marine space utilization. Additionally, the construction plan for the national marine ranching demonstration area, unveiled in 2017, prioritized the restoration of ecological environments in marine ranching waters, aiming to maximize comprehensive benefits encompassing ecological, economic, and social aspects. Moreover, in 2018, the National Marine Ecological Environment Protection Plan (2017–2020) was introduced, providing a systematic framework delineating the timetable and roadmap for marine ecological environment protection. This plan underscored the critical significance of marine ecological preservation. Throughout this period, the overarching focus of China's IOMP was on achieving sustainable utilization of marine resources, safeguarding marine ecological environments, and fostering the robust development of the marine economy, with a concerted effort toward systematic enhancement.

Analyzed the title and content of China's IOMP text from 2010 to 2017 and reported the statistical results of keyword frequency in Table 4. During this period, the term "protection" appeared 28 times in the policy samples, with "marine management", "reclamation", and "coastal conservation" being commonly referenced. During this period, China's comprehensive maritime management system prominently emphasizes protecting marine resources and the marine ecological environment. Analysis of the keyword matrix in this time, as shown in Figure 5, demonstrates strong correlations between "ocean" and "protection", as well as "resources" and "integration", suggesting a tight association among them. China's IOMP showed increased maturity from 2010 to 2017, marked by a more methodical and uniform method.

Table 4. Keyword frequency statistics (2010–2017).

Serial	Keywords	Word Frequency	Serial	Keywords	Word Frequency
1	Marine utilization	28	6	Tidal flat	6
2	Protection	28	7	Coastal conservation	5
3	Marine management	11	8	Marine ranches	4
4	Reclamation	11	9	Intensive marine utilization	2
5	Sea area usage rights	10	10	Sustainable development	2

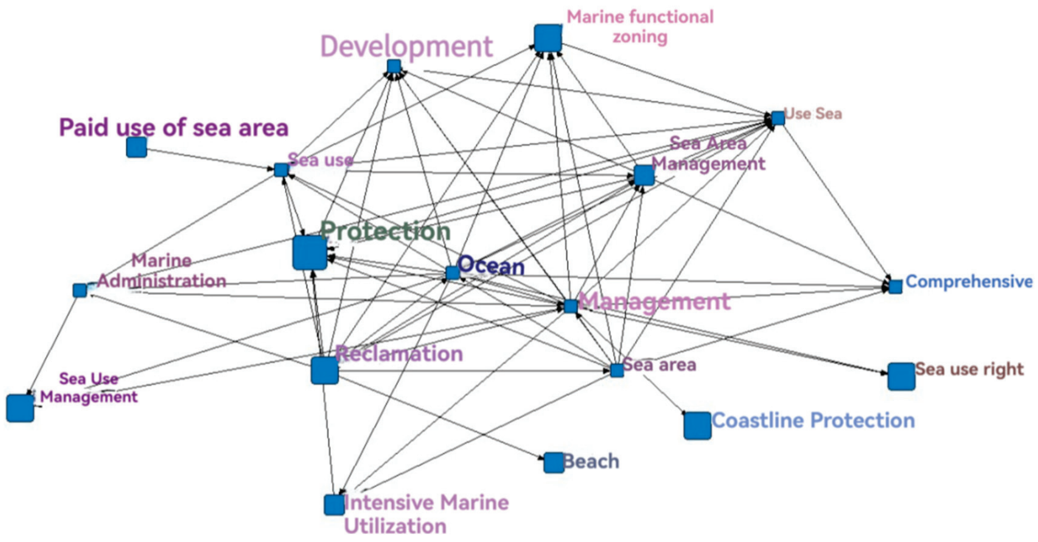

Figure 5. Social network and semantic network analysis (2010–2017).

4.3.4. IOMP Strategization Period (2018–Present)

Since the 18th National Congress of the Communist Party of China, China has elevated the strategy of maritime power to the national strategic level. The 2018 National Marine Ecological Environment Protection Plan articulates the principles of "conforming to nature and ecological management of the sea", and delineates six key aspects: governance, utilization, protection, monitoring, regulation, and prevention. The revision of the Marine Environmental Protection Law of the People's Republic of China in 2023 emphasizes the fundamental principles of "land and sea coordination and comprehensive management", with a focus on bolstering efforts to prevent and control marine pollution, mitigate ecological damage, and enhance comprehensive management practices. Furthermore, the enactment of relevant laws and regulations during this period, including measures to fortify the protection of coastal wetlands, impose strict controls on reclamation activities, manage island and sea area protection funds, and explore the implementation of three-dimensional and hierarchical sea area management, underscores the comprehensive advancement of China's IOMP during the strategization period.

The titles and contents of China's IOMP texts from 2018 to 2024 were thoroughly examined. The statistical analysis of keyword frequency, as depicted in Table 5, reveals significant patterns. "Protection" remains the most frequently mentioned term, appearing 36 times in the policy samples during this period. This underscores the continued emphasis on marine ecological preservation within China's IOM framework. Additionally, keywords such as "three-dimensional layered rights allocation", "land and sea coordination", and "integrated management" have emerged, signaling a shift towards a more holistic approach. This transition is characterized by a move from a "plane" to a "stereoscopic" perspective and from "two-dimensional" to "three-dimensional" considerations. Notably, as shown in Figure 6, the correlation between management, protection, development and other nodes is further strengthened, indicating that the policy content has evolved from mere coordination between land and sea to a strategic reorientation of this coordination.

Table 5. Keyword frequency statistics (2018–present).

Serial	Keywords	Word Frequency	Serial	Keywords	Word Frequency
1	Protection	36	6	Intensive	7
2	Sea area usage rights	23	7	Land and sea coordination	4
3	Reclamation	18	8	Offshore mariculture	3
4	Three-dimensional layered rights allocation	12	9	Integrated management	2
5	Marine ecology	7	10	Mariculture	1

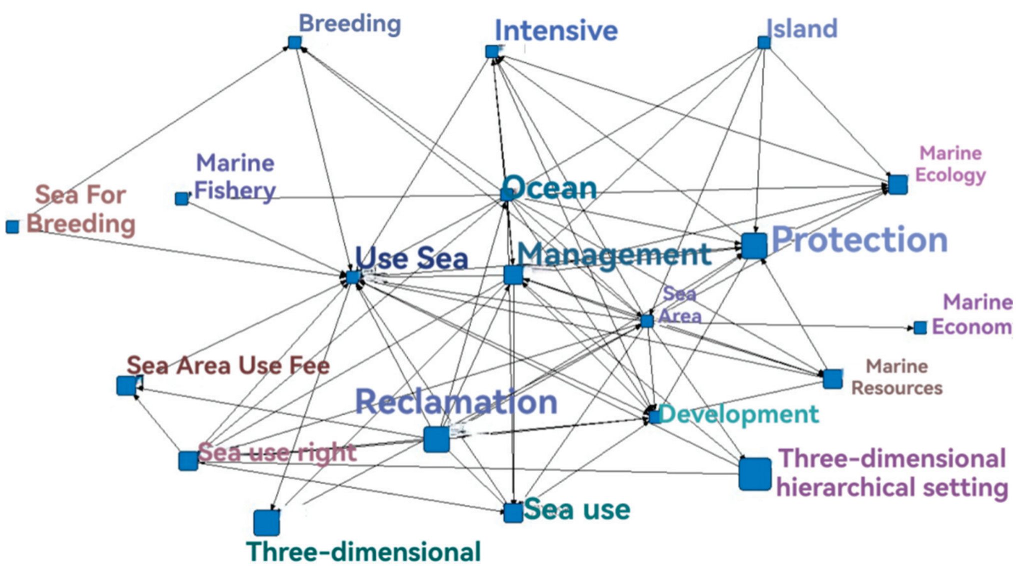

Figure 6. Social network and semantic network analysis (2018–present).

4.4. IOMP Evolution Characteristics

After the reform and opening-up period, the Chinese government recognized the significance of its maritime territory, thus initiating the formulation and execution of China's IOMP. This policy underwent a rigorous exploration phase in its embryonic stage, experienced rapid development during the construction period, underwent comprehensive adjustment in the systematic period, and witnessed transformation and enhancement during the strategization period. A review of this evolution reveals several notable characteristics of China's IOMP.

4.4.1. The Purpose of IOMP Evolution Is Achieving the Harmonious Coexistence of Humans and the Sea

Since the reform and opening-up period, there has been a gradual increase in the number of China's IOMPs, as depicted in Figure 7. This expansion signifies the evolution and refinement of marine policy from early regulations by various sea-related departments and single fields to a more comprehensive approach. It reflects the adaptability of policy to changes in national development strategy and the international landscape, as well as the progressive enhancement of China's marine management system. During the IOMP germination period, China recognized the significance of its maritime territory, leading to the establishment of a dedicated marine management agency, the SOA. This agency was tasked with overseeing sea area usage approvals, with the policy focus primarily directed towards the development of marine resources and sea area management. Subsequent reforms within the SOA propelled China's IOMP into the construction period. Throughout this period, efforts were concentrated on initiatives such as marine functional zoning, sea area fund management, and delineation, all of which were comprehensively and concurrently advanced. In the systematic period, China shifted its focus towards the preservation of marine resources and ecosystems, adopting a scientific approach to marine development aimed at maximizing overall benefits. Subsequently, in the strategization period, China embarked on a comprehensive drive to implement governance measures, including the establishment of sea areas in three dimensions and hierarchical fashion, fostering coordination between land and sea, promoting harmony between humans and the sea, and fostering sustainable development of the marine economy. Through an analysis of the aforementioned stages of policy evolution, China's maritime policy transitioned from its germination phase to the strategic phase, emphasizing resource development while also addressing the comprehensive development of all societal aspects. However, the ultimate goal remains singular: achieving harmonious coexistence between humanity and the sea.

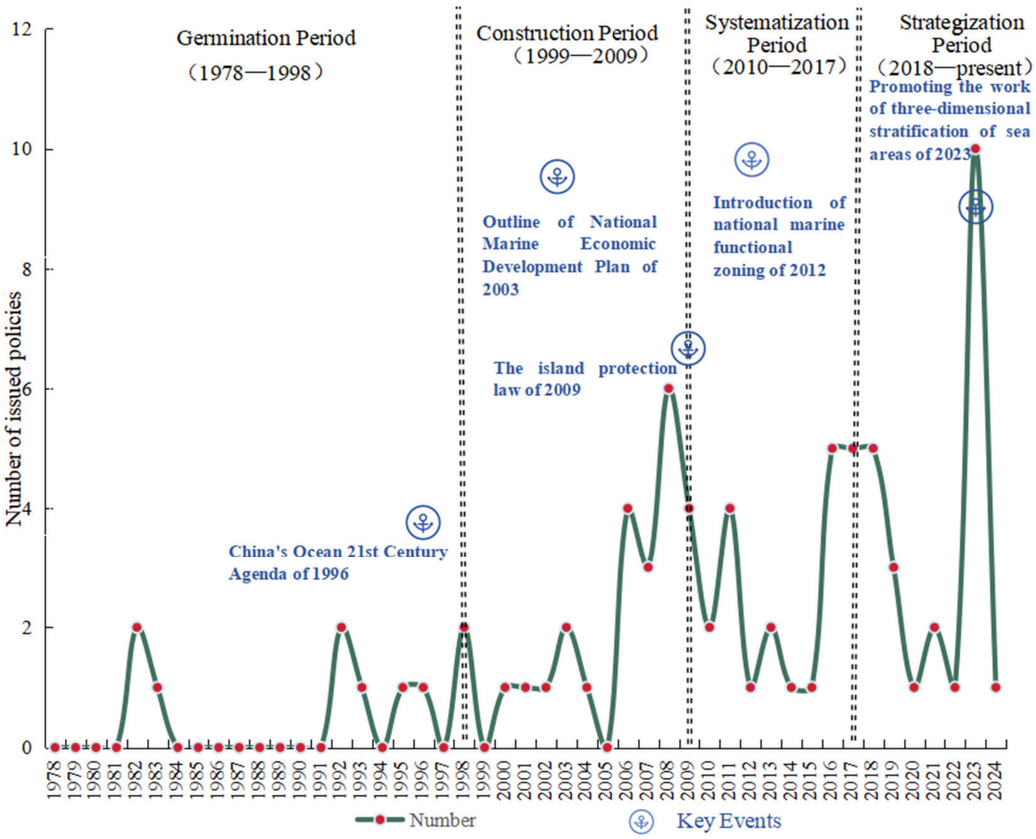

Figure 7. Number of IOMPs (1978–present).

4.4.2. The External Conditions of IOMP Evolution Are Influenced and Constrained by Many Factors

In the 1970s, China experienced social and economic turbulence, ecological degradation, and soil erosion. However, by the 1980s, as the social environment stabilized, significant changes were observed in the macroeconomic landscape shaping China's marine industry development. The maritime security situation began to stabilize, accompanied by an increasing emphasis placed by the Chinese government on marine affairs [43]. In the germination period, the rapid development of marine resources not only yielded significant dividends but also brought forth numerous challenges, including ecological damage and environmental pollution [44]. This backdrop marked the initiation of further exploration of China's IOMP. With peace and development prevailing in the international arena and domestic maritime activities on the rise, China responded to the challenges confronting marine management by enhancing its IOMP. This included a focus on supervising and managing sea area usage, including coastal zones, marking the transition of policy evolution into the construction period. During the systematic period, amidst worsening marine ecological issues and a growing awareness of resource conservation and environmental protection, the government turned its attention to policy implementation aimed at the coordinated development of marine resource exploitation and marine ecological preservation. Against the backdrop of deepening reforms in the marine management system and the strategic aspiration to become a maritime power, policies during the strategization period emphasized mitigating marine ecological damage and enhancing the level of comprehensive management. Consequently, the comprehensive management of the ocean evolved from a two-dimensional approach to a three-dimensional one. It is evident that external conditions, both constraining and promoting, play a pivotal role in shaping the evolution of IOMP.

4.4.3. The External Performance of IOMP Evolution Is Reflected in the Dynamic Process of Continuous Correction and Adjustment

In response to fluctuations in the domestic and international marine landscape, as well as the evolving needs of economic and social development, scientific advancement, and marine resource and environmental conservation, China continually evaluates and adjusts existing policies to meet new development imperatives. The enactment of international legal frameworks like the UNCLOS prompted adjustments in China's maritime policy. These include the introduction of China's Oceans 21st Century Agenda and the advancement of its IOMP. During the stage of constructing IOMP, the surge in marine activities posed challenges to the utilization of sea area resources. China promptly adapted its policy content to address these challenges and further bolstered the management of sea area ownership. This is exemplified by the enactment of the Law of the People's Republic of China on the Use and Management of Sea Areas. In the systematic period, marine policy incorporated considerations of climate change's impact on the marine environment, including sea level rise and ocean acidification. Measures were taken to bolster the protection and restoration of the marine environment; these included revising the implementation measures of the regulations of the People's Republic of China on the environmental protection management of marine oil exploration and development and management measures for the acceptance of the use of sea areas for the completion of reclamation projects. During the strategization period, the SCPRC's endorsement of the "14th Five-Year" marine economic development plan underscored the implementation of the new development concept, prompting dynamic adjustments in marine policy in alignment with national development strategy. Since the inception of reform and opening-up, China's IOMP has undergone continuous exploration, reform, and enhancement. Responding to practical needs and pertinent policies of marine management, an integrated management system encompassing marine rights and interests, sea area use, marine resources, marine environment, marine economy, and marine science and technology was established, as illustrated in Figure 8.

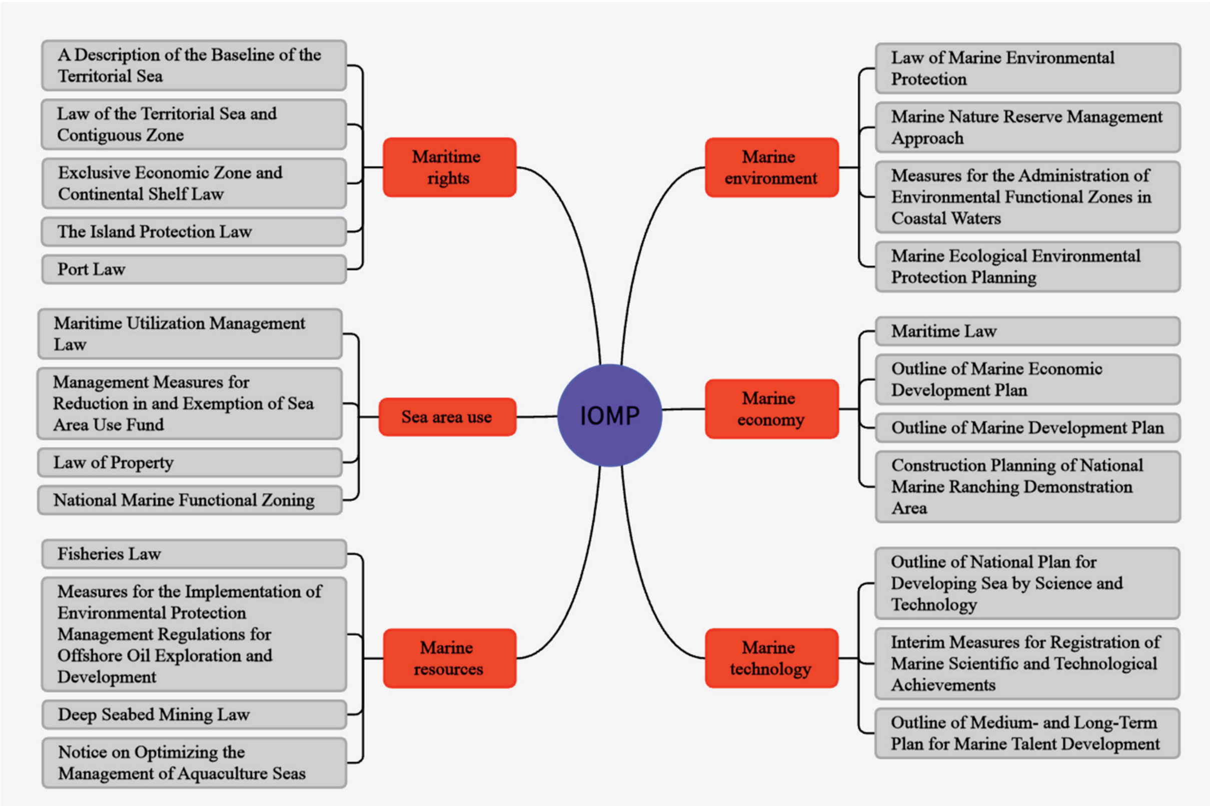

Figure 8. China's IOMP system (only some representative policies are listed).

5. Challenges of the IOMP

5.1. The Sea-Related Legal System Needs to Be Updated and Improved

A perfect maritime policy is very important for a country to become a maritime power [45]. Currently, China's IOM is undergoing significant transformations. The implementation of the "Deepening the Reform Plan of the Party and State Institutions" policy in 2018 brought about systematic changes in the national and coastal local marine management institutions. Concurrently, the fundamental system of IOM experienced substantial modifications through reforms in the "multi-regulation" land and space planning system, the real estate registration system, and the tax and fee system. Certain provisions within the existing legal framework pertaining to maritime affairs proved inadequate to address the evolving demands of marine management. Moreover, several sea-related policies continue to exhibit deficiencies, including incomplete content, unreasonable structures, and inadequate coordination [46], which impede the high-quality economic development of coastal areas. To address the emerging challenges and meet the evolving demands, it is imperative to revise maritime laws based on accumulated practical experiences and rectify the inadequacies within existing content and systems [47].

5.2. The Multitude of Sea-Related Policies Lack Sufficient Cohesion and Coordination

Currently, there exist a multitude of sea-related policies, resulting in insufficient alignment and lax implementation. These policies encompass spatial regulations such as marine main functional area planning, marine functional zoning, the marine ecological red line system, overall planning for coastal zone comprehensive protection and utilization, coastal strategic planning, land use planning in coastal zone areas, urban planning, coastal development zone planning, as well as policies for industries like port and shipping, fisheries, salt production, tourism, and others. From the perspective of the issuing authority, these policies emanate from both national and provincial levels. The variety of policies often leads to conflicts and inefficiencies in policy enforcement. Furthermore, many of these sea-related policies lack long-term considerations, primarily aiming to address current socio-economic needs and local coastal development while neglecting the sustainability of marine resources and the principle of intergenerational equity [48].

5.3. Domestic Maritime Legal Policies Related to the Convention Require Adjustment

Since the conclusion of the Convention, China has always been actively involved in the negotiation of the UNCLOS [49] and has attained recognition as a maritime power within the international community. It boasts several representative institutions and organizations that actively contribute to shaping international regulations (Table 6). Moreover, China has enacted numerous policies aligned with international conventions. For instance, the 1992 Law of the People's Republic of China on the Territorial Sea and the Contiguous Zone elucidates provisions regarding the entry of foreign military vessels into China's territorial waters, signaling China's stance on freedom of navigation and its proactive engagement with international conventions. However, China continues to face challenges, including a limited influence on and a muted presence in shaping international regulations [50, 51], posing significant hurdles for IOM [52]. Given the evolving international maritime legal landscape and ongoing advancements in domestic maritime activities, China must regularly review and refine its domestic maritime legal framework concerning the UNCLOS. This process should prioritize safeguarding national maritime rights and interests while ensuring compliance with international legal standards and effectively protecting maritime rights.

Table 6. Major international maritime conventions have been signed in China.

Name of the Convention	Signing Place and Time	Effective Time	China's Participation
UNCLOS	Montego Bay, 10 December 1982	16 November 1994	On 10 December 1982, the Convention was signed; on 7 June 1996, the instrument of ratification was deposited; entered into force for China on 7 July 1996
Protocol of 1996 to the 1972 London Convention	London, Washington, Moscow, Mexico City, 29 December 1972	30 August 1975	Instrument of accession deposited on 14 November 1975
Treaty on Antarctica	Washington, D.C., 1 December 1959	23 June 1961	On 8 June 1983, the instrument of accession was deposited; effective for China on the same day
Protocol of the Antarctic Treaty on Environmental Protection	Madrid, 23 June 1991	14 January 1998	On 4 October 1991, the protocol was signed; on 2 August 1994, the instrument of approval was deposited; entered into force for China on 14 January 1998
Protocol of Intervention on Non-Oil Pollution of the High Seas, 1973	London, 2 November 1973	30 March 1983	On 23 February 1990, the instrument of accession was deposited; entered into force for China on 24 May 1990
Protocol of 1978 to the International Convention for the Prevention of Pollution from Ships, 1973	London, 17 February 1973	2 October 1983	Instrument of accession deposited on 1 July 1983; entered into force for China on 2 October 1983
Amendment to Annex I of Protocol 1978 to the International Convention for the Prevention of Pollution from Ships, 1973	London, 2 November 1973 and 17 February 1978	7 September 1984	Accepted by default on 7 January 1986; entered into force for China on 7 January 1986

Table 6. *Cont.*

Name of the Convention	Signing Place and Time	Effective Time	China's Participation
1990 International Convention on Oil Pollution Preparedness, Response and Cooperation	London, 30 November 1990	13 May 1995	On 30 March 1998, the instrument of accession was deposited; entered into force for China on 30 June 1998
Convention for North Pacific Marine Science Organization	Ottawa, 12 December 1989	24 March 1992	On 22 October 1991, the Convention was signed; entered into force for China on 24 March 1992
Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR)	Canberra, 20 May 1980	7 April 1982	Entered into force for China on 2 October 2007
International Convention on Control of Harmful Anti-Fouling Systems on Ships	London, October 2001	17 September 2008	On 3 March 2011, the instrument of accession was deposited; entered into force for China on 7 June 2011
2007 Nairobi International Convention for the Removal of Wrecks from Ships	Nairobi, May 2007	14 April 2015	On 11 November 2016, the instrument of accession was deposited; entered into force for China on 11 February 2017
International Convention for the Control and Management of Ship Ballast Water and Sediments	London, 13 February 2004	8 September 2017	On 22 October 2018, the instrument of accession was deposited; entered into force for China on 22 January 2019
BBNJ	New York, 20 September 2023	Not yet in force	On 20 September 2023, the Convention was signed

6. Prospects of the IOMP

6.1. Speeding up the Revision and Improvement of Maritime-Related Laws and Regulations

Scientific and comprehensive maritime laws and regulations serve as the cornerstone for the effective implementation of IOM. To this end, efforts must be made to enhance the legal framework and address any deficiencies in sea-related legislation. It is advisable to expedite legislative processes and promptly enact long-awaited maritime laws, such as the "Basic Law on the Oceans", which have been included in legislative plans but faced delays. Additionally, outdated laws and regulations that no longer align with economic and social development should be promptly revised, such as amending the "Law on the Administration of Sea Area Use" [53]. Through the revision and enhancement of laws and regulations pertaining to maritime affairs, it becomes feasible to formulate sea-related policies that not only align with national interests but also cater to local needs [54]. Additionally, it is imperative to advance the achievement of China's marine environmental protection objectives within the strategic framework of bolstering the rule of law both domestically and internationally [55]. Integral to China's foreign-related legal framework, maritime law encompasses both legislation concerning international maritime affairs and the domestic application of international treaties. Strengthening the promulgation of foreign-related maritime laws and regulations can furnish a robust legal framework for advancing maritime prowess and affording a legal foundation for proactive engagement in the global arena.

6.2. Integrating Sea-Related Policies to Play the Role of Land and Sea Coordination

The government places significant emphasis on the coordinated development of land and sea, which entails the unified planning of both land and sea development and serves as a pivotal concept guiding integrated land–sea development [56,57]. Leveraging the compilation of land and sea planning as a strategic opportunity, the state integrates all sea-related planning initiatives, grounded in marine ecosystem considerations, with a focus on both protection and development. Tailored control objectives are delineated across various scales, and development timelines are clarified accordingly. Through meticulous planning and strategic guidance, the objective is to achieve the efficient and intensive utilization of the "production–living–ecological" space (comprising ecological, production, and residential areas). The current sea-related policies and land-related policies are fragmented, highlighting the need for comprehensive consolidation of sea-related policies. It is essential to enhance the coordination, transparency, and execution of marine policies through integration, ensuring seamless alignment between marine and land policies. Unified planning is crucial to guiding the scientific development and protection of marine resources, fostering a cohesive development model of land–sea integration [58].

6.3. Strengthening International Judicial Collaboration

To address the challenges in maritime rule-of-law construction, China should actively enhance international judicial cooperation. Firstly, timely adjustments to maritime policies are crucial. The UNCLOS serves as a comprehensive global treaty with near-universal applicability [59]. Its dispute settlement mechanism offers an institutionalized platform for strengthening international maritime environmental law judicially [60]. Building upon the UNCLOS, there is a need to enhance marine legislation to address existing issues concerning the protection of marine rights and interests [50]. Furthermore, it is imperative to bolster both international and regional cooperation. China should persist in advancing the development of the "South China Sea Code of Conduct" in collaboration with Association of Southeast Asian Nations (ASEAN), fostering a regional maritime governance framework within the South China Sea to effectively uphold regional security and stability [61]. Moreover, enhancing exchanges and collaboration between Chinese judicial institutions and courts worldwide is essential. Actively exploring practices for judicial protection of the marine environment can significantly contribute to this endeavor [62]. Establishing an international maritime justice center would further augment maritime soft power [63]. The Chinese delegation attended the United Nations Conference on the Decade of Ocean Science for Sustainable Development in 2024, sharing its practices and experiences in marine scientific research, environmental protection, and disaster reduction. The delegation called on all countries to invest more efforts and resources to contribute to the effective implementation of the Decade of Ocean Science and the 2030 Agenda for Sustainable Development. China must continue to strengthen international judicial cooperation to promote the establishment of a fair and equitable maritime trade order. By sharing its experience and insights, China can contribute to the development of a maritime community with a shared future.

7. Conclusions and Discussion

7.1. Main Conclusions

This paper utilizes literature analysis and content analysis to investigate China's IOMP from 1978 to the present, focusing on its evolution characteristics, challenges, and prospects. Drawing from the international landscape of marine management and the policy's specific content, this paper categorizes the evolution of China's IOMP into four stages: a germination period (1978–1998), a construction period (1999–2009), a systematization period (2010–2017), and a strategization period (2018–present). In terms of the purpose of this evolution, it is mainly geared towards achieving the harmonious coexistence of humans and the sea; in terms of its external conditions, it is influenced and constrained by many factors; and in terms of its external performance, it is reflected in a dynamic process of continuous correction and adjustment. Although the Chinese government has made remarkable achievements in its IOMP, it still faces some challenges, mainly reflected in the following aspects: the sea-related legal system needs to be updated and improved; the multitude of sea-related policies lacks sufficient cohesion and coordination; and domestic maritime legal policies related to the UNCLOS require adjustment. Responding effectively to these challenges holds paramount importance for the prudent utilization of marine resources, the preservation of the marine environment, and the safeguarding of marine rights and interests. It is recommended to improve the IOMP by focusing on three aspects: speeding up the revision and improvement of maritime-related laws and regulations; integrating sea-related policies to play the role of land and sea coordination; and strengthening international judicial collaboration.

7.2. Limitations and Discussions

This paper showed that the evolution of China's IOMP is continuously progressing. By consistently exploring, improving, and reforming, it may effectively tackle new difficulties and practical needs arising from increasing scientific discoveries and environmental changes. This paper endeavored to delve deeply into China's IOMP through content analysis methods for the first time. Sample selection underwent preliminary screening by human judgment, which introduced a degree of subjectivity. Additionally, China boasts numerous coastal prefecture-level cities, many of which have issued a plethora of sea-related policies not extensively discussed in this paper. This paper solely focuses on examining the quantity and specific content of China's IOMP. However, policy issues frequently encounter political, economic, social, and technical hurdles during the implementation process, warranting further investigation into their implementation efficiency in the future. As China is a prominent maritime power globally, the execution of China's IOMP holds immense significance not only for China itself but also for influencing global ocean governance, environmental preservation, peace, stability, and sustainable development positively. The successful execution of its IOMP can furnish other nations with valuable experiences and models to emulate, foster international policy discourse, bolster mutual comprehension and trust, and collaboratively devise more efficacious global ocean policies. For instance, Xiamen, China, as the sole city case, has been included in the global Integrated Marine Management Blue Book. The specific practices of "legislation first, centralized coordination, scientific and technological support, comprehensive law enforcement, and public participation" in the comprehensive management of Xiamen's coastal zones have been summarized as the "Xiamen Model". This model has been disseminated both domestically and internationally and has contributed to training a significant number of marine management professionals for Southeast Asia. However, this paper does not provide a more in-depth study of international IOMP. Many maritime countries around the world have developed relatively mature policy systems. Notable examples include the US's ecosystem-based integrated marine management, Japan's science and technology-driven marine environmental governance, the EU's regional cross-border sea cooperation and governance, and ASEAN's cooperative marine environmental management. In the future, we will focus on the ocean management policies and practices of these countries and other international maritime organizations to promote mutual learning and exchange.

Author Contributions: Conceptualization, H.K. and Y.X.; methodology, Y.Z. (Yi Zhang); software, Y.Z. (Yuqi Zhang) and Y.Z. (Yuqi Zhang); validation, S.W. and G.Z.; formal analysis, H.K. and Y.X.; visualization, Y.X.; resources, H.K.; data curation, Y.Z. (Yuqi Zhang), Y.X. and G.Z.; writing—review and editing, S.W. and Y.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (Grant No. 72303124), the Natural Science Foundation of Shandong Province (Grant No. ZR2023QG037), the Fujian Provincial Foundation for Public Welfare Scientific Research Institution, China (Grant No. 2023R1007004), the Qingdao Social Science Planning and Research Project (No. QDSKL2301136), and the Fujian Provincial Key Laboratory of Coast and Island Management Technology Study (Grant No. FJCIMTS 2023-05).

Data Availability Statement: All data generated or analyzed during this study are included in this article.

Acknowledgments: The authors thank the editor and the anonymous reviewers for providing constructive suggestions and comments on this manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

ASEAN	Association of Southeast Asian Nations
BBNJ	Marine Biodiversity of Areas Beyond National Jurisdiction
CCAMLR	Commission for the Conservation of Antarctic Marine Living Resources
EU	European Union
IOM	Integrated Ocean Management
IOMP	Integrated Ocean Management Policy
MNR	Ministry of Natural Resources
UNCLOS	United Nations Convention on the Law of the Sea
US	United States
SCPRC	State Council of the People's Republic of China
SDGs	United Nations Sustainable Development Goals
SOA	State Oceanic Administration

References

1. United Nations. *United Nations Convention on the Law of the Sea*; Brill: Montego Bay, Jamaica, 1982. Available online: https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf (accessed on 2 March 2024).
2. Xu, C. *The Discussion about the Legal System of Use and Administration of Sea Area*; Dalian Maritime Publishing House: Dalian, China, 2006. Available online: https://www.doc88.com/p-972197204107.html (accessed on 5 March 2024).
3. Claus, S.; De Hauwere, N.; Vanhoorne, B.; Deckers, P.; Souza Dias, F.; Hernandez, F.; Mees, J. Marine regions: Towards a global standard for georeferenced marine names and boundaries. *Mar. Geod.* **2014**, *37*, 99–125. [CrossRef]
4. Underdal, A. Integrated Marine Policy: What? Why? How? *Mar. Pol.* **1980**, 159–169. [CrossRef]
5. Winther, J.G.; Dai, M.; Rist, T.; Hoel, A.H.; Li, Y.; Trice, A.; Morrissey, K.; Juinio-Meñez, M.A.; Fernandes, L.; Unger, S.; et al. Integrated ocean management for a sustainable ocean economy. *Nat. Ecol. Evol.* **2020**, *4*, 1451–1458. [CrossRef] [PubMed]
6. Skallerud, K.; Armbrecht, J. A segmentation of residents' attitudes towards mariculture development in Sweden. *Aquaculture* **2020**, *521*, 735040. [CrossRef]
7. Wang, Q.Y. *Sustainable Development of Mariculture: Challenges and Countermeasures*; Ocean Press: Beijing, China, 2007; pp. 1–7; ISBN 9787502769079. Available online: https://book.douban.com/subject/2327367/ (accessed on 10 March 2024).
8. Yin, T. *Research on China 's Maritime Property Rights System*; China Legal Publishing House: Beijing, China, 2004. Available online: http://www.law-lib.com/shopping/shopview_p.asp?id=15126 (accessed on 12 March 2024).
9. He, H.W.; Suo, A.N. *Overview of Integrated Management of China's Maritime Areas*; Ocean Publishing House: Beijing, China, 2022. Available online: https://item.kongfz.com/book/38518025.html (accessed on 15 March 2024).
10. Winther, J.-G.; Dai, M. *Integrated Ocean Management*; World Resources Institute: Washington, DC, USA, 2020. Available online: https://www.oceanpanel.org/blue-papers/integrated-ocean-management (accessed on 17 March 2024).
11. Xing, B. *From This Coast to the World—The International Impact of Xiamen's Experience in Ocean Governance*; Guangming Dail: Beijing, China, 2024. Available online: https://news.gmw.cn/2024-02/21/content_37155629.htm (accessed on 20 March 2024).
12. Wang, Y.; Zhong, Q.; Cui, X.; Bu, H.; Yu, F. *The Butterfly Change of Yundang Lake*; Xiamen Daily: Xiamen, China, 2024. Available online: https://epaper.xmrb.com/xmrb/pc/con/202402/21/content_15655.html (accessed on 20 March 2024).
13. Li, F.; Xi, Z.; Liang, X. Review of China's policy and management system for the paid use of sea area. *Chin. J. Pop. Res. Environ.* **2019**, *17*, 58–66. [CrossRef]
14. Joana, B.; Ambre, S.; Christopher, K.P.; Eva, G.; Gui, M.; Jeroen, S.; David, C.; Telmo, M. Systematic evaluation of a spatially explicit ecosystem model to inform area-based management in the deep-sea. *Ocean Coast. Manag.* **2023**, *224*, 106807. [CrossRef]
15. Zhang, H. On the conflict between the right in fisheries and the right to the use of sea areas and its coordination. *J. Hainan Univ. (Hum. Soc. Sci.)* **2015**, *33*, 48–53. (In Chinese) [CrossRef]
16. Kong, H.; Shen, J.; Zhao, Y.; Sun, Q. Assessment of sea-area benchmark pricing: Using Chinese aquaculture to evaluate and revise the price structure of resources. *J. Coast. Res.* **2022**, *38*, 925–936. [CrossRef]
17. Yue, Q.; Zhao, M.; Yu, J. Sea use fees in China: An effective economic tool for sea use management. *Coast. Manag.* **2018**, *46*, 510–526. [CrossRef]
18. Yang, L.; Wu, L.; Yan, S. Market-based sea use management in China: Features and countermeasures. *Mar. Pol.* **2020**, *120*, 104091. [CrossRef]
19. Liu, S.; Hou, Z.; Xu, W.; Zhao, M. On the sea usage right mortgage and related management policies in China. *Ocean Dev. Manag.* **2016**, *33*, 81–83. (In Chinese)
20. Yu, X.; Lin, S.; Shen, W.; Chen, Q. The tiered transaction system for sea use rights in China: Theoretical basis and market construction. *Mar. Pol.* **2023**, *147*, 105403. [CrossRef]
21. Xue, Y.; Yan, J.; Zheng, H. Integrated ocean management (IOM) for marine sustainable development goal (SDG)14: A case study of China's Bohai Sea. *Sustainability* **2023**, *15*, 5979. [CrossRef]
22. Wang, S.; Lu, B.; Yin, K. Financial development, productivity, and high-quality development of the marine economy. *Mar. Pol.* **2021**, *130*, 104553. [CrossRef]

23. Wang, S.; Li, W.; Xing, L. A Review on marine economics and management: How to exploit the ocean well. *Water* **2022**, *14*, 2626. [CrossRef]
24. Wang, N.; Zhu, G.; Li, X.; Cheng, J.; Yi, W.; Liu, S.; Xie, Z. Transitions and suggestions for China's coastal port reclamation policies. *Ocean Coast. Manag.* **2023**, *236*, 106532. [CrossRef]
25. Sui, X.; Hu, M.; Wang, H.; Zhao, L. Measurement of coastal marine disaster resilience and key factors with a random forest model: The perspective of China's global maritime capital. *Water* **2022**, *14*, 3265. [CrossRef]
26. Yuan, R.; Xu, R.; Zhang, H.; Hua, Y.; Zhang, H.; Zhong, X.; Chen, S. Detecting shoreline changes on the beaches of Hainan island (China) for the period 2013–2023 using multi-source data. *Water* **2024**, *16*, 1034. [CrossRef]
27. Duan, H.; Zhang, H.; Huang, Q.; Zhang, Y.; Hu, M.; Niu, Y.; Zhu, J. Characterization and environmental impact analysis of sea-land reclamation activities in China. *Ocean Coast. Manag.* **2016**, *130*, 128–137. [CrossRef]
28. Wang, X.; Chen, W.; Zhang, L.; Jin, D.; Lu, C. Estimating the ecosystem service losses from proposed land reclamation projects: A case study in Xiamen. *Ecol. Econ.* **2010**, *69*, 2549–2556. [CrossRef]
29. Yu, M.; Huang, Y.; Fu, Q. Sustainable management of marine biodiversity in areas beyond national jurisdiction by establishing protected areas on the high seas: A Chinese perspective. *Sustainability* **2023**, *15*, 1927. [CrossRef]
30. Chang, Y.; Xin, S.; Zhang, X. A proposal for joint marine scientific research activities in the disputed maritime areas of the south China sea. *Coast. Manag.* **2024**, *50*, 215–236. [CrossRef]
31. Bai, J.; Yan, Y.; Cao, Y.; Cui, Y.; Chang, I.-S.; Wu, J. Marine ecological security shelter in China: Concept, policy framework, mechanism and implementation obstacles. *J. Environ. Manag.* **2024**, *351*, 119662. [CrossRef] [PubMed]
32. Jiang, R.; Guo, P. Sustainable management of marine protected areas in the high seas: From regional treaties to a global new agreement on biodiversity in areas beyond national jurisdiction. *Sustainability* **2023**, *15*, 11575. [CrossRef]
33. Li, W.; Yue, Q.; Hu, H.; Liu, L. Current status of ecological compensation for Bohai Sea reclamation and management countermeasures. *Mar. Pol.* **2023**, *155*, 105778. [CrossRef]
34. Lu, H. *Research on the Construction of Marine Ecological Civilization in Our Country*; Dalian Maritime University: Dalian, China, 2017.
35. Li, F.; Ding, D.; Chen, Z.; Chen, H.; Shen, T.; Wu, Q.; Zhang, C. Change of sea reclamation and the sea-use management policy system in China. *Mar. Pol.* **2020**, *115*, 103861. [CrossRef]
36. Lin, Y.; Xue, X.; Hu, W.; Chen, Q.; Zhang, Y.; Huang, F.; Huang, J.; Wang, C. Implementing Regional Sea Use Planning system in China: Evolution, drivers and experiences. *Mar. Pol.* **2022**, *146*, 105298. [CrossRef]
37. Guo, Y.; Song, W.L.; Yang, N. The comparison between the statistical system of sea-related departments and the national statistical investigation system. *Stat. Decis.* **2014**, *10*, 21–23. [CrossRef]
38. Yu, J.K.; Liu, J.T. Exploring governance policy of marine fishery litter in China: Evolution, challenges and prospects. *Mar. Pollut. Bull.* **2023**, *188*, 114606. [CrossRef]
39. Harwood, T.; Garry, T. An overview of content analysis. *Mrk. Rvw.* **2003**, *3*, 479–498. [CrossRef]
40. Ma, J.; Li, H.; Wang, F. Textual analysis of China's scientific and technological achievements transformation policy—Based on the dual perspectives of policy tools and innovation value chain. *Sci. Tech. Manag. R.* **2017**, *37*, 34–42.
41. Jin, W.; Xu, L.; Wu, S.; Xu, Y.; Han, S. Green development policies for China's manufacturing industry: Characteristics, evolution, and challenges. *Sustainability* **2023**, *15*, 10618. [CrossRef]
42. Ge, Z.; Song, W. Research on the new policy of local government to promote the transformation of scientific and technological achievements. *Sci. Tech. Manag. R.* **2015**, *35*, 30–35. [CrossRef]
43. Zhang, H. Ideas and institutional change: An analysis of the changes in the comprehensive marine management system of new China. *Contem. World Soc.* **2015**, *6*, 162–167. [CrossRef]
44. Shi, C.; Ma, W. Reform of China's Marine Management System Since 1978: Review and Prospect. Ministry of Education, State Oceanic Administration, China Marine Development Research Center. Available online: https://aoc.ouc.edu.cn/2019/1022/c9821a272934/page.htm (accessed on 11 April 2024).
45. Wu, W. The construction process of China's maritime legal system and global maritime governance. *APAC Secy. Mar. Aff.* **2021**, *6*, 55–68+3.
46. Cao, X.; Chu, B. The systematic improvement path of China's sea-related laws. *Pac. J.* **2016**, *24*, 9–16.
47. He, G. *Speed up the Revision of the Law, Improve the Level of Sea Area Management*; China Marine Development Research Center: Qingdao, China, 2024. Available online: https://aoc.ouc.edu.cn/2024/0307/c9824a456087/page.htm (accessed on 13 April 2024).
48. Wang, H.J.; Ding, N.; Yue, Q.; Cui, D.D. *Analysis on the Integrated Management of Sea Areas under the Background of Land and Sea Coordination*; China Marine Development Research Center: Qingdao, China, 2021. Available online: https://aoc.ouc.edu.cn/2021/0822/c9821a344369/page.htm (accessed on 14 April 2024).
49. Gao, S.X. United Nations Convention on the Law of the Sea at 40: Relevant practice of the regime of islands. *Law Rvw.* **2024**, *42*, 172–185. [CrossRef]
50. Yang, Z. China and the United Nations Convention on the Law of the Sea 40 years: History, influence and future Prospects. *Contem. Law Rvw.* **2022**, *36*, 29–40.
51. Pan, X. Research on the implementation of the arbitral proceedings under annex VI of UNCLOS. *Chin. J. Mar. Law.* **2023**, *34*, 3–15.
52. Zhang, H. The 40th anniversary of the opening for signature of the United Nations Convention on the Law of the Sea: Retrospect and prospect. *Wuhan Univ. Int. Law Rvw.* **2022**, *6*, 1–14.

53. Sun, Y. Interpretation on the major changes and contents of the revised Marine Environmental Protection Law of 2023. *Envion. Prot.* **2023**, *51*, 14–18.
54. Shi, Q. *The Deputy Director of the Bureau of Ocean Affairs Interprets the "Management Measures for the Protection and Utilization of Coastline"*; Central People's government of the People' s Republic of China: Beijing, China, 2017. Available online: https://app.www.gov.cn/govdata/gov/201704/07/402497/article.html (accessed on 16 April 2024).
55. Qin, T. Regulations on Chinese marine nature conservation in the context of advancing the rule of law in domestic and foreign-related affairs. *J. Pol. Sci. Law* **2023**, *5*, 43–60.
56. Li, X.; Fu, W.; Miu, D.; Su, G. Shenzhen coastal zone planning under land-sea integration guidance. *Planners* **2019**, *35*, 18–24.
57. Yuan, H.; Tang, H.; Xu, Z.; Zhang, D. Path and practice of territorial space ecological restoration in coastal areas from the perspective of land-Sea integration. *Planners* **2024**, *40*, 89–97.
58. Xu, Y.; Mou, X.; Liu, X.; Wang, Y. The key contents and approaches of land-sea coordination in the new era of land space planning. *Ocean Devt. Manag.* **2021**, *38*, 75–79.
59. Martin-Nagle, R. Offshore freshwater aquifers: Toward equitable distribution. *WIREs Water* **2020**, *7*, 8709. [CrossRef]
60. Zhang, H. The judicial strengthening of international marine environmental law and its enlightenment to China. *Contem. Law Rvw.* **2022**, *36*, 145–160.
61. Ge, M. The Code of Conduct in the South China Sea (COC) and innovation in Regional Ocean Governance Mechanisms. *Southeast Asian St.* **2024**, 70–87+156–157. [CrossRef]
62. Qiao, W. Contribute Judicial Wisdom and Strength to Global Marine Environmental Protection. China Court Network. 2021. Available online: https://www.chinacourt.org/article/detail/2021/10/id/6334133.shtml (accessed on 23 April 2024).
63. Wang, S. Build an International Maritime Justice Center to Boost the Construction of a Maritime Power. State Oceanic Administration, China Marine Development Research Center. 2018. Available online: https://aoc.ouc.edu.cn/2018/0803/c9821a207515/page.psp (accessed on 25 April 2024).

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Research on Responsible Innovation Performance Evaluation in the Blue Economic Zone of Marine Industry

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Abstract: Responsible innovation is attracting theoretical and practical research attention worldwide due to global climatic changes, severe resource shortages and intensifying environmental deterioration. However, there are still no studies concerning the performance evaluation of responsible innovation in the marine industry. Based on the practices of blue economic zones in China, a responsible innovation performance evaluation system for the marine industry was developed. Based on the data from 2013 to 2018, the responsible innovation performance of the blue economic zone of the marine industry in Shandong Province was evaluated by principal component analysis. The results demonstrated that (1) There was a rank of regions in terms of the comprehensive responsible innovation performance from high to low: Qingdao > Yantai > Weifang > Weihai > Dongying > Binzhou > Rizhao. (2) Considering annual variations, the comprehensive performance of responsible innovation of different regions exhibited slight fluctuations; however, Weihai had demonstrated significant improvement since 2016. (3) The performance trends across various regions indicated that regions exhibiting high performance consistently expanded their advantage over the six-year period. There was a "Matthew effect" in regional development, particularly evident in the disparities between Qingdao and other regions. (4) In regions that rank at the lower end, such as Rizhao, Binzhou, and Dongying, the development of responsible innovation progressed slowly. Finally, some management suggestions to improve innovation performance in the blue economic zone of the marine industry were proposed.

Keywords: blue economic zone of marine industry; responsible innovation; performance evaluation

1. Introduction

In the 21st century, human beings are still facing challenges such as resource scarcity, environmental degradation, and a widening gap between the rich and the poor, making humans reflect on whether innovation is conducive to the development of human society and whether innovation is responsible for various issues [1–3]. Responsible innovation is an emerging innovation management concept proposed after the concept of sustainable development was defined [4]. The main goal is to closely integrate corporate technological innovation practice with social responsibility and to evaluate and influence technological innovation from an ethical perspective to ensure the sustainability and social acceptability of the results [5–7]. Since then, responsible innovation has continued to be enriched and expanded, both in theory and practice, going beyond the field of science and technology to the integrated development of science and technology, economy, society, and government decision making [8].

The "13th Five-Year National Science and Technology Innovation Plan" issued by the State Council proposes adhering to the development concepts of coordination, greenness, openness, and sharing, advocating responsible research and innovation, strengthening the construction and education of scientific research ethics, improving scientific and technological workers' ethical awareness and guiding enterprises to pay attention to and assume social responsibilities such as protecting the ecology and ensuring safety in technological innovation activities [9]. Innovation-driven development is not only limited to the technological advancement and economic growth of innovation but also requires the country to adhere to the goal of improving the quality and efficiency of economic development, pay more attention to meeting the needs of the people, and promote the realization of quality, efficiency and sustainable development to realize the value of responsible innovation under the medium- and long-term development concepts of innovation, coordination, greenness, openness and sharing [10,11].

With the wide application of high technology in the marine field, marine ecological environment pollution, ecological degradation, resource depletion and other marine problems are becoming increasingly prominent, not only destroying the ecological environment of the ocean itself but also posing serious challenges to the sustainable development of human society and the living space of human beings themselves. However, at present, no regional industry-level responsible innovation performance evaluation system exists, and there is a lack of relevant research on combining evaluation methods to establish an innovation performance evaluation mechanism [12,13]. In practice, the problem of social fairness becomes increasingly prominent, which has adverse impacts on the public and attracts high concerns from the government. The government not only has realized the importance of technological innovation but also is concerned about employment and social guarantees, information sharing, etc.

The Shandong Peninsula Blue Economic Zone has 68 industrial parks at or above the provincial level. It has planned three new marine economic zones, including the Qingdao West Coast, three marine economic international cooperation parks, including the Sino-German Ecological Park, and nine centralized and intensive sea areas, to promote the agglomeration and development of the marine industry with solid carrier support. This study focuses on the blue economic zone of the marine industry, selecting seven regions within the Shandong Blue Economic Zone as research subjects: Qingdao, Dongying, Yantai, Weifang, Weihai, Rizhao, and Binzhou. Sustained innovation activities can be facilitated by establishing a scientific evaluation system for the responsible innovation performance of industrial parks and mastering the level of responsible innovation performance of industrial parks [14,15]. The main contributions of this research are as follows. First, general research on innovation performance is aimed at measuring the effects of innovation activities at the enterprise, regional and national levels. This research conducts a responsible innovation performance evaluation of regional industrial development, enriching the theoretical basis for innovation performance evaluation. Second, most of the research on innovation performance evaluates innovation activities based on indicators of one aspect of input or output. This research establishes a multidimensional and multilevel responsible innovation performance measure based on the three dimensions of innovation input, innovation output and innovation environment. The evaluation system provides a research framework for the innovative development of the marine industry. Third, this study pioneers the idea of enhancing the responsible innovation system of the marine industry, making the research results and conclusions more feasible.

The framework of this research is as follows: first, the theoretical connotation of responsible innovation is reviewed; next, a responsible innovation performance evaluation system is established; then, principal component analysis is used to evaluate the responsible innovation performance of the Shandong Peninsula Blue Economic Zone; finally, conclusions and recommendations are presented.

2. The Connotation and System of Responsible Innovation Theory

2.1. The Connotation of Responsible Innovation Theory

The concept of responsible innovation comes from the community of philosophers, aiming to reflect social concerns caused by studies on policy-level responses and innovation [16]. It has attracted wide attention from academic circles since it was proposed by Hellstrom [17]. The connotations of the concept are expanding and deepening continuously. At present, the widely used definition is that responsible innovation is a transparent and interactive process in which social actors and innovators support each other and give full consideration to the acceptability, sustainability and social expectations of the innovation process and marketable products (ethically), thus embedding technological progress into our social life appropriately.

Scholars have reached a basic consensus on the connotation of "responsible innovation":

(1) The theory of "responsible innovation" is centered on human behaviors and activities with innovative characteristics. By embedding "responsibility" demands into the process and various aspects of innovation, its extension involves theoretical innovation, institutional innovation, cultural innovation, technological innovation, etc. [18–20].
(2) Technological innovation is an indispensable path to achieve sustainable development, but technological innovation may also cause harmful consequences. Therefore, the combination of responsibility and innovation is an important strategic path to achieve sustainable development for a "better tomorrow" [21].
(3) The high risks implied by technological innovation and the vicious consequences of technological abuse and misuse have caused people's distrust of technological innovation and even the government, enterprises, scientific research institutes and other innovation entities and governance entities [22,23].
(4) Science and technology have an unprecedented strategic position as an important way for the country, society, enterprises and institutions to win core competitiveness, and their role and influence are also comprehensive and integral [24,25].

Therefore, an understanding of the comprehensive impact of scientific and technological innovation on the economy, society, environment, etc., is helpful for ensuring harmless innovation and pursuing the humanization of innovation so that innovation results can be effectively combined with national needs, people's requirements, and market demands.

2.2. Theoretical System of Responsible Innovation

Grunwald notes that responsible innovation is based on the tradition of technical evaluation, including evaluation procedures, participation of different doers and technical foresight, adding ethical reflection on responsibility to various methods and processes of technical evaluation. The process includes the theoretical results of science, technology, innovation and social research [17,26,27].

Regarding the theory of responsible innovation, the classic model is the four-dimensional model established by Stigoe, which includes inclusiveness, reflectiveness, responsiveness, and anticipation [28–30].

(1) Inclusiveness means facilitating the public and different stakeholders to conduct collective discussions on innovative visions, goals, problems and dilemmas through dialog, participation and debate, listening to the voices of different stakeholders and facilitating innovation to be better embedded in society. Inclusiveness aims to open up the participation of multilevel stakeholder entities in innovation activities. Innovative entities engage in discussions on terms of reference, roles, division of labor, and interdisciplinary collaboration, listening to the demands of different entities for specific innovations, and realizing the openness of technological innovation. (2) Reflectiveness means that innovative entities need to examine themselves as a part of the larger society and understand the impact of their own behavior on social development in time and region in addition to prediction and innovation activities, reflecting on the impact of innovation, including known and unknown, related uncertainties, risks, areas of ignorance, assumptions, problems, and dilemmas, and proposing effective coping strategies through introspection. (3) Responsiveness means using the process of collective reflection to determine the direction, trajectory and pace of innovation through effective participation and expected governance mechanisms. This is an iterative, inclusive, open and adaptive learning process with dynamic ability. Responsible innovation is the basis for the ability to place innovation activities

under the conditions of dynamic matching between technological evolution and social activities, addressing innovation uncertainties through institutional modularization to establish a continuous adaptive learning process and to realize the institutional coupling of the innovation evolution process in response to societal value. (4) Anticipation describes and analyzes the social, economic, environmental and other impacts that may occur, whether intentional or unintentional, not only to clarify the expected commitment narrative but also to explore other ways of impact to promote scientists and innovators in enquiries into "what will happen" and "what else can be done". Existing innovation practices have introduced a large number of forward-looking governance models, which have triggered the skills required for technological innovation under forward-looking mechanisms, as well as thinking about the adjustment of culture, processes, and organizational plans involved in existing policy governance, relying on technical evaluation and value sensitivity analysis, vision evaluation, scanning and other methods as support [31].

In addition, the three-dimensional space model proposed by Stahl includes a three-dimensional space model of actors-activities-norms [32], which regards responsible innovation as a future-oriented, uncertain, and complex collective behavior, having attracted widespread attention. Actors are stakeholders, such as scientists, universities, innovators, companies, and policy makers, who are critical to innovation activities. Activities are related technologies for detecting and controlling innovation activities, such as risk assessment, impact assessment, technology assessment, predictive activities, value-sensitive design, internal feedback, and ethical assessment. Normative foundations are used to evaluate whether a particular type of research or innovation is indeed desirable or acceptable. The three-dimensional space model covers most of the dimensions and aspects proposed by scholars in this field [33]. This study believes that the three-dimensional model and the four-dimensional model are essentially the same (Figure 1). The establishment of a responsible innovation performance evaluation system combines these two theoretical models.

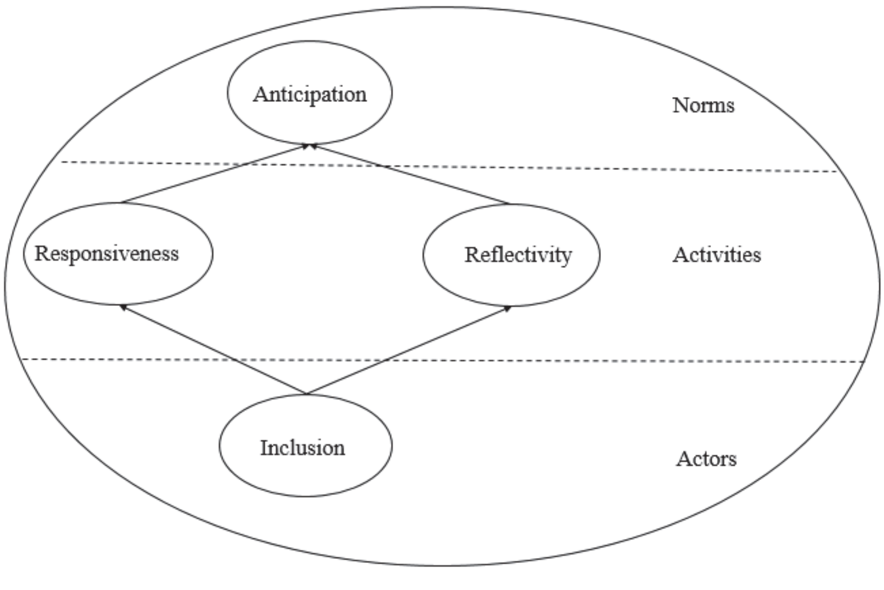

Figure 1. Theory of responsible innovation.

3. Responsible Innovation Performance Evaluation System for the Blue Economic Zone

The responsible innovation performance evaluation system for the Blue Economic Zone is designed from three aspects: actors in responsible innovation, responsible innovation activities, and normative foundations of responsible innovation.

(1) Actors in responsible innovation. Actors in responsible innovation represent the input factor in the responsible innovation process. If there are many input factors and relatively more innovative activities, the results will be more ideal. Input factors in-

clude human resources, material resources, financial resources, information resources, relationship resources, etc. Different combinations of resources yield considerable differences in the process and results of the relationship. However, material resources, information resources, and relationship resources are numerous and difficult to quantify and obtain. With reference to previous studies, combined with the needs of this research, resource inputs are investigated from human resources, capital, resources, and other dimensions. Human resource input uses the full-time equivalence of R&D personnel and full-time equivalence of R&D personnel in industrial enterprises above a designated size. Capital input chooses general public budget expenditures, R&D expenses and R&D expenses in industrial enterprises above a designated size. The resource input chooses the power consumption.

(2) Responsible innovation activities. Innovation activities represent the process and results of activities occurring between innovation elements. The essence of management lies in the division of labor and integration. If the ability to integrate resources is strong, the result of innovation activities, namely, innovation performance, will be ideal. Considering that management factors and data are difficult to quantify and obtain, the indicators of responsible innovation activities in the Blue Economic Zone are examined from the output dimension. Referring to the research process of related scholars, combined with the needs of this research, patent, standardization, foreign trade and capital output are common index contents. Combined with the reasonability of data, patents choose the number of three types of patent applications in China and the number of three types of granted patents in China. Standardization chooses high-quality provinces and the implementation and standardization tasks of brand strategies. Foreign trade chooses the gross import value and gross output value. Capital output chooses revenue in the general public budgets and the main business income of industrial enterprises above a designated size.

(3) Normative foundations of responsible innovation. Normative foundations of responsible innovation represent the environment in which innovation actors, innovation activities and innovation results occur. Social, economic, and environmental factors are all included in responsible innovation norms. However, under different environmental backgrounds, there are obvious differences in innovation actors, innovation activities, and innovation results. The environment for responsible innovation in the Blue Economic Zone involves economic conditions and information exchanges. With reference to the research process of relevant scholars, combined with the needs of this research, economic indexes include per capita GDP, household consumption level and total wages of employees in urban units. Social insurance indexes choose retirement insurance benefits, basic endowment insurance of residents and number of health institutions. Information exchange chooses enterprise informatization and e-commerce level as the measurement indexes of responsible innovation norms.

The construction of a responsible innovation performance evaluation system for the blue economic zone adheres to the previously mentioned four-dimensional and three-dimensional models. The actors in responsible innovation align with the principle of inclusiveness, while the activities align with the principles of responsiveness and reflexivity. Additionally, the normative foundations are consistent with the principle of anticipation. The marine industry responsible innovation performance evaluation system includes an element system of 3 first-level indicators and 21 third-level indicators, as shown in Table 1.

Table 1. The responsible innovation performance index system.

Level-1 Indexes	Level-2 Indexes	No.	Level-3 Indicators	Units	Hemphill [34]	Buhmann & Fieseler [35]	Ko et al. [36]	Kwee et al. [37]	Sovacool et al. [38]	Zhang et al. [39]	Wang et al. [40]
Actors in responsible innovation	Human resource input	f_1	Full-time equivalence of R&D personnel	Person/year	✓	✓	✓	✓	✓	✓	✓
		f_2	Full-time equivalence of R&D personnel in industrial enterprises above the designated size	Person/year	✓	✓	✓	✓	✓	✓	✓
	Capital input	f_3	General public budget expenditures	10,000 yuan	✓	✓	✓	✓	✓	✓	✓
		f_4	R&D expenses	10,000 yuan	✓	✓	✓	✓	✓	✓	✓
		f_5	R&D expenses in industrial enterprises above designated size	10,000 yuan	✓	✓			✓	✓	✓
	Resource input	f_6	Power consumption	100 million kWh	✓				✓	✓	✓
Responsible innovation activities	Patents	f_7	Number of three types of patent applications in China	pcs	✓	✓	✓	✓			
		f_8	Number of three types of granted patents in China	pcs	✓	✓	✓	✓			
	Standardization	f_9	High-quality provinces and the implementation of brand strategies	pcs			✓		✓		
		f_{10}	Standardization	pcs						✓	✓
	Foreign trade	f_{11}	Gross imports	10,000 dollars						✓	✓
		f_{12}	Gross outputs	10,000 dollars						✓	✓
	Capital output	f_{13}	General public budgets	10,000 dollars		✓	✓	✓		✓	✓
		f_{14}	Main business income of industrial enterprises above designated size	100 million yuan		✓	✓	✓		✓	✓
Normative foundations of responsible innovation	Economic conditions	f_{15}	Per capita GDP	yuan	✓			✓	✓	✓	✓
		f_{16}	Household consumption level	yuan	✓	✓		✓	✓	✓	
		f_{17}	Total wages of employees in urban units	100 million yuan	✓	✓		✓	✓	✓	
	Social security	f_{18}	Retirement insurance benefits	10,000 yuan	✓			✓	✓	✓	✓
		f_{19}	basic endowment insurance of residents	Person	✓			✓	✓	✓	✓
		f_{20}	number of health institutions	pcs	✓			✓	✓		✓
	Information exchange	f_{21}	Enterprise informatization and E-commerce level	10,000 yuan	✓			✓	✓	✓	✓

4. Responsible Innovation Performance Evaluation of the Blue Economic Zone

4.1. Evaluation Method

Principal component analysis (PCA) is chosen as the performance evaluation method of responsible innovation in the blue economic zone. PCA is a multivariate statistical analysis method that screens some important variables through linear transformation of several variables. When studying multivariate problems based on statistical analysis, too many variables will increase the complexity of the topic. In many cases, there are some correlations among variables. When there is a correlation between two variables, it can be interpreted that these two variables overlap to reflect the information of this topic. PCA is used to delete repeated variables from all original variables and establish as few new variables as possible. These new variables are independent from each other and can maintain the original information of the topic as much as possible.

The idea of PCA in this study is introduced as follows: first, the annual condition has to be calculated since the data span is from 2013 to 2018 (The Blue Economic Zone of Marine Industry was approved and established by the Chinese central government in 2011, and official statistics became available in 2013, with the latest statistics as of 2018. The data interval of this study is limited to 2013–2018). Next, the overall condition is calculated according to the average level. In this process, the mean of the variables is calculated, and then the overall condition is calculated by the same method as the annual condition. Second, data normalization is performed first when calculating the annual performance level, and then it tries to calculate how many principal components are there by PCA. According to the calculation results, there are 3 factors with characteristic roots higher than 1. There are 3 principal components. The proportions of these 3 principal components are calculated by PCA, which are weights in the following text. On this basis, the factor score matrix is obtained, which contains scores of variables on 3 principal components. Third, the annual performance is calculated by Equation (1), and the performance scores of different regions are acquired through range standardization by Equation Finally, the annual performance scores from 2013 to 2018 and the comprehensive performance scores of different regions are calculated by Equation (3).

$$F_j = \sum_{i=1}^{21} f_i \times comp_i \quad j = 1, 2, 3 \tag{1}$$

$$F_j = (f_i - f_{min}) / (f_{max} - f_{min}) \quad j = 1, 2, 3 \tag{2}$$

$$F = \sum_{j=1}^{3} F_j \quad j = 1, 2, 3 \tag{3}$$

4.2. Evaluation Results

Data from 2013 to 2018 are collected from the statistical yearbooks. Here, only the data from 2013 are selected for a detailed analysis of the process and results due to the article's length constraints. The PCA results are shown in Table 2. A total of 6 principal components are extracted, including 3 with characteristic roots higher than 1. In other words, there are 3 principal components that can be used. Principal component 1 interprets 71.07% of the factors, principal component 2 interpreted 11.92% of the factors, and principal component 3 interprets 9.04% of the factors. The cumulative contribution of these three principal components is 92.03%.

The factor score matrix is shown in Table 3. This coefficient is the factor gained by various indexes on the principal components, which refers to coefficients of all principal components on the above three principal components. The product of index (variable) and the principal component is the performance in the responsible innovation stage. After weight calculation, the responsible innovation performance is gained. During the calculation of the annual performance level, data normalization is performed first to eliminate the influences of different units. In the process of data normalization, the comparison results with means might be positive or negative, and the negative values are not reasonable. Range standardization is carried out during the comparison of regional differences in responsible innovation, and all results range between 0 and 1, indicating that range standardization is relatively reasonable.

Table 2. PCA results.

Principal Component	Initial			Extracted		
	Eigenvalue	Proportion	Cumulative	Eigenvalue	Proportion	Cumulative
1	14.9257	0.7107	0.7107	14.9257	0.7107	0.7107
2	2.5026	0.1192	0.8299	2.5026	0.1192	0.8299
3	1.8979	0.0904	0.9203	1.8979	0.0904	0.9203
4	0.9907	0.0472	0.9675			
5	0.5123	0.0244	0.9919			
6	0.1709	0.0081	1.0000			

Table 3. Factor score matrix.

Index (Variables)	No.	Principal Component 1	Principal Component 2	Principal Component 3
	f_i	Component 1	Component 2	Component 3
Full-time equivalence of R&D personnel	f_1	0.2563	−0.0294	0.0202
Full-time equivalence of R&D personnel in industrial enterprises above the designated size	f_2	0.2500	−0.1072	0.0571
General public budget expenditures	f_3	0.2524	0.0824	−0.0721
R&D expenses	f_4	0.2543	0.0725	0.0477
R&D expenses in industrial enterprises above designated size	f_5	0.2487	0.0074	0.1011
Power consumption	f_6	0.1954	−0.3694	0.0106
Number of three types of patent applications in China	f_7	0.2287	0.1466	−0.1010
Number of three types of granted patents in China	f_8	0.2417	0.0102	−0.0360
High-quality provinces and the implementation of brand strategies	f_9	0.2212	−0.2712	0.0139
Standardization	f_{10}	−0.1387	−0.3167	0.4289
Gross imports	f_{11}	0.1225	0.2906	−0.4943
Gross outputs	f_{12}	0.2406	0.1807	−0.0911
General public budgets	f_{13}	0.2547	0.0780	−0.0492
Main business income of industrial enterprises above designated size	f_{14}	0.2235	−0.0239	0.2893
Per capita GDP	f_{15}	0.0042	0.3537	0.5076
Household consumption level	f_{16}	0.0375	0.3937	0.3781
Total wages of employees in urban units	f_{17}	0.2463	0.1213	0.1212
Retirement insurance benefits	f_{18}	0.2540	0.0752	0.0606
Basic endowment insurance of residents	f_{19}	0.1807	−0.4434	−0.0293
Number of health institutions	f_{20}	0.2319	−0.1510	0.1475
Enterprise informatization and E-commerce level	f_{21}	0.2525	0.0071	−0.0493

The responsible innovation performances and comprehensive performances of regions from 2013 to 2018 are shown in Table 4. The results demonstrated that (1) the ranking of regions based on comprehensive responsible innovation performance, from highest to lowest, was as follows: Qingdao, Yantai, Weifang, Weihai, Dongying, Binzhou, and Rizhao. The scores for Qingdao, Yantai, and Weifang were significantly higher than those of the other regions. The results are presented in Figure 2. (2) In view of annual changes, the comprehensive responsible innovation performances of different regions fluctuated slightly. Only Weihai began to exceed Dongying in 2016, indicating that the responsible innovation elements of Weihai were improved significantly. The trends and changes are shown in Figure 3. Weihai, in accordance with the strategic plan of building the Blue Economic Zone on the Shandong Peninsula, actively promotes the integrated development of sea and land, vigorously implements the strategy of high-end, high-quality and high-efficiency development, and focuses on introducing modern industrial organization methods such as industrial chain and value chain into the marine economy, becoming a national modernized fishery demonstration area, China's ocean-going aquatic products processing and cold chain logistics base, China's leisure fishery capital, and a national marine high-tech industrial base. (3) Regarding the variation trends of different regions, Figure 4 demonstrates that those with high performance extended their lead over the six-year period. The differences among the top three regions—Qingdao, Yantai, and Weifang—became more pronounced in 2018, indicating the presence of a "Matthew Effect" in regional development. Specifically, the gap between Qingdao and Yantai widened more rapidly, while the gap between Qingdao and Weifang also increased. In contrast, the gap between Yantai and Weifang remained stable. Qingdao established a more comprehensive marine industry system, and its marine industry structure was optimizing development more rapidly than in other regions. (4) In regions that rank at the bottom, such as Rizhao, Binzhou, and Dongying, responsible innovation has developed slowly. This reflects that it is necessary to increase resource input and resource integration levels to increase stocks and optimize structures, thus improving the comprehensive performance level.

Table 4. General orders of scores.

Year	Region ①	Region ②	Region ③	Region ④	Region ⑤	Region ⑥	Region ⑦
2013	Qingdao (1)	Yantai (0.6167)	Weifang (0.5041)	Dongying (0.2563)	Weihai (0.1761)	Binzhou (0.1269)	Rizhao (0)
2014	Qingdao (1)	Yantai (0.6151)	Weifang (0.4918)	Dongying (0.2559)	Weihai (0.2309)	Binzhou (0.1444)	Rizhao (0)
2015	Qingdao (1)	Yantai (0.5893)	Weifang (0.4724)	Dongying (0.2322)	Weihai (0.2285)	Binzhou (0.1120)	Rizhao (0)
2016	Qingdao (1)	Yantai (0.5220)	Weifang (0.3890)	Weihai (0.2002)	Dongying (0.1867)	Binzhou (0.1018)	Rizhao (0)
2017	Qingdao (1)	Yantai (0.5272)	Weifang (0.3826)	Weihai (0.2120)	Dongying (0.1933)	Binzhou (0.0926)	Rizhao (0)
2018	Qingdao (1)	Yantai (0.4708)	Weifang (0.3572)	Weihai (0.1407)	Dongying (0.1371)	Binzhou (0.0747)	Rizhao (0)
Total	Qingdao (1)	Yantai (0.5350)	Weifang (0.4243)	Weihai (0.1698)	Dongying (0.1691)	Binzhou (0.1015)	Rizhao (0)

Notes: scores are shown in the brackets.

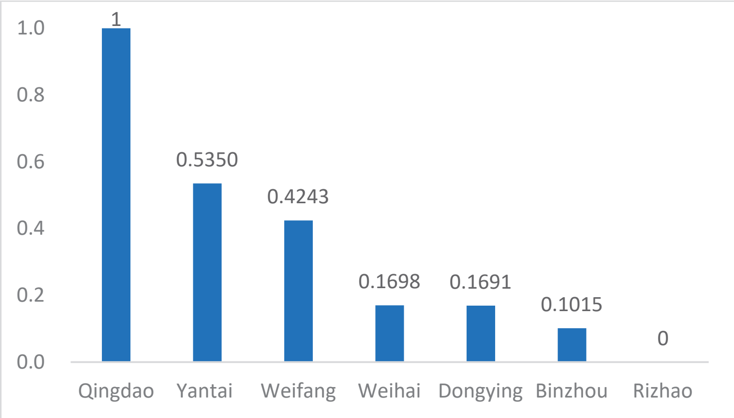

Figure 2. Ranking of regions in comprehensive performance scores.

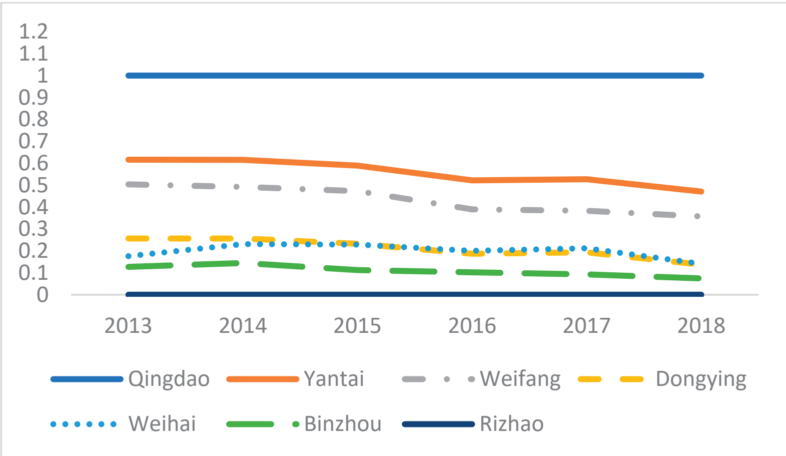

Figure 3. Annual performance scores of 7 regions.

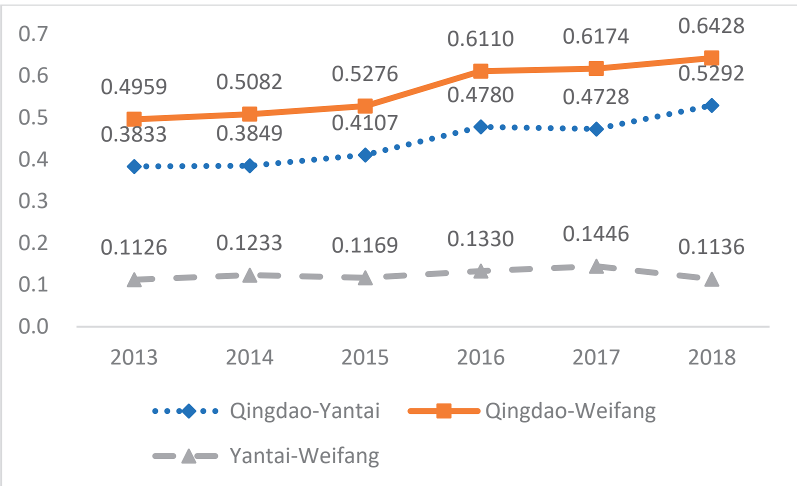

Figure 4. The gap between regions with high performance.

5. Conclusion and Insights

The major research conclusions of this study are as follows: (1) The ranking of regions based on comprehensive responsible innovation performance, from highest to lowest, was as follows: Qingdao, Yantai, Weifang, Weihai, Dongying, Binzhou, and Rizhao, with Qingdao showing significant leading advantages. (2) With respect to annual changes, the comprehensive responsible innovation performances of different regions fluctuated slightly;

however, Weihai had surpassed Dongying since 2016, indicating a significant improvement in the responsible innovation elements of Weihai. (3) In terms of variation trends, regions with high performance extended their lead over the six-year period. The differences among the top three regions—Qingdao, Yantai, and Weifang—became more pronounced in 2018, indicating the presence of a "Matthew Effect" in regional development. Specifically, the gap between Qingdao and Yantai widened more rapidly, while the gap between Qingdao and Weifang also increased. (4) In regions that rank at the bottom, such as Rizhao, Binzhou, and Dongying, responsible innovation has developed slowly.

5.1. Theoretical Significance

(1) The four-dimensional model and three-dimensional model of responsible innovation are integrated, and a conceptual framework of responsible innovation in the blue economic zone is constructed. At present, no agreement on responsible innovation has been reached in academic circles. This study deems that the three-dimensional model and four-dimensional model are essentially consistent. Responsible innovation covers the overall framework of the actors—activities—norms. Responsible innovation performance in the blue economic zone shall contain the logic framework of input—transformation—output.

(2) Based on the overall framework of the actors—activities—norms, the performance evaluation index system of innovation performance in the blue economic zone is built by PCA. This index system has three dimensions and involves 21 indexes. Specifically, the responsible innovation elements of actors include human resource input, capital input and resource input. The responsible innovation activity includes patent, standardization, foreign trade and capital incomes. The responsible innovation norms include economic conditions, social insurance and information exchange.

(3) The responsible innovation performance in the blue economic zone is evaluated using data from 7 regions from 2013 to 2018. As the process of establishing the index system follows the principles of being mutually exclusive and collectively exhaustive, the results prove the validity of the index system. In addition, it is found that the rank of regions in terms of comprehensive responsible innovation performance in the blue economic zone of the marine industry changed slightly, but the regional gap was expanding. In view of the time span, regions with high performance achieved higher performance, and regions with low performance achieved poorer performance. There is a "Matthew effect" in regional development.

5.2. Practical Significance

(1) Increase input and pay attention to elements of actors in responsible innovation in the blue economic zone from the source. As a directional behavior, innovation involves not only correlations among the scientific community and scientific research institutes and social organizations but also conflict between the right to speak and comprehensive benefits. The stakeholders involved in responsible innovation development are diverse and are expected to share the associated responsibilities and risks. Responsible innovation is a huge systematic process that requires responsibility of the leader but also supports and participates in all social sectors, including government, universities, scientific institutions and social organizations.

(2) Strengthen resource integration to assure high utilization of resources in the process. When perfecting the national innovation system, the government should further explore technological development strategies that conform to social needs, meet public expectations and realize the long-term win–win of stakeholders from the perspective of national innovation-driven development values. The value dimensions of innovation activities in public health and environmentally friendly aspects are recreated by responsible innovation. The social consequences of technological innovation, especially emerging technologies, are evaluated by constructive technological evaluation.

Potential opportunities and threats are investigated systematically, and evaluations are feedback to the innovation process.

(3) Paying attention to institutional innovation, building a long-term guarantee mechanism of responsible innovation, further perfecting laws and regulations about innovations, and determining the innovation management system and duties and properties of participating subjects in the blue economic zone through legislative forms are important tasks to assure innovation development in the blue economic zone. These are also beneficial to realize a uniform layout of innovative development in the blue economic zone, thus making local innovation management legalized and standard. It is suggested to build "responsible" management and service institutions for innovative development in the blue economic zone and provide one-stop services for innovation to assure the implementation of relevant innovation policies and regulations.

5.3. Limitations and Future Research

There are limitations in this research owing to the knowledge level and research conditions. This paper obtains the relevant data from statistical yearbooks as the main analysis object. However, some other important measurement index data are difficult to obtain, and only relative conclusions can be drawn under relative conditions due to the limitation of the existing provisions of the statistical yearbook. It is believed that more accurate evaluation conclusions will be drawn as statistical indicators gradually improve. Additionally, the most recent data from this source is only available up to the year 2018. Future research endeavors should prioritize continuous monitoring of this area and analyze the data promptly upon updates to ensure that the research accurately reflects the latest trends. In addition, the use of expert evaluations to obtain qualitative indicators can be a useful supplement to the existing statistics, which cannot cover all the connotations of "responsible innovation performance". Therefore, the next step involves the development of a comprehensive evaluation system that incorporates both qualitative and quantitative indicators.

Author Contributions: D.J.: Data curation, Methodology, Formal analysis, Writing—original draft, Writing—review & editing. S.W.: Formal analysis, Methodology, Writing—review & editing, Project administration. Z.C.: Conceptualization, Methodology, Investigation, Project administration, Supervision, Funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding authors..

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Ma, H.R.; Steernberg, K.; Riera-Palou, X.; Tait, N. Well-to-wake energy and greenhouse gas analysis of SOX abatement options for the marine industry. *Transp. Res. Part D Transp. Environ.* **2012**, *17*, 301–308. [CrossRef]
2. Carbajo, R.; Cabeza, L.F. Renewable energy research and technologies through responsible research and innovation looking glass: Reflexions, theoretical approaches and contemporary discourses. *Appl. Energy* **2018**, *211*, 792–808. [CrossRef]
3. Guido, G. Voluntary measures, participation and fundamental rights in the governance of research and innovation: Reflections on a 'constitutional' model for Responsible Research and Innovation. *ORBIT J.* **2018**, *1*, 1–21. [CrossRef]
4. Mei, L.; Rodríguez, H.; Chen, J. Responsible Innovation in the contexts of the European Union and China: Differences, challenges and opportunities. *Glob. Transit.* **2020**, *2*, 1–3. [CrossRef]
5. Lovdal, N.; Neumann, F. Internationalization as a strategy to overcome industry barriers—An assessment of the marine energy industry. *Energy Policy* **2011**, *39*, 1093–1100. [CrossRef]
6. Eizagirre, A.; Rodríguez, H.; Ibarra, A. Politicizing responsible innovation: Responsibility as inclusive governance. *Int. J. Innov. Stud.* **2017**, *1*, 20–36. [CrossRef]
7. Setiawan, A.D. The influence of national culture on responsible innovation: A case of CO_2 utilisation in Indonesia. *Technol. Soc.* **2020**, *23*, 101306. [CrossRef]

8. Molla, F.S.; Line, B.; Harald, T.H. Practicing responsible research and innovation in a crowdsourcing project in Norway. *ORBIT J.* **2018**, *2*, 1–28. [CrossRef]
9. Rosemann, A.; Molyneux-Hodgson, S. Industrial biotechnology: To what extent is responsible innovation on the agenda? *Trends Biotechnol.* **2020**, *38*, 5–7. [CrossRef]
10. Castellucci, L. Economic assessments of the value of marine industries and services and user requirements. *Elsevier Oceanogr. Ser.* **2002**, *66*, 45–56.
11. Koirala, B.P.; Van Oost, E.; Van Der Windt, H. Community energy storage: A responsible innovation towards a sustainable energy system? *Appl. Energy* **2018**, *231*, 570–585. [CrossRef]
12. Genus, A.; Iskandarova, M. Responsible innovation: Its institutionalisation and a critique. *Technol. Forecast. Soc. Chang.* **2018**, *128*, 1–9. [CrossRef]
13. Peng, D.M.; Hou, X.M.; Li, Y.; Mu, Y.T. The difference in development level of marine shellfish industry in 10 major producing countries. *Mar. Policy* **2019**, *106*, 103516. [CrossRef]
14. Petraite, M.; Ceicyte, J. Conceptual model for responsible innovation management in business organizations. *Procedia Soc. Behav. Sci.* **2014**, *156*, 121–124. [CrossRef]
15. Wang, Y.X.; Wang, N. The role of the marine industry in China's national economy: An input–output analysis. *Mar. Policy* **2019**, *99*, 42–49. [CrossRef]
16. Schillo, R.S.; Robinson, R.M. Inclusive innovation in developed countries: The who, what, why, and how. *Technol. Innov. Manag. Rev.* **2017**, *7*, 34–46. [CrossRef]
17. Hellström, T. Systemic innovation and risk: Technology assessment and the challenge of responsible innovation. *Technol. Soc.* **2003**, *25*, 369–384. [CrossRef]
18. Owen, R.; Goldberg, N. Responsible innovation: A pilot study with the U.K. engineering and physical sciences research council. *Risk Anal.* **2010**, *30*, 1699–1707. [CrossRef] [PubMed]
19. Stahl, B.C.; Chatfield, K.; Holter, C.T.; Brem, A. Ethics in corporate research and development: Can responsible research and innovation approaches aid sustainability? *J. Clean. Prod.* **2019**, *239*, 118044. [CrossRef]
20. Umbrello, S. Atomically precise manufacturing and responsible innovation: A value sensitive design approach to explorative nanophilosophy. *Int. J. Technoethics* **2019**, *10*, 1–21. [CrossRef]
21. Loureiro, P.M.; Conceicao, C.P. Emerging patterns in the academic literature on responsible research and innovation. *Technol. Soc.* **2019**, *58*, 101148. [CrossRef]
22. Pavie, X.; Carthy, D. Leveraging uncertainty: A practical approach to the integration of responsible innovation through design thinking. *Procedia Soc. Behav. Sci.* **2015**, *213*, 1040–1049. [CrossRef]
23. Inigo, E.A.; Blok, V. Strengthening the socio-ethical foundations of the circular economy: Lessons from responsible research and innovation. *J. Clean. Prod.* **2019**, *233*, 280–291. [CrossRef]
24. Lukovics, M.; Flipse, S.M.; Udvari, B.; Fisher, E. Responsible research and innovation in contrasting innovation environments: Socio-Technical Integration Research in Hungary and the Netherlands. *Technol. Soc.* **2017**, *51*, 172–182. [CrossRef]
25. Hadj, T.B. Effects of corporate social responsibility towards stakeholders and environmental management on responsible innovation and competitiveness. *J. Clean. Prod.* **2019**, *250*, 119490. [CrossRef]
26. Genus, A.; Stirling, A. Collingridge and the dilemma of control: Towards responsible and accountable innovation. *Res. Policy* **2018**, *47*, 61–69. [CrossRef]
27. Bronson, K. Looking through a responsible innovation lens at uneven engagements with digital farming. *NJAS Wagening. J. Life Sci.* **2019**, *90–91*, 100294. [CrossRef]
28. Owen, R.; Stilgoe, J.; Macnaghten, P.; Gorman, M.; Fisher, E.; Guston, D. A Framework for Responsible Innovation. In *Responsible Innovation: Managing the Responsible Emergence of Science and Innovation in Society*; Owen, R., Bessant, J., Heintz, M., Eds.; John Wiley & Sons Ltd.: Hoboken, NJ, USA, 2013; pp. 27–50.
29. Stilgoe, J.; Owen, R.; Macnaghten, P. Developing a framework for responsible innovation. *Res. Policy* **2013**, *42*, 1568–1580. [CrossRef]
30. Stemerding, D.; Betten, W.; Rerimassie, V.; Robaey, Z.; Kupper, F. Future making and responsible governance of innovation in synthetic biology. *Futures* **2019**, *109*, 213–226. [CrossRef]
31. Steven, F. Using an ICT tool to stimulate multi-disciplinary innovation teams in establishing responsible research and innovation practices in industry. *ORBIT J.* **2018**, *1*, 1–13. [CrossRef]
32. Stahl, B.C. Responsible research and innovation: The role of privacy in an emerging framework. *Sci. Public Policy* **2013**, *40*, 708–716. [CrossRef]
33. Grasenick, K.; Guerrero, M. Responsible research and innovation & digital inclusiveness during Covid-19 crisis in the human brain project (HBP). *J. Responsible Technol.* **2020**, *1*, 100001. [CrossRef]
34. Hemphill, T.A. The innovation governance dilemma: Alternatives to the precautionary principle. *Technol. Soc.* **2020**, *63*, 101381. [CrossRef]
35. Buhmann, A.; Fieseler, C. Toward a deliberative framework for responsible innovation in artificial intelligence. *Technol. Soc.* **2021**, *64*, 101475. [CrossRef]
36. Ko, K.C.; Nie, J.; Ran, R.; Gu, Y. Corporate social responsibility, social identity, and innovation performance in China. *Pac. Basin Financ. J.* **2020**, *63*, 101415. [CrossRef]

37. Kwee, Z.; Yaghmaei, E.; Flipse, S. Responsible research and innovation in practice an exploratory assessment of Key Performance Indicators (KPIs) in a Nanomedicine Project. *J. Responsible Technol.* **2021**, *5*, 100008. [CrossRef]
38. Sovacool, B.; Hess, D.J.; Cantoni, R. Energy transitions from the cradle to the grave: A meta-theoretical framework integrating responsible innovation, social practices, and energy justice. *Energy Res. Soc. Sci.* **2021**, *75*, 102027. [CrossRef]
39. Zhang, Y.; Mao, Y.; Jiao, L.; Shuai, C.; Zhang, H. Eco-efficiency, eco-technology innovation and eco-well-being performance to improve global sustainable development. *Environ. Impact Assess. Rev.* **2021**, *89*, 106580. [CrossRef]
40. Wang, Z.; He, Q.; Xia, S.; Sarpong, D.; Xiong, A.; Maas, G. Capacities of business incubator and regional innovation performance. *Technol. Forecast. Soc. Chang.* **2020**, *158*, 120125. [CrossRef]

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A Dynamic Simulation and Evaluation of the Coupling Coordination Degree of the Marine Economy–Resource–Environment System in China

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Abstract: As the scale of the marine economy continues to expand, the problems of environmental pollution and the over-exploitation of marine resources have become increasingly severe. The purpose of this study is to realize the sustainable growth of the marine economy, the rational utilization of resources, and the coordinated development of environmental protection. Method: This research first adopts the system dynamics (SD) model. It then uses the entropy method to weigh the evaluation indicators and create a coupling coordination degree (CCD) assessment simulation of the marine economic–resource–ecological environment. We use the created SD model to build and simulate four standard scenarios: current, economic, resource, and environmental. Finally, we propose suitable recommendations for the long-term development of the marine economy based on the coordination evaluation results of the CCD model. Results: Results show the following: (1) In the immediate term, the economic scenario is poorly coordinated, whereas the environmental scenario is more effectively coordinated. However, in the long-term development process, the resource scenario is reasonably well coordinated. (2) Priority attention must be given to improving the energy mix and protecting the natural environment to promote the sustainable development of the marine economy. (3) To achieve a virtuous cycle between marine economic development and environmental protection, governments, businesses, and all sectors of society need to work together to formulate and implement relevant policies and initiatives.

Keywords: marine ERE system; SD model; CCD model; sustainable marine development

1. Introduction

With the global emphasis on sustainable development and the depletion of marine resources [1,2], people have become increasingly concerned about how to use and manage marine resources more effectively while protecting the marine environment [3–6]. China has large ocean areas, and the marine sector is a significant aspect of the country's economic development [7]. According to the "2024 China Marine Economic Statistical Bulletin", the national marine GDP reached CNY 9909.7 billion in 2023, accounting for 7.9% of the total GDP. However, the rapid development of the marine economy has led to problems such as overfishing and illegal fishing in some sea areas, resulting in the continuous depletion of marine resources and the deterioration of the ecological environment [8]. The excessive use of fossil fuels has negatively affected the environmental quality in China, and pollutants such as marine garbage and chemical wastewater have caused serious damage to the marine ecosystem and affected the development of marine industries [9]. The "2023 China Marine Ecological Environment Bulletin" reported that in 2023, 455 marine pollution sources in the country discharged approximately 7.76 billion tons of sewage, with an estimated 3.2 billion cubic meters of marine garbage dumped. Indeed, marine pollution has significantly impacted the development of China's marine economy [10].

To promote the sustainable growth of the marine industry, China has passed numerous environmental and marine resource protection policies in recent years [11]. For example, the "Law of the Sea" and other relevant laws and regulations were promulgated, a marine management system was established, and the protection and rational use of marine resources were strengthened [12]. Many marine protected areas were also established to protect coral reefs, marine ecosystems, and marine biodiversity, as well as promote the restoration and protection of the marine ecological environment [13]. Measures were taken to strengthen marine pollution prevention and control, promote the building of a marine environmental monitoring network, strengthen cleanup emergency response capabilities for marine oil pollution, and ensure the cleanliness and safety of the marine environment [14]. Moreover, investments in marine scientific research have increased, marine scientific and technological innovations are being promoted, and marine resource survey and assessment capabilities have been enhanced to support the scientific and effective protection and consumption of marine resources.

However, scientific decision-making necessitates a thorough grasp of the economic, resource, and environmental subsystems as well as the key factors that interact with them under various policies [15]. On the one hand, the marine economic–resource–ecological environment (ERE) is a complicated system with several interactions. The system dynamics (SD) model can consider issues such as marine economic development, resource exploitation, and environmental preservation, aiding in the analysis of these elements and revealing the overall evolution law of the system. At the same time, the creation of the marine ERE system is typically a long-term process that must consider the impact and changes over various time periods. The SD model is suitable for long-term prediction and simulation, helping decision makers formulate sustainable development strategies and plans [16]. On the other hand, there are complex feedback mechanisms in the marine ERE system, and changes in a certain factor may cause reactions in other parts of the system [17]. The SD model can capture these feedback effects, help researchers understand the nonlinear characteristics of system behavior, and help avoid unexpected results. At the same time, the marine ERE SD model can provide a scientific basis for governments and management departments to support decision making and implementation. By simulating the effects of different policy measures, the model can evaluate their impacts on the marine economy, resource utilization, and environmental protection, providing decision makers with more comprehensive information [18,19].

2. Literature Review

The marine ERE system is affected by a variety of factors, such as the marine ecological environment, climatic factors, and marine topography, the interaction of which complicates the operation of the system [20]. A coupling coordination degree (CCD) analysis, which can vividly express the relationship between systems, has been widely used in the study of economic management. Various models have been used to analyze the coupling effect between multiple factors, including the environmental Kuznets curve (EKC), double exponential model [21], nonlinear dynamics model [22], coupling degree model, gray correlation degree analysis, dynamic coupling model, vector autoregressive (VAR) model [23], spatial regression model [24], and ArcGIS center of gravity curve optimization classification. Among these, the CCD model (CCDM) is notable for its simplicity and ease of calculation. It uses coupling degree to explain the interrelationship between several subsystems and employs the coordination development degree for a comprehensive evaluation of the whole system. Owing to its intuitive results, the CCDM has been widely used in empirical research on the coupling development level of various systems, including the environment, economy, social development, urbanization, agriculture, industry, transportation, population, across different scales and regions. To date, scholars have conducted various research on mathematical model construction, simulation, index construction.

First, the marine ERE system is complicated and characterized by numerous dynamic relationships. Various methodologies have been developed and implemented to analyze the performance and functioning of composite systems. The primary objective of these studies was to offer recommendations for system coordination, albeit with differing focal points. These studies can be categorized according to three aspects. First, an index system was established to assess the coordination level of composite systems. Luiz C Terra Dos Santos (2023) utilized a five-sector sustainable development model to evaluate the environmental, economic, and social factors of the circular economy across three economic blocs from 2000 to 2020 [25]. Jing Zhaorui (2020) used a complex network approach to create a system of evaluation indexes for sustainable growth that prioritizes social harmony, economic progress, and environmental enhancement. They conducted a dynamic system analysis of China's RBC (Shuozhou) development process up to 2016. A comparison of individual social, economic, or environmental subsystems revealed that the entire socioeconomic environmental system exhibits the highest connectivity and information transfer efficiency [26]. Wang Yuanhui (2023) likewise developed an SD model for the ERE system. The model evaluated ERE system coordination under various trade-off scenarios by establishing and applying a CCDM based on weight ranking. Furthermore, the author optimized the ERE system in Xining, the largest city on the Qinghai–Tibet Plateau [27].

Second, researchers have developed numerous mathematical models to analyze the causes of important elements in complex systems. Liu Fan (2020) developed a co-equation model using data from China's coastal regions between 2001 and 2020. The study investigated the relationship between marine environmental contamination, aquatic product commerce, and the coastal fisheries economy in China. A matrix correction framework was used to study the interplay of variables and determine their level of interaction [28]. In 2022, Sun Jing determined a way to establish the carrying capacity of marine ecosystems. He based the method on the analytic hierarchy process (AHP) and entropy theory to examine carrying capacity from different points of view. Between 2008 and 2017, a dynamic analysis was performed on data from Shandong Province [29]. Guo Jing (2022) used the energy-based model and data envelopment analysis to assess the marine economic efficiency of 11 coastal areas in China from 2007 to 2017. The researcher also looked at the spatiotemporal evolution trend of marine economic efficiency and built a spatial Durbin model to understand the relevant elements and mechanisms at work [30].

Third, other studies have focused on modeling and predicting dynamic outcomes for composite systems. SD is a common method to deal with such problems. Other research focuses on modeling and predicting dynamic outcomes for composite systems. Cao (2022) developed a framework for assessing integrated regional resource restoration, utilizing an SD model to simulate relationships in human–environment systems [31]. Based on data on Wuhan City from 2000 to 2015, Xing (2019) established a CCDM of ERE SD and power system coordination with an emphasis on the SD method [32].

In summary, although the ERE SD development method is often used to study the influencing factors, interactions, and dynamic changes of different complex systems, the study of marine ERE systems is rarely involved. The index system method of marine sustainable development assessment can effectively integrate multiple factors affecting the ERE system into a comprehensive index. However, this approach does not adequately reflect the dynamic interactions between these factors. The marginal contribution of this paper lies, first, in the prediction analysis of the coordinated development system of the marine ERE using the SD and CCD models, which enriches the theoretical research mechanism of the sustainable development of China's marine economy. Therefore, the dynamic model of the marine ERE system is established in this study. Second, the evaluation model of the marine ERE CCD is established. Finally, this study provides feasible suggestions for the sustainable development of the marine economy.

In conclusion, research on marine ERE systems is rare despite the frequent use of the ERE SD development approach to study the influencing variables, relationships, and dynamic changes of many complex systems. While the indicator system approach of marine sustainable development evaluation may effectively incorporate many aspects influencing the ERE system into a single indicator, this method does not adequately capture the dynamic interactions among these components. To study the marine ERE system in depth, comprehensive dynamic models, system analysis, comprehensive evaluation, and other methods must be used to reveal the relationships and interactions between different elements. By establishing dynamic models, the changing trends in various elements in the marine system can be simulated and predicted, thereby providing a scientific basis for formulating effective management strategies and sustainable development planning. To achieve this goal, this work first developed a dynamic model of the marine ERE system, followed by a model for evaluating marine ERE coupling coordination. Finally, we present reasonable proposals for the steady growth of the marine economy.

The marginal contributions of this paper are as follows: (1) SD and the coupled coordinated development model are used to predict and analyze the coordinated development of the marine ERE system. The SD method can better reflect the internal structure and dynamic evolution of complex systems, while the coupled coordinated development model helps reveal the interaction and influence among different elements. (2) By combining these methods, researchers can more comprehensively consider the complex relationship between the marine economy, environment, and resources, as well as predict and evaluate the future development trend of the system. This comprehensive analysis method enriches the theoretical research mechanism of sustainable development of our country's marine economy and provides a more scientific reference for relevant decision making. (3) The research results also help deepen the understanding of the coupled coordinated development mechanism in the marine field and provide new ideas for exploring the paths and measures to promote the sustainable development of marine ERE. Through system-level analysis and prediction, we can better grasp the regularity and sustainability of marine development and make deeper theoretical and practical contributions to the coordinated development of the marine economy and ecological environment.

3. Research Methods and Data Sources

3.1. SD Model

3.1.1. ERE System

The marine ERE system considers the influence of diverse marine economic activities on the development and usage of marine resources and economic advantages, as well as the impact of these activities on the marine ecological environment and its sustainability assessment. When studying the marine ERE system, the complex interactions of various factors must be considered comprehensively. Marine economic activities involve many variables, including the marine industrial structure, marine economic growth, and the number of persons employed in the marine sector. These activities compete and clash with the development and exploitation of marine resources and have an impact on the marine environment, causing problems such as water quality deterioration and biodiversity loss. These influencing elements have a relationship (Figure 1).

The marine resource subsystem is a complex, multi-level system that includes a variety of resource types and ecological processes [33,34]. We further classify these subsystems into biological resources (e.g., fish, seaweed), abiotic resources (e.g., minerals, energy), and ecological service systems (e.g., coral reefs, wetlands). While marine resource extraction and use have provided enormous economic benefits, they have also caused significant environmental damage. The growth of marine resources, such as fishing, offshore oil and gas exploitation, and tourism [35], immediately provides a great number of jobs and helps many coastal towns. The expansion of marine resources has fueled the growth of corresponding industry sectors, including processing and manufacturing, shipbuilding, and port logistics, as well as the diversification and comprehensive development of the overall economy [36,37]. Marine resource products, such as seafood, minerals, and energy, are important parts of international trade, facilitating the flow and economic interconnection of global markets [38,39]. However, these factors have also caused ecological damage and marine environmental pollution [40]. For example, human activities such as offshore project construction, extraction activities, and pollution can destroy marine habitats (e.g., coral reefs, seagrass beds, mangroves), leading to a decline in biodiversity [41]. The extraction and burning of fossil fuels increase greenhouse gas emissions and exacerbate global climate change, causing marine environments to become more acidic and threatening coral reefs and shellfish [42].

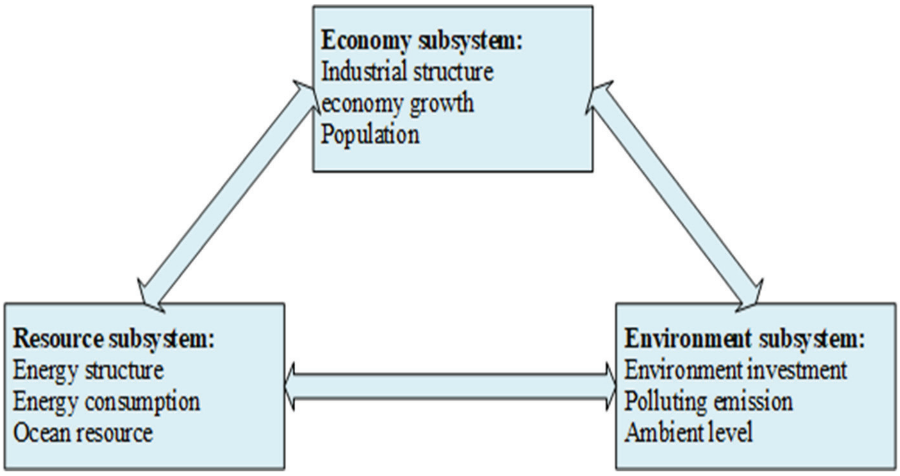

Figure 1. Structure and main feedback sources of the marine ERE system.

The marine economic subsystem comprises the collection of economic activities and industries associated with the development and use of marine resources. It includes the development, use, and preservation of marine resources, as well as a wide range of economic and social activities [43,44]. The primary fields are fishery, shipping, marine energy, marine tourism, marine biological medicine, and marine mineral resources [45,46]. The marine economic system has not only aided economic and technological progress but has also contributed significantly to resource utilization, environmental protection, and sociocultural development [46]. Through integrated management and sustainable development strategies, marine economic systems will bring long-term, sustainable benefits to human society [47]. At the same time, various marine economic activities, such as fisheries, marine transportation, and marine energy development, provide numerous jobs for coastal communities and related industries, including fisheries, tourism, shipbuilding, and research. They also promote the development of many industrial chains; the growth of related industries such as manufacturing, information technology, and services; and the growth of local and national economies [48].

The marine environmental subsystem is a significant part of the marine economic system because it is dedicated to maintaining the marine ecological environment, monitoring marine ecological changes, managing marine pollution, and ensuring the sustainable use of marine resources. It includes a wide range of actions and initiatives, from natural ecosystem protection to the application of environmental management laws, all with the goal of preserving healthy and functional marine ecosystems to enable the long-term development of other marine economic activities. Xu (2023) and Xin (2022) conducted an analysis on the influence of marine energy consumption and economic growth on greenhouse gas emissions and climate change. They also investigated the importance of emission reduction policies and technological innovation in environmental protection [49,50]. Delphi Ward (2022) and Guo (2022) assessed the impacts of marine resource exploitation on ecosystems and biodiversity and explored strategies for sustainable resource management and conservation [51,52]. Sun (2022) and Zhou (2023) studied the impact of marine energy development on local jobs and economies and how it balances economic growth and social development with environmental protection [29,53]. The effective operation of the marine environmental subsystem is crucial for maintaining the marine ecological environment, ensuring the sustainable utilization of resources, and promoting the healthy development of the marine economy. Through scientific management and collaborative cooperation, we can achieve a virtuous cycle of the marine environment and economy and help build a sustainable marine economic system. These studies provide a scientific basis for understanding the environmental impacts of marine energy consumption and economic growth, providing important references for managers and policymakers to formulate sustainable development policies and conservation measures.

3.1.2. SD Model

The SD model is a mathematical modeling method for investigating the behavior of dynamic systems. It can help us understand and predict the interactions and evolutionary laws between various elements in complex systems and has many advantages: (1) Comprehensive analysis: The SD model can comprehensively consider the complex relationship between marine economic activities, resource development and utilization, and environmental protection. By establishing a mathematical model, it reveals the causal relationship among various elements and helps managers fully understand the system operation mechanism. (2) Predictive analysis: SD can make a dynamic model of the marine ERE system, which can then be used to compare how different policies and measures affect system development, predict future development trends, and give a scientific basis for decision-making. (3) Sensitivity analysis: SD can analyze the impact of changes in system elements on stability and sustainability, identifying critical factors and weak links. (4) System optimization: Using the SD model, solutions may be compared and optimized across many scenarios to determine the best development route and accomplish the coordinated growth of the marine economy, resource exploitation, and environmental protection. (5) Decision support: The SD model is a systematic decision support tool that can assist government departments and firms in developing long-term development plans and management policies for the sustainable growth of the marine ERE system. As a result, it has considerable application prospects in evaluating the sustainable development of the marine ERE, helping us better understand and deal with complex challenges in the marine system while also promoting sustainable growth in the marine field.

3.1.3. VENSIM-PE Software

This research project applies the SD modeling software Vensim-PE (http://vensim (accessed on 12 July 2024) to determine the interaction of various factors in the marine ERE system, as well as simulate the influence of current ERE settings on the long-term development of China's marine economy. We use data from 2011 to 2020 as samples and extend the simulations to 2050. In that example, the time boundary of the model is in the 2011–2050 period (i.e., 40 years) with a step length of one year. Furthermore, the SD model produces reliable and accurate findings through a comprehensive and scientific modeling approach.

3.2. Evaluation of the Coupling Coordination Degree

3.2.1. Data Source and Pre-Processing

We gather statistics for this research from the China Fishery Statistical Yearbook (2010–2022), China Marine Statistical Yearbook (2010–2022), and China Urban Statistical Yearbook (2010–2022). Using the two formulas below, we standardize the indicators to make conclusions comparable and avoid the effect of dimensions.

(1) Raw data preprocessing

Quantifying the original data is an important step in building a CCDM. The main reasons are as follows: first, the original data often have different scales and units. Through quantification, different data types can be unified into the same standard range, which is conducive to the comparison and analysis of the model. Second, the original data may have missing values, outliers, and other problems. Through quantification, the impact of these problems can be reduced, and the stability and reliability of the model can be improved. Finally, quantification can reduce the data dimension and number of features, thereby reducing the time and computational cost of model training

Positive indicator:

$$r_{ij} = (X_{ij} - \min X_j)/(\max X_j - \min X_j) \quad (1)$$

Negative indicator:

$$r_{ij} = (\max X_j - \min X_{ij})/(\max X_j - \min X_j) \quad (2)$$

where $\max X_j$ and $\min X_j$ are the maximum and minimum, respectively, of indicator *j* in all years; X_{ij} and r_{ij} are the original and standardized values of indicator *j* in year *i*. A positive indicator implies that a higher value corresponds to a more favorable outcome for the system's development, and vice versa.

(2) To assure accuracy in data processing, zero values in the data after standardized processing must be eliminated. Therefore, a global translation operation on the data is required, that is, each data point is redefined as $X'_{ij} = x'_{ij} + \alpha$. To maximize the retention of the original data information, the value of α should be as small as possible, because when the value of α is small, the response of the system is more stable. By reducing the value of α, the sensitivity of the model to the input data can be reduced, and system fluctuation in the face of noise or uncertainty can be reduced, thereby improving the stability of the model. For this reason, we choose α = 0.0001 in this study.

Proportion (P) of indicator j in year i:

$$P_{ij} = r_{ij} / \sum_{i=1}^{m} r_{ij} \quad (3)$$

Information entropy (e) of each indicator j:

$$e_j = \frac{1}{\ln m} \sum_{i=1}^{m} (P_{ij} \times \mathrm{Ln} P_{ij})(0 \le e_j \le 1) \quad (4)$$

Entropy redundancy (e) of each indicator j:

$$d_j = 1 - e_j \quad (5)$$

Weight (W) of each indicator j:

$$W_j = d_j \Big/ \sum_{j=1}^{n} d_j \quad (6)$$

Evaluation of level (L) of indicator j in year i:

$$L_{ij} = W_j \times r_{ij} \quad (7)$$

Comprehensive level (CL) of subsystem in year i:

$$CL_i = \sum_{j=1}^{n} S_{ij} \quad (8)$$

In a subsystem, we use either Formula (1) or (2) to compute r_{ij}, where n represents the number of indicators, and m represents the number of years. We use Formulas (3) and (4) to calculate the weights for each indication and apply Formulas (7) and (8) to calculate the total level of each subsystem.

3.2.2. Coupling Coordination Degree Model

The CCDM is a model that can describe the overall operating characteristics of the system by considering the interactions and influences among various subsystems in system analysis and design. This model can not only reveal the relationships among various subsystems but also evaluate the overall performance and efficiency of the system. The main reasons for choosing the CCDM in this study are as follows: (1) There are complex relationships and interactions among the marine ERE. The various parts are coupled with one another, and changes in one part will have an impact on other parts. Therefore, the CCDM can better reveal the internal connection and influence mechanism between them. (2) The development of the marine ERE system is a dynamic process. With the passage of time, the status and relationship of each element will change. The CCDM can dynamically simulate the system and better reflect the process of system evolution. (3) The CCDM can comprehensively evaluate the marine ERE system, including its stability, sustainability, and coordination. Through CCDM evaluation, scientific basis and reference suggestions can be provided for relevant decision making. (4) The CCDM can be used for system analysis and evaluation and provide decision support and policy suggestions for relevant managers and decision makers. Through simulation and evaluation, paths and measures can be provided for the coordinated development of the marine ERE system [54,55]. The standard formula below shows the CCDM for three subsystems [56–58]:

$$C = \left(\frac{f(X)g(Y)h(W)}{\left[\frac{f(X)g(Y)h(W)k}{3}\right]^4} \right)^{\frac{1}{3}}$$

$$D = \sqrt{CT} \text{ and } T = \alpha f(X) + \beta f(Y) + r f(W)$$

where C denotes the connection degree, and f (X), g (Y), and h (Z) represent the comprehensive levels of the marine economy, resource, and environment subsystems, respectively. Sias calculates the values of f(X), g(Y), and h(Z), as shown in Formula (8). D is the CCDM, and T is the overall development of the maritime ERE system, including subsystem contributions. The research presented here assigns equal priority to each subsystem in the coordinated development of the marine ERE system, resulting in $\alpha = \beta = \gamma = 1/3$.

Often, scholars subjectively categorize the CCDM into different levels after calculation. In this study, the quartile method is utilized for CCDM classification, which may provide a more objective approach to assessing CCDM levels. Table 1 displays the breakdown of the CCDM based on this method.

Table 1. The division of the development stages of the marine ERE system is important.

Value of D	$0 \leq D \leq 0.25$	$0.25 \leq D \leq 0.5$	$0.5 \leq D \leq 0.75$	$0.75 \leq D \leq 1$
Development stages	Seriously unbalanced	Slightly unbalanced	Barely balanced	Superior balance

3.2.3. Indicator Construction

Based on our previous investigation and the SD model framework we developed, we establish an index system to comprehensively assess the development level and coupling relationship of each subsystem within the marine ERE system. On the one hand, indicator selection should ensure that the evaluation indicators can cover the key elements of each subsystem of the marine ERE system to reflect its overall development status; on the other hand, the mutual influence and correlation between different indicators should be considered to avoid selecting independent or highly repetitive indicators and thus fully reflect the coupling relationship within the system. Table 2 shows the indicator architecture, which includes 19 indications. The marine economic subsystem shows how developed the marine economy is through four indicators: the total value of the marine environment's output, the pattern of the marine industry's three sectors, and the fund income of marine academic institutions [59]. The marine resources subsystem measures the development potential of marine resources using indicators such as aquaculture area, wetland area, marine fishing output, marine aquaculture output, and sea salt production. The marine environmental subsystem reflects the growth status of the marine environment through indicators such as the direct discharge of a large amount of industrial wastewater into the marine environment, the amount of wastewater outlets discharged into the ocean, the types of marine nature reserves in coastal areas, and storm tide disaster areas (Table 2).

Table 2. The indicator system used to assess the CCD of the marine ERE system.

Subsystem	Indicator	Direction	Unit	Weight
Economy subsystem	Gross ocean product (GOP)	+	Million yuan	0.2260
	Proportion of gross marine product in gross national product	+	%	0.1354
	Proportion of marine secondary industry	+	%	0.1390
	Proportion of marine tertiary industry	+	%	0.1450
	Port cargo throughput	+	Ten thousand tons	0.0830
	Marine shipbuilding completions	+	Ten thousand boats	0.1243
	Marine industry employees	+	Thousands of people	0.0560
	Investment in marine scientific research	+	Million yuan	0.0913
Resource subsystem	Sea water breeding area	+	Ten thousand hectares	0.2430
	Confirm area of sea area	+	Ten thousand hectares	0.1560
	Wetland area	+	Ten thousand hectares	0.2370
	Marine fishing yield	+	Million tons	0.1620
	Mariculture yield	+	Million tons	0.0920
	Sea salt yield	+	Million tons	0.1100
Environment subsystem	Direct discharge of industrial wastewater	−	Ten thousand tons	0.1212
	Comprehensive utilization of industrial solid waste	−	Ten thousand tons	0.2520
	Number of sewage outlets into the sea	−	Quantity	0.2436
	Marine-type nature reserves in coastal areas	+	Quantity	0.1350
	Storm surge damage area	−	Ten thousand hectares	0.2482

Notes: "+" and "−" represent the positive and negative indicators, respectively.

4. The Modeling of the SD Model of the Marine ERE System

4.1. The Conceptualization of the Marine ERE System

Based on the above discussion of the marine ERE system structure, the SD model of the coupled and coordinated development of China's marine ERE is built using VENSIM, and a causal relationship diagram is drawn (Figure 2).

The causal relationship diagram contains three core elements: economy, resources, and environment. The marine economy, comprising the marine primary, marine secondary, and marine tertiary industries, forms the core of this causal relationship diagram. Labor and capital have an impact on the development of the marine industry. The development of the marine secondary industry may result in high pollution. The current study identifies a feedback loop between marine economic development, energy consumption, and environmental pollution. Another path shows the opposite process. The declining state of the marine environment could hinder the growth of the marine economy or endanger human health. However, boosting investment in maritime environmental protection or streamlining the industrial structure can help bridge the gap between economic development and environmental protection. The response path is as follows: marine environment, energy consumption, and marine economic development.

4.2. Establish Stock Flow Diagram (SFD)

The stock flow diagram (SFD) is a commonly used graphical tool in the SD method, used to describe the relationship between the stock and flow of various factors in the system. In the SFD, the stock represents the amount of material or information accumulated in the system, while the flow represents the flow rate of these materials or information. Through the SFD, we can clearly see the interaction between elements in the system, which helps us better understand the behavior and change trends in the system. The SFD helps reveal the cause-and-effect relationship in the system and provides an important reference for formulating effective policies and decisions. Based on the cause-and-effect relationship in Figure 2, the SFDs of the economic, environmental, and resource subsystems were established, respectively, in Figures 3–5.

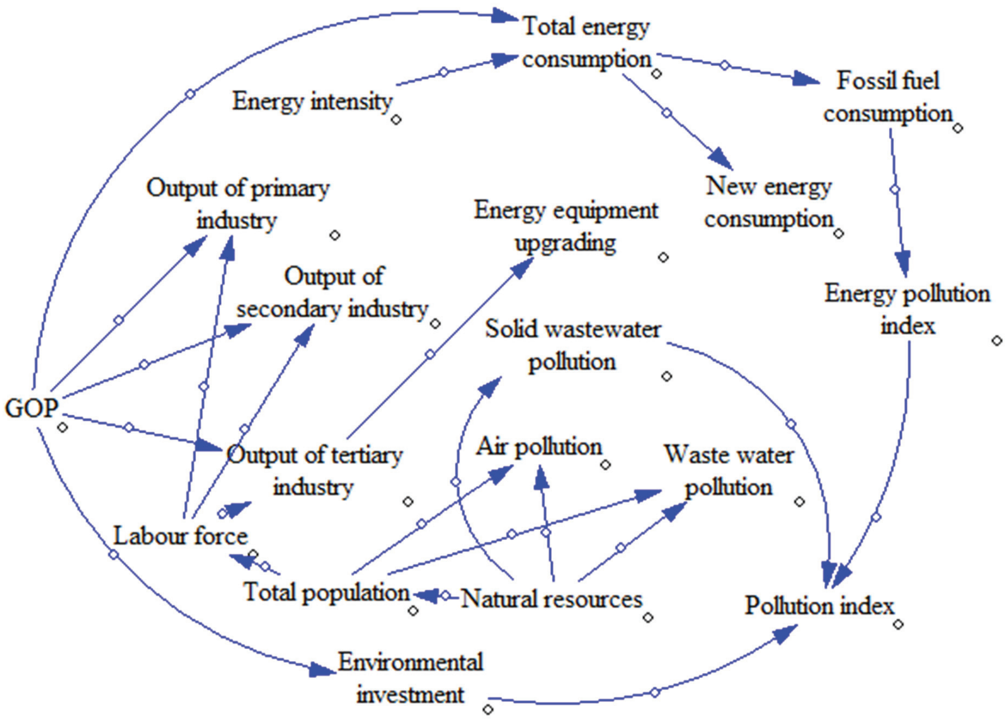

Figure 2. Causal loop diagrams of the marine ERE system.

(1) Economic subsystem

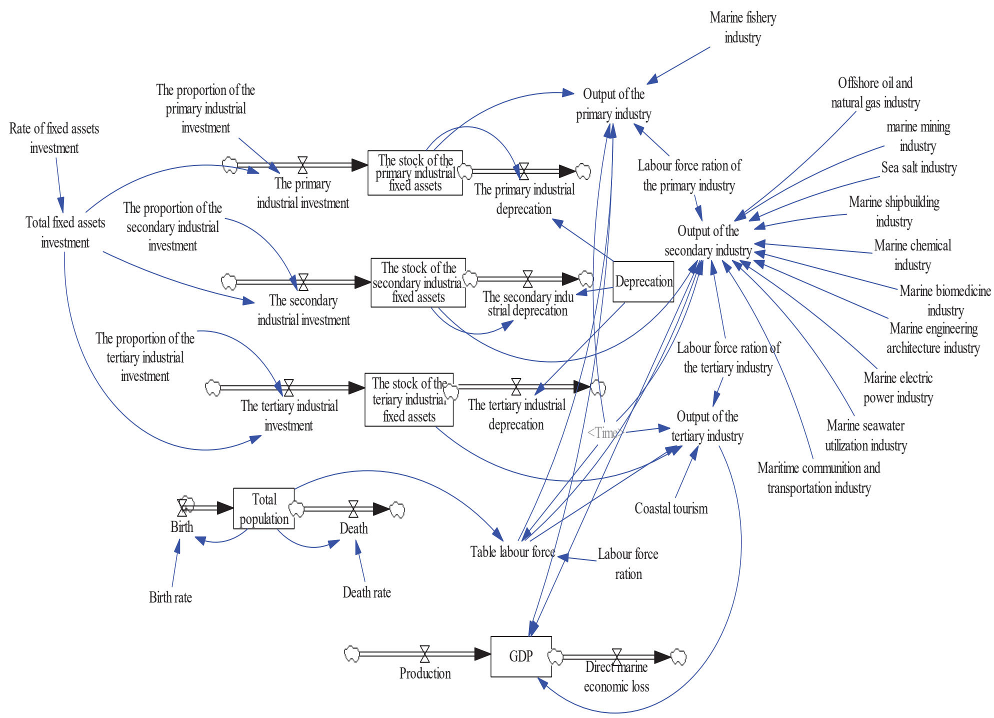

Figure 3. The SFD of the marine economy subsystem.

(2) Resource subsystem

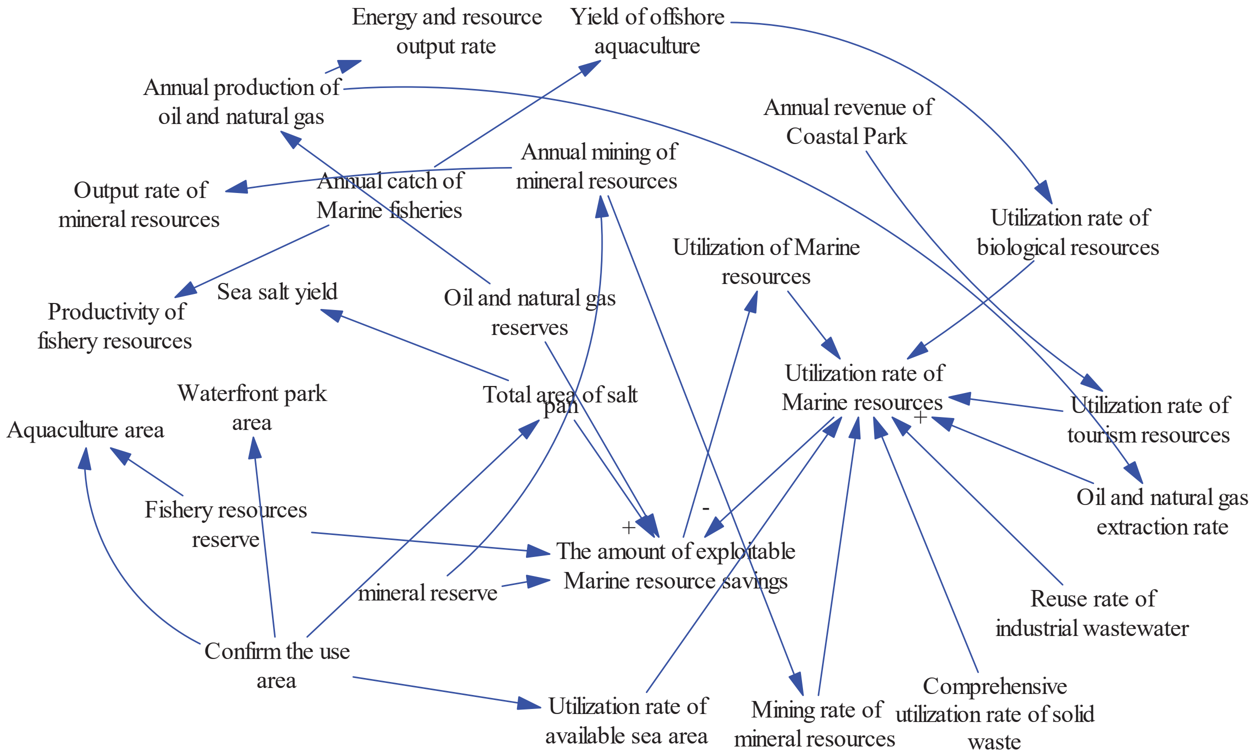

Figure 4. The SFD of the marine resource subsystem.

(3) Environmental subsystem

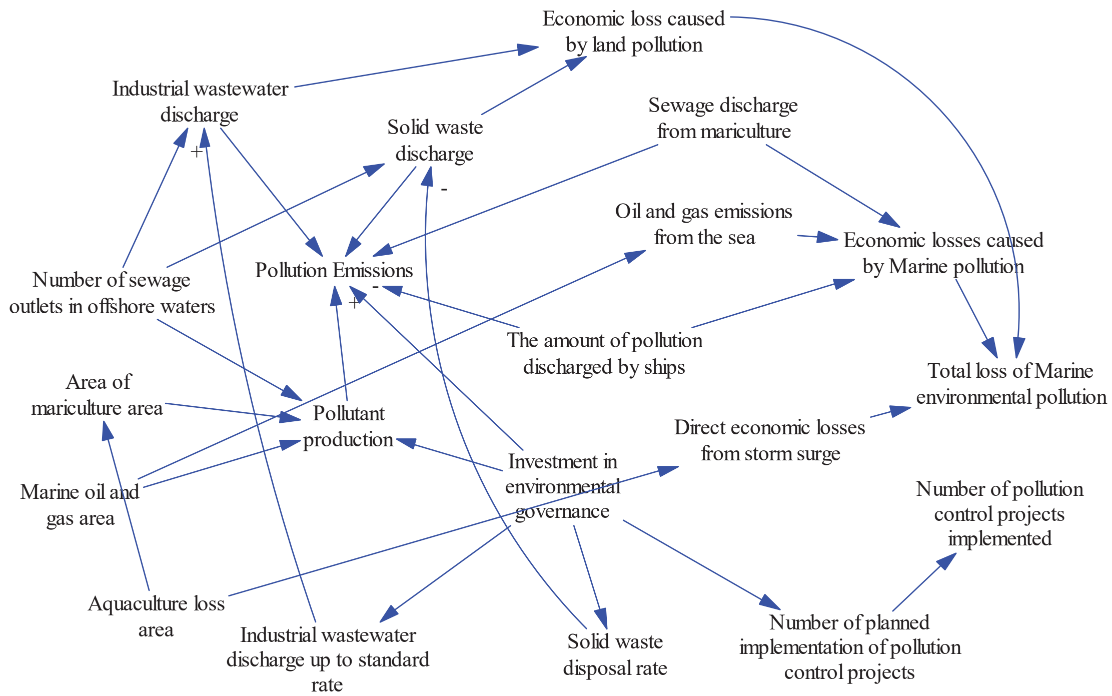

Figure 5. The SFD of the marine environmental subsystem.

4.3. Model Testing and Scenario Design

4.3.1. Model Run Check

The model running test includes two aspects: structure running test and dimension consistency test. Referring to the research by Yaman (1996), this study uses the model check tool to test the structure of the model [60]. The result demonstrates that the model is OK, which means that the structure of the model is correct, and all relations and equations are correctly defined without internal logic errors. The model is tested with the Unites Check tool, and the Unites is OK, indicating that all equations and calculations in the model have dimensional consistency. This means that the units of all variables in the model coordinate with one another, and there is no case of unit mismatch. Therefore, the model constructed in this paper passes the running test.

4.3.2. Model History Check

Compare the historical data with the simulation results of each variable after running to examine the overall prediction accuracy and effectiveness of the model. The error of the simulation results of the SD is controlled within 10% to improve the accuracy of the model, reduce uncertainty, increase credibility, and ensure its effectiveness. This allows the model to be better applied to the analysis and decision-making process of practical problems. According to the characteristics of the system model, three variables, namely, GOP, wastewater discharge, and aquaculture area, are selected for historical testing, representing the economic system, environmental system, and resource system, respectively. The simulation interval is the 2010–2022 period, representing the historical value, simulation value, and relative error of the variables. The results are shown in Table 3. In particular, the relative errors are all within 10%, which means there is a small deviation between the simulation results and actual observation values, and the model can better describe the dynamic characteristics and change laws of the system. In this case, we can compare the prediction ability of the trust model to better analyze and understand the system's behavior. We find that the model constructed in this study can truly reflect the development status of China's marine ERE system, and the model simulation effect is good.

Table 3. Historical test results.

Years	GOP			Wastewater Discharge			Aquaculture Area		
	True Value	Simulated Value	Relative Error (%)	True Value	Simulated Value	Relative Error (%)	True Value	Simulated Value	Relative Error (%)
2010	39,619.20	40,134.25	1.30%	617.00	637.98	3.40%	2080.90	2135.00	2.60%
2011	45,580.40	47,266.87	3.70%	659.00	676.13	2.60%	2106.40	2142.21	1.70%
2012	50,172.90	54,387.42	8.40%	685.00	695.96	1.60%	2180.90	2320.48	6.40%
2013	54,718.30	56,305.13	2.90%	695.00	755.47	8.70%	2315.60	2380.44	2.80%
2014	60,699.10	61,488.19	1.30%	716.00	760.39	6.20%	2305.50	2395.41	3.90%
2015	65,534.40	68,483.45	4.50%	735.00	766.61	4.30%	2317.80	2375.75	2.50%
2016	69,693.70	71,366.35	2.40%	711.00	724.51	1.90%	2098.10	2232.38	6.40%
2017	76,749.00	77,976.98	1.60%	699.66	726.25	3.80%	2084.10	2119.53	1.70%
2018	78,077.80	82,528.23	5.70%	682.30	718.46	5.30%	2043.10	2114.61	3.50%
2019	84,191.30	88,990.20	5.70%	669.00	687.06	2.70%	1992.20	2049.97	2.90%
2020	79,549.80	82,095.39	3.20%	655.80	672.85	2.60%	1995.60	2065.45	3.50%
2021	90,385.00	91,469.62	1.20%	633.58	666.53	5.20%	2025.50	2112.60	4.30%
2022	89,415.00	92,455.11	3.40%	629.36	649.50	3.20%	2074.40	2132.48	2.80%

4.3.3. The Set of Different Development Scenarios

The marine economy, resources, and environment are inseparably connected, forming a complex and interdependent system. Marine resources form the foundation of the marine economy, which propels economic growth via the marine industrial chain. Marine resources, such as fisheries, minerals, and energy, provide the foundation and support for the marine economy. These resources, directly or indirectly, supply human production and living needs while promoting the growth of the social economy. However, environmental concerns frequently accompany the growth and consumption of maritime resources. Overfishing consumes fishery products, marine pollution disrupts the ecological balance of the ocean, and the marine ecosystem faces rising strain. Therefore, maintaining the marine environment is crucial to achieving sustainable marine economic development. Only through the conservation of the marine environment can we use marine resources sustainably and ensure the steady expansion of the marine economy. To promote the development of the marine economy, it is essential to embrace sustainable resource utilization, environmental protection, and the coordinated development of economic benefits. This approach should prioritize green and sustainable development within the marine sector. Countries should strengthen cooperation, jointly formulate and implement relevant policies and measures, and work toward the coordinated development of the marine ERE, thereby contributing to the sustainable development of human society. In light of these realities, this study examines various development scenarios, on the basis of which we propose feasible policies and suggestions.

By changing the variables and settings in the existing SD model, this study assumes four development scenarios: (1) Current scenario. This scenario maintains the original values of all parameters and variables and serves as a reference for other scenarios. (2) Economic scenario. We raise investment in economic development by raising the amount of fixed asset investment in the marine industry relative to the total investment. Meanwhile, China's "14th Five-Year Plan" for marine economic growth focuses on scientific and technological innovation and industrial upgrading to support the transformation and upgrading of traditional maritime sectors. As a result, we strengthen the proportion of investment in the marine tertiary industry. (3) Resource scenario. This scenario emphasizes marine resources, mainly fishery resources. (4) Environmental scenario. This scenario emphasizes industrial structure adjustment and environmental protection investment. Investment should be increased in tertiary industries, environmental protection initiatives, and the upgrading of energy equipment.

4.4. Simulation Result

Figure 6 simulates the dynamic changes in the marine ERE system under different scenarios, with a particular focus on the evolution of the GOP under the economy, resources, environment, and current scenarios from 2010 to 2050. According to the results, the economic scenario has the highest level, followed by the resource scenario, while the current and environmental scenarios have lower levels. This result shows that the current society is relatively strong in economic development but still has weaknesses in resource utilization and environmental protection. From an economic perspective, increasing economic investment can promote economic growth and increase employment and industrial development. Especially in the case of a high current economic scenario, more economic investment is expected to accelerate economic improvement and raise the economic level. In the resource scenario, improving the energy structure will help improve environmental cleanliness, reduce resource waste and environmental pollution, and provide more sustainable support for economic development. By optimizing resource utilization, effective resource allocation can be achieved, and the healthy development of the economy can be promoted. However, in the environmental scenario, increasing environmental investment may bring certain GOP costs because environmental protection and governance often require a certain amount of funds, labor, and material resources. This may lead to a relatively low economic level in the short term. In the long run, however, protecting the environment and improving ecological conditions are also important components of sustainable development. Therefore, considering the three aspects of ERE, balance must be sought between economic growth and resource utilization; focus on sustainable development; actively promote economic transformation and upgrading; achieve a benign interaction between the economy, resources, and environment; and achieve a win–win situation for the economy and society.

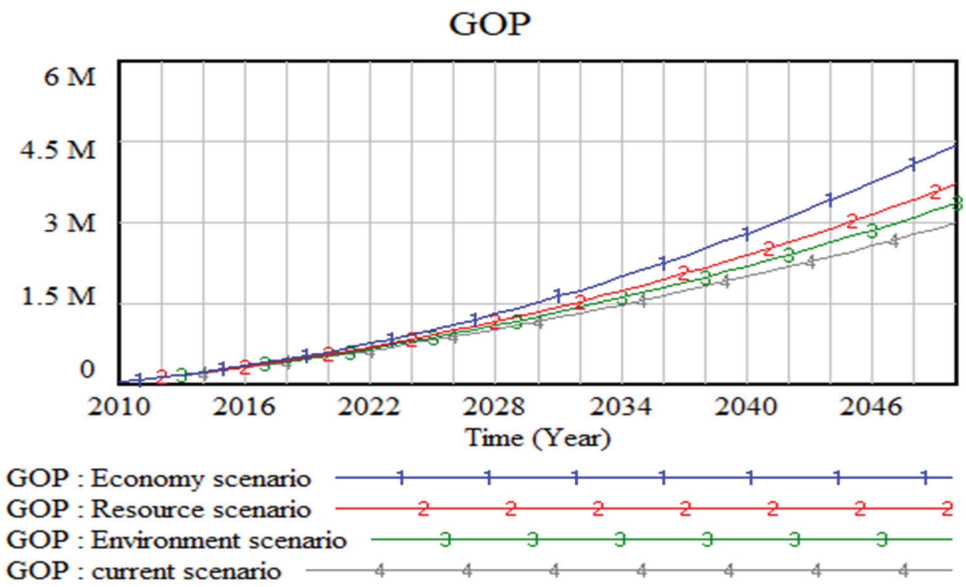

Figure 6. Simulated results of GOP under different scenarios.

Figure 7 shows the changing patterns in the marine tertiary industry under different conditions. According to the statistics, the marine tertiary industry is experiencing sluggish expansion. The rapid development of this sector has accelerated economic growth. Simultaneously, promoting the growth of the marine tertiary sector can help improve and optimize the structure of the marine industry. As an important part of the marine economy, the marine tertiary industry holds significant potential for development. Accelerating the development of sectors such as marine tourism and marine cultural and creative industries can attract more investment and resources, extend and improve related industrial chains, and inject new vitality into the marine economy. At the same time, the development of the marine tertiary industry can drive the coordinated development of related industries, promote the optimization and adjustment of the marine industrial structure, and boost overall industrial competitiveness.

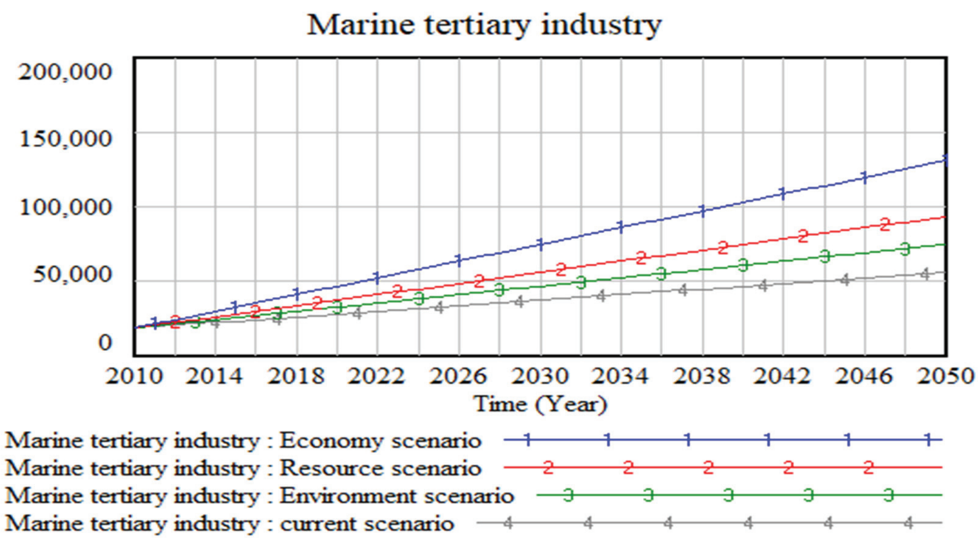

Figure 7. Simulated results of marine tertiary industry under different scenarios.

Figure 8 shows that from 2010 to 2050, the pollution index shows a trend of initially increasing and then decreasing across all scenarios–environmental, economic, resource, and current. This indicates that, over time, the pollution problem may worsen, thus attracting the attention of all sectors of society. Notably, the pollution index in the environmental scenario is relatively low, which reflects that the pollution level can be effectively controlled when environmental protection is prioritized. The pollution index in the economic scenario may be relatively high, possibly because economic development is often accompanied by industrialization and urbanization, which increase pollution emissions. The pollution index in the resource scenario may be affected by the method of resource exploitation and utilization, and if such method is not environmentally friendly, then the pollution index may rise. The pollution index in the current scenario reflects the combined effect of the current level of social and economic development and environmental protection measures.

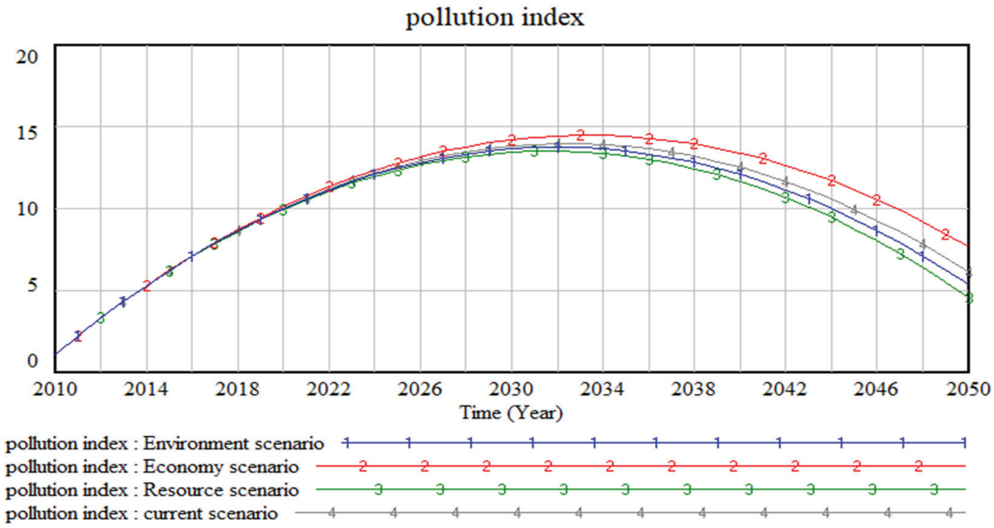

Figure 8. Simulated results of the pollution index under different scenarios.

Figure 9 shows the trend of marine wastewater accumulation from 2010 to 2050. In the economic scenario, the amount of wastewater accumulated may be relatively high, suggesting that in the pursuit of economic growth, the environmental cost (i.e., long-term investment in wastewater treatment), may be overlooked. From an economic perspective, this neglect can lead to external diseconomy, in which the total cost to society exceeds the sum of private costs plus benefits. The resource scenario may show trends in wastewater accumulation under the more efficient use of resources, including wastewater treatment resources. The increase in wastewater accumulation usually has a negative impact on the environment, such as the deterioration of water quality and the destruction of ecosystems. These effects tend to have externalities; they are not directly reflected in market transactions, so the market cannot automatically correct these problems. In the environmental scenario, the amount of wastewater accumulated is relatively low, suggesting that through environmental policy interventions (e.g., stricter discharge standards, environmental regulations), market failures can be reduced and the environment protected from pollution.

Figure 10 shows projected trends in the aquaculture area from 2010 to 2050 under different scenarios. Under the economic scenario, the aquaculture area shows a relatively significant growth trend, reflecting the increasing demand for aquatic products driven by economic growth and population increase. This trend suggests that the expansion of the aquaculture industry will likely help meet market demand and become a new driver of economic growth. However, by around 2030, the growth rate of consumer demand for aquatic products may slow down due to market saturation, resulting in a weakened impetus for further expansion of aquaculture areas. With regard to sustainability, the trends in aquaculture acreage under the current scenario are likely to fall between those observed in the economic and environmental scenarios. This indicates that while pursuing economic benefits, it is necessary to consider environmental and social costs to achieve sustainable development goals.

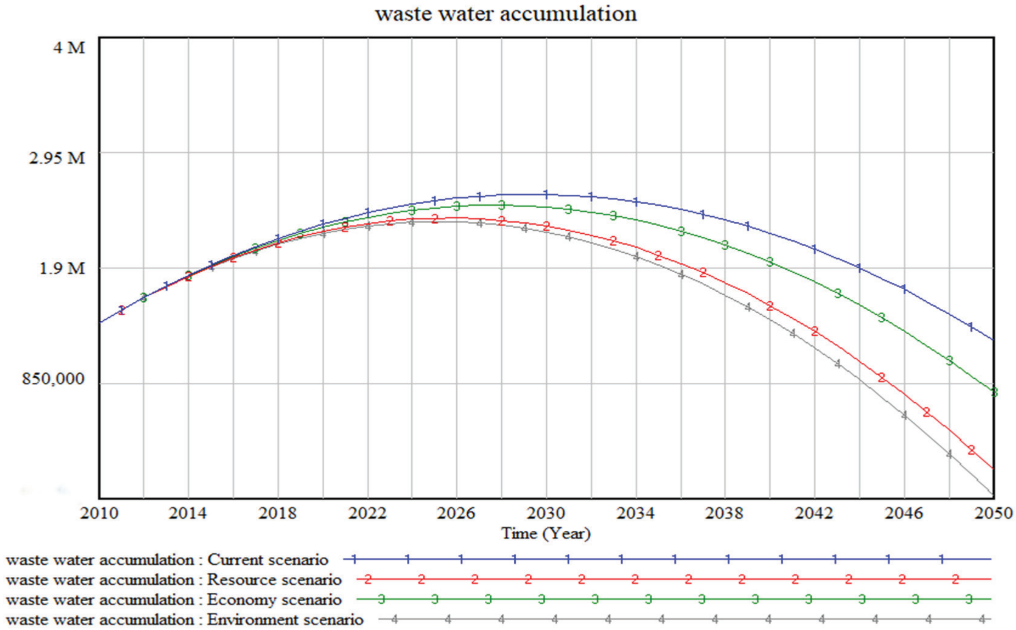

Figure 9. Simulated results of wastewater accumulation under different scenarios.

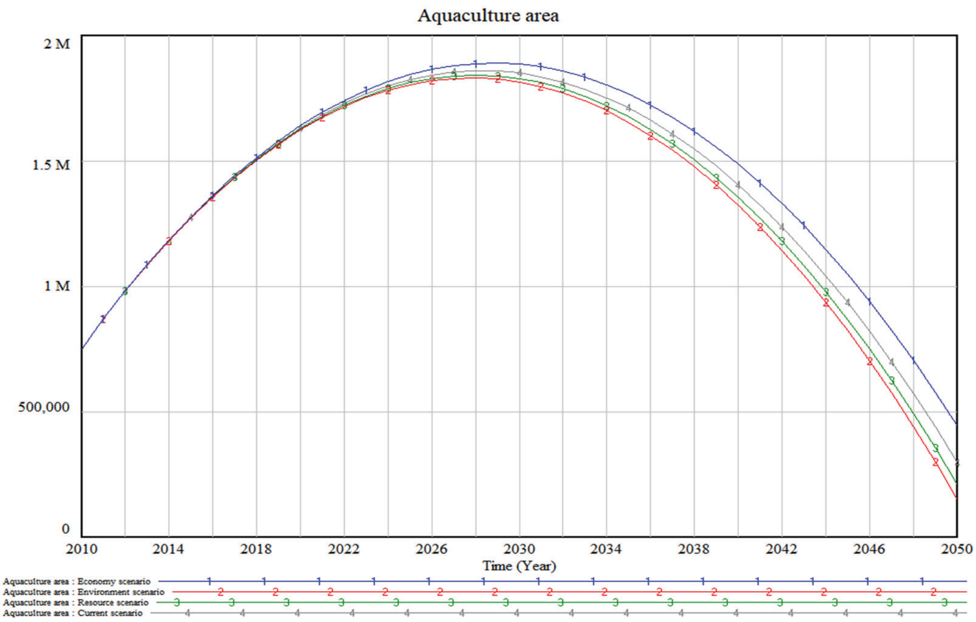

Figure 10. Simulated results of the aquaculture area under different scenarios.

In conclusion, the marine ERE model developed in this study offers a more comprehensive depiction of the dynamic interplay among economic, resource, and environmental subsystems.

5. An Evaluation of the Coupling Coordination Degree

5.1. Development of Each Subsystem under Different Scenarios

Table 2 illustrates how the value of the marine industry has the highest index weight within the economic subsystem, followed by the marine tertiary industry, secondary industry, and completion of ship construction [30]. As a result, between 2010 and 2022, the economic advancement of the marine industry was an essential element in the evolution of China's maritime sector, with the marine tertiary industry providing the fundamental push for the development of the economic subsystem. The rapid expansion of the marine economy not only fosters economic growth in coastal regions but also drives scientific and technological innovation while enhancing the sustainable utilization of marine resources. The economic upsurge of the marine industry serves as a potent driving force for the advancement of China's maritime sector and is poised to continue playing a crucial role in the future. The development of the marine secondary industry and the construction of ships symbolize the establishment of maritime infrastructure, which serves as a fundamental catalyst for the growth of China's marine economy. Ports and shipping are critical to the infrastructure of the marine economy. Modern port facilities and efficient shipping networks can significantly improve logistics efficiency and reduce transportation costs, thereby boosting international trade and economic growth. Many important ports in China, such as the Shanghai Port and Ningbo Zhoushan Port, are constantly upgrading and expanding, providing strong support for shipping.

Figure 11 depicts the growth of the economic subsystem under different scenarios. Over the next 30 years, the aggregate level of all scenarios will rise, with the increase rate accelerating after 2030. After 2030, the growth rate will accelerate significantly due to technological breakthroughs, policy improvements, and other factors. Driven by technology, policy, and market forces, the marine economy will develop into a new growth point for the global economy, bringing extensive economic, ecological, and social benefits.

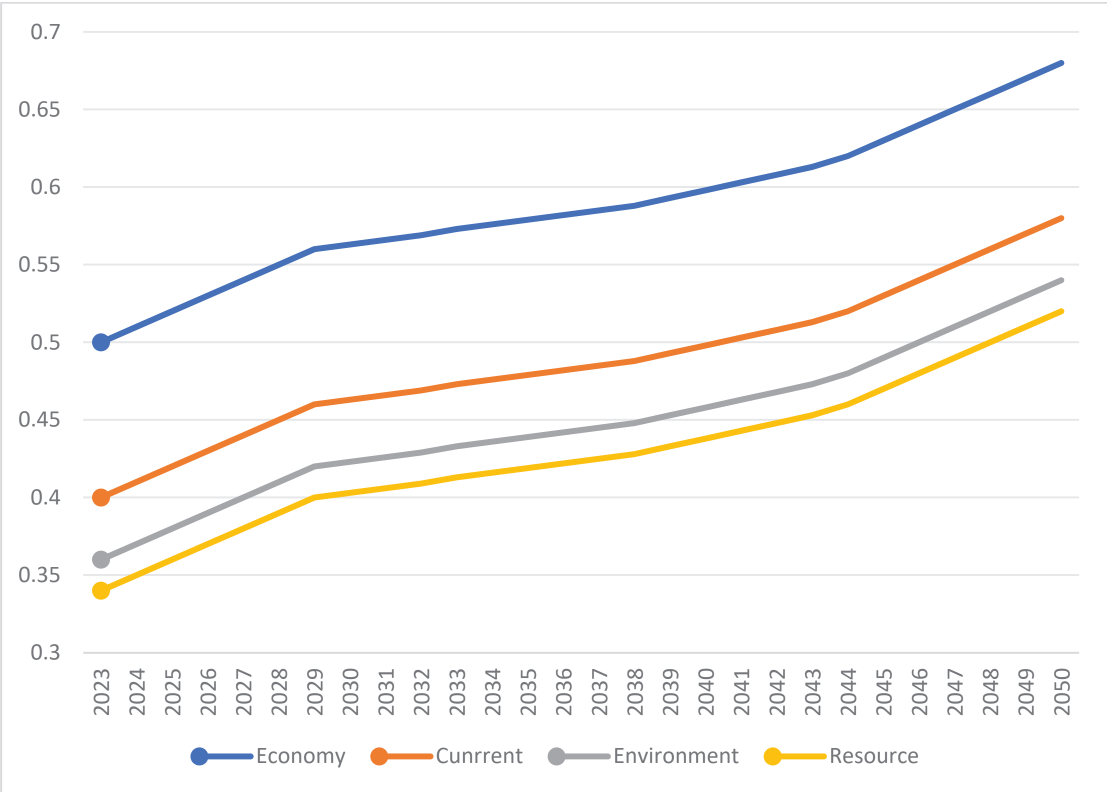

Figure 11. Trends in the comprehensive level of the economy subsystem under different scenarios.

We select six indexes in the resource subsystem, with the mariculture and wetland areas exerting a greater influence. Through intensive and scientific management methods, mariculture can greatly improve the utilization efficiency of marine living resources. Compared to traditional fishing methods, it can produce marine products in a more controlled manner, reducing the dependence and pressure on wild populations. Wetlands are important ecosystems with various ecological functions, such as water purification, flood regulation, soil conservation, and biodiversity maintenance. They can effectively filter pollutants, improve water quality, and play a key role in maintaining the ecological balance of marine and coastal areas. Wetlands have a strong carbon capture capacity and can absorb and store large amounts of carbon dioxide, thus playing a key role in combating climate change. Protecting and restoring wetlands is one of the most effective ways to reduce greenhouse gas concentrations. The second is the production of marine fishing and farming. Fishing is one of the key sources of global protein supply, especially in developing countries, where many people's diets derive important animal protein from products caught from marine environments. Reasonable fishing helps maintain the numbers of certain stocks, but overfishing can lead to the depletion of fish stocks and disrupt the balance of marine ecosystems. All scenarios in China showed an increasing trend during the simulation period (Figure 12).

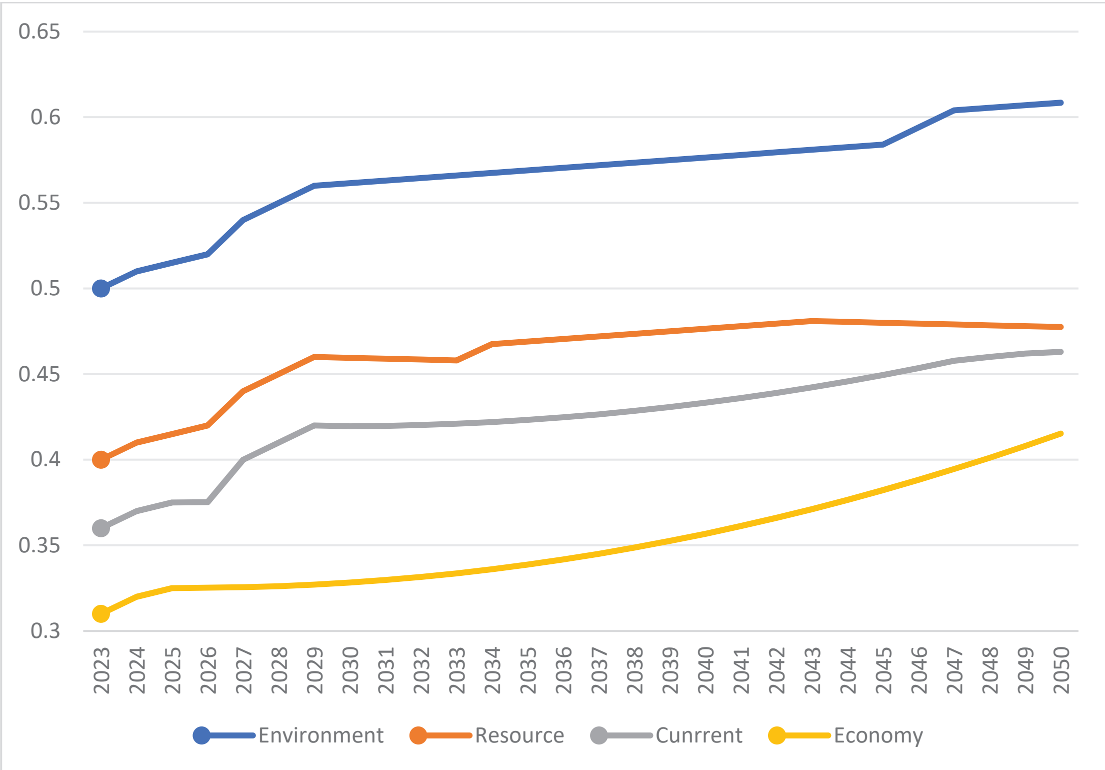

Figure 12. Trends in the comprehensive level of the resource subsystem under different scenarios.

Figure 12 depicts how the marine economic subsystem develops under various scenarios. The aggregate level of all scenarios will rise over the next 30 years, with the rate of growth picking up after 2030. With the exception of the resource scenario, we rank the remaining possibilities as follows: environment, current, and economy. Combined with Figure 11, we see that the higher the economic system, the lower the resource system. This finding suggests that the progress of China's marine economy is mainly dependent on resource extraction.

The marine environment subsystem is heavy, and the weights of the five indicators are level. The storm surge disaster area, number of sewage discharge outlets into the sea, marine type of nature reserves in coastal areas, and large-scale direct discharge of industrial wastewater all contribute to the comprehensive exploitation of industrial solid waste. Industrial solid waste is the most extensively used type of waste, and it plays a significant role in the marine environmental subsystem. The integrated use of industrial solid waste effectively protects the marine environment and brings significant economic and social benefits by reducing land-based pollution, promoting a circular economy, preventing marine litter and pollution, promoting sustainable development, and enhancing technological and management innovation. Storm surges not only affect human activities but also damage natural ecosystems. Wetlands and mangroves are important components of coastal ecosystems, and storm surges can lead to the destruction of plant and animal habitats in these areas. Storm surges can carry sediment and pollutants, causing water quality to deteriorate and affecting the survival of aquatic life. Powerful waves and rapid changes in the marine environment can cause damage to marine habitats in coastal and shallow waters, affecting biodiversity.

Figure 13 depicts how the comprehensive level of environmental subsystems changes from 2023 to 2050 under various scenarios. The outcomes, similar to the two other subsystems, follow an upward trend across all scenarios throughout the simulation period. The environmental scenario outperforms the economic scenario. The resource scenario marginally outperforms the current scenario, with the difference between the two increasing over time. We can link this discovery to the positive environmental consequences of continuous improvements in the energy mix.

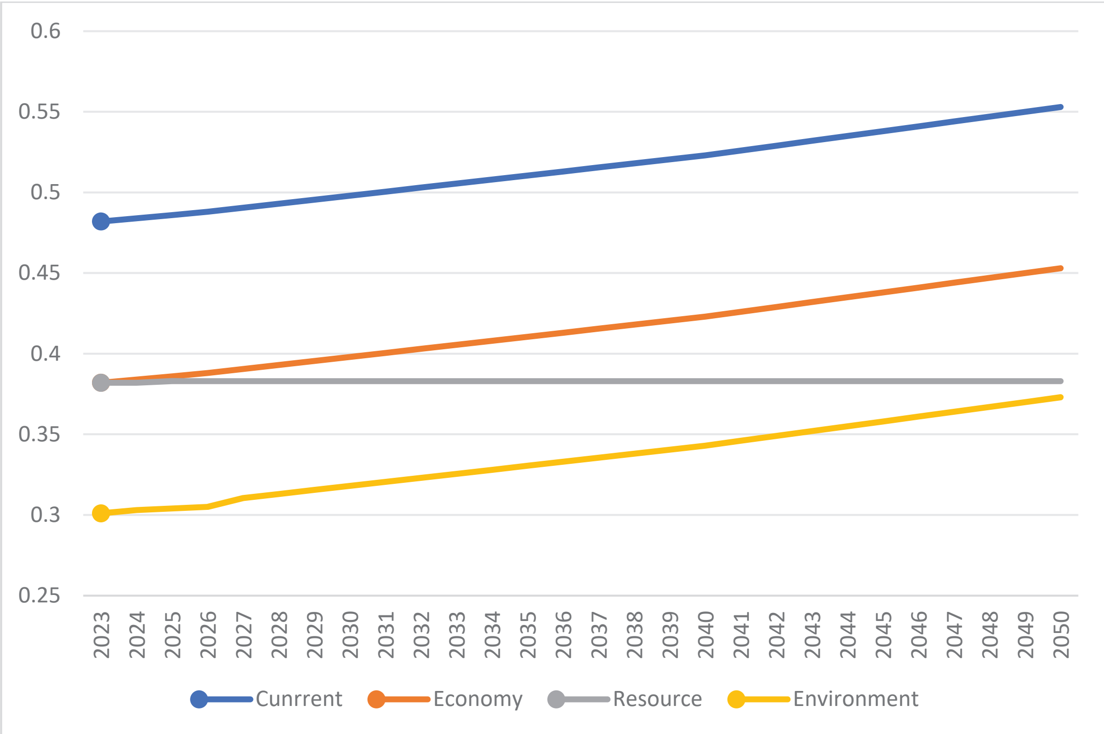

Figure 13. Trends in the comprehensive level of the environment subsystem under different scenarios.

5.2. CCD Results Under Different Scenarios

The above data show that the evolutionary paths of marine subsystems vary across circumstances. Hence, a complete evaluation approach should be used to examine and compare the effectiveness of each strategy. As the marine ERE model has many complicated relationships, this study uses the CCDM from Section 3.2 to determine the degree of coupling and the best case scenario.

Figure 14 displays the pattern of coupling degree changes over the four scenarios, indicating the interaction of various subsystems. Clearly, the patterns in these four scenarios vary significantly. Although the total connectivity grows across the simulation period, the economic scenario remains at its lowest level. The other three possibilities fluctuate slightly but remain between 0.30 and 0.34. The resource scenario has the lowest degree of coupling at the start of the simulation interval, but it rapidly increases with time, eventually surpassing the environment and current scenarios in 2035. In the later stages, the general state of the environment and current condition fluctuates and eventually declines.

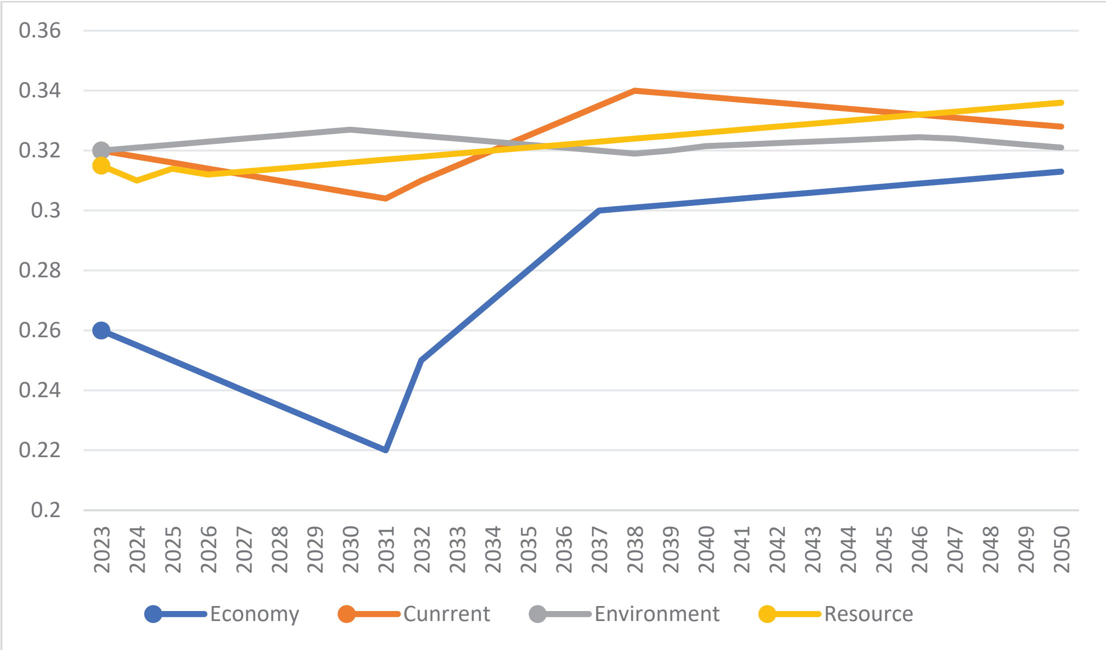

Figure 14. Trends in the coupling degree under different scenarios.

A comparison of the CCD under the four scenarios shows that, although there are some differences, the overall trend is consistent (Figure 14). The results in Table 3 show that all scenarios are slightly uneven during the simulation period. Figure 15 shows that weak coupling between the three subsystems is the primary cause of the low CCD level. We then investigate and comment on the evolution of CCD in each scenario.

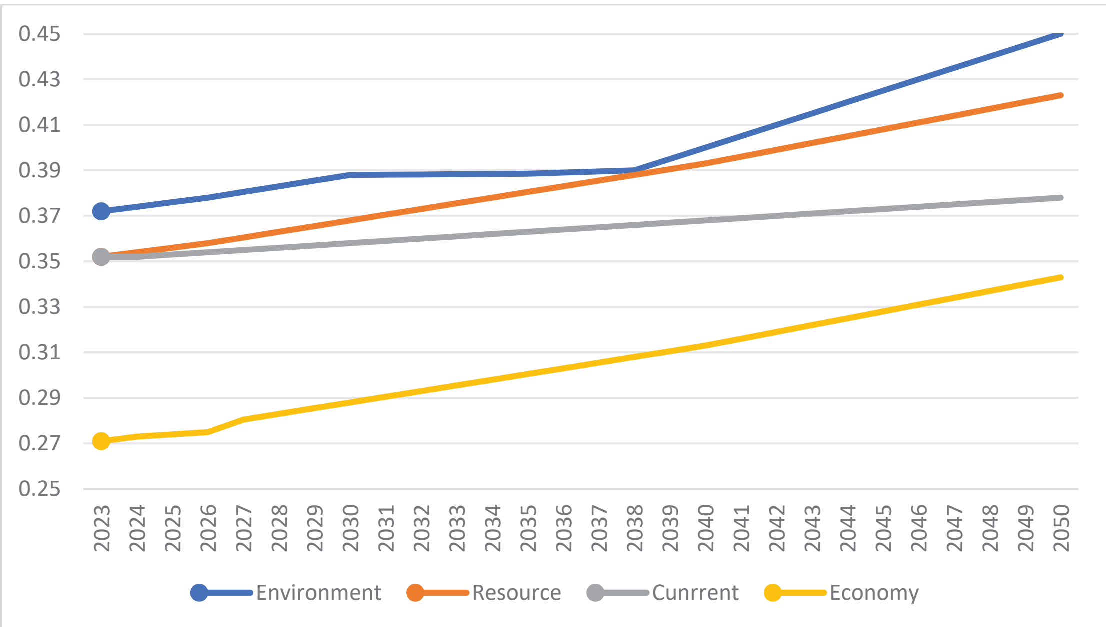

Figure 15. Trends in the CCD under different scenarios.

(1) Economic scenario: The CCD value grew from 0.28 to 0.32, the lowest among all scenarios. Throughout the simulation interval, the marine economic subsystem performed well, while the marine resources and environment subsystem performed poorly. These findings help clarify the lack of coupling phenomena depicted in

Figure 14, demonstrating that an overemphasis on economic development will result in disorganized expansion in China's maritime economy.

(2) Resource scenario: In this scenario, the CCD value rose from 0.53 to 0.2 before finally reaching the ideal level. This expansion can be separated into two stages (Figure 15). Although the resource level in this scenario peaked between 2023 and 2050, the economic and environmental levels were relatively modest, resulting in a lesser coupling degree than the current and environmental scenarios (Figure 13). As the benefits of enhanced energy structure and natural environment become more obvious after 2023, we see an acceleration in the CCD value during this period.

(3) Environmental scenario: In this scenario, the CCD value rose from 0.37 to 0.46 and remained in the optimal condition. The proportions of each component in this scenario stay high in comparison to other scenarios (Figures 10–12). However, as the resource level decreases after 2035, coupling begins to gradually decrease (Figure 11).

6. Conclusions

6.1. Results

We investigated and appraised the simulation results of China's marine industry system using the methods and theories of SD and the CCDM. We first used SD to create a system model that integrates the interactions of the marine ERE subsystems. We then evaluated the CCD under various circumstances using the developed CCDM. Specifically, our SD model adjusts parameters to replicate four typical scenarios: the maritime economy, resources, environment, and the present. This research aimed to clearly illustrate the interdependence of various components within the marine ERE system through a comparative analysis of these four scenarios and, ultimately, offer guidance for the sustainable development of the marine industry in other countries. This investigation's conclusions reveal the following: (1) The SD model we developed can accurately replicate the dynamic interactions in the marine ERE system. (2) Different scenarios highlight different elements. Compared to the current scenario, the marine economic scenario promotes economic growth while harming the environment and resources. On the contrary, the resource and environmental scenarios are both beneficial to energy conservation and emission reduction but not to marine economic development. (3) The coupling levels of the various scenarios differ. In comparison to the current scenario, the economic scenario performs poorly, while the environmental scenario performs well. However, the resource scenario has a greater influence on the long-term coordinated growth of the urban ERE system.

These conclusions may differ from the research of other scholars in that this study focuses on the relationship between different factors. Some scholars may be more inclined to emphasize the importance of economic growth and believe that the development of the marine economy is a priority. They may believe that the development of the marine economy can create employment opportunities, promote industrial upgrading, and increase fiscal revenue, thereby driving the growth of the entire economy. Long-term economic development must be based on the sustainable use of the environment and its resources.

This view often focuses on the positive impact of economic development on social stability and the improvement of people's lives. To achieve sustainability in the marine economy, China and governments around the world should take beneficial actions to promote diversification and technological innovation, rationally manage and efficiently use marine resources, effectively protect the marine ecological environment, and strengthen international cooperation and coordination, beginning with the economy, resources, and environment. These efforts will not only serve to foster the healthy development of the maritime sector but also contribute to the global aim of sustainable development.

6.2. Research Shortcomings

This study has some limitations that need to be improved in future research: (1) The complexity of model construction. The marine ERE system is a huge and complex system involving the interaction of multiple factors. The establishment of a dynamic simulation and evaluation model needs to consider the influence of various factors, making model construction very complicated. (2) Difficulty in data acquisition. The marine ERE system involves data from multiple fields, including economic data, resource data, and environmental data, among various others. The acquisition and organization of these data require considerable time and effort, and sometimes, the quality and integrity of the data cannot be guaranteed. (3) Uncertainty in parameter settings. Various parameters need to be set when building a model, but the values of some parameters may have certain uncertainties. Different parameter settings may lead to different simulation results, thus affecting the accuracy of the evaluation.

Author Contributions: Conceptualization, W.Y.; Methodology, X.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by [Sino-Indonesian technical cooperations in coastal marine ranching, Asian Cooperation Fund Program] grant number [12500101200021002]; [Research on Trading System Based on Marine Carbon Sink Accounting in Guangdong Province, Guangdong Provincial Department of Education Youth innovative talent project] grant number [2023WQNCX022]; [Study on the value and realization of mangrove carbon Sink in Guangdong Province, Humanities and Social Sciences project, Guangdong Ocean University] grant number [030301522302]; [2024 Youth Innovation Talent Program in Ordinary Universities of Guangdong Province] grant number [2024WQNCX097]; And The APC was funded by [12500101200021002]. Information regarding the funder and the funding number should be provided.

Data Availability Statement: The data is included in the article. The data used are from Marine Information Network of PRC (http://www.nmdis.org.cn), Ministry of Ecology and Environment, PRC (https://www.mee.gov.cn).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Zeller, D.; Palomares, M.L.; Pauly, D. Global Fisheries Science Documents Human Impacts on Oceans: The Sea Around Us Serves Civil Society in the Twenty-First Century. *Annu. Rev. Mar. Sci.* **2023**, *15*, 147–165. [CrossRef] [PubMed]
2. Chen, J.; Chen, H.; Smith, T.F.; Rangel-Buitrago, N. Analyzing the impact and evolution of ocean & coastal management: 30 years in retrospect. *Ocean Coast. Manag.* **2023**, *242*, 106697. [CrossRef]
3. Desiderius, C.P.M. Coastal and marine resource use conflicts and sustainable development in Tanzania. *Ocean Coast. Manag.* **2000**, *43*, 475–494.
4. Qian, X. Research on the coordinated development model of marine ecological environment protection and economic sustainable development. *J. Sea Res.* **2023**, *193*, 102377. [CrossRef]
5. Wang, S.; Li, W.; Xing, L. A Review on Marine Economics and Management: How to Exploit the Ocean Well. *Water* **2022**, *14*, 2626. [CrossRef]
6. Li, J.-M.; Jiang, S.-S. How can governance strategies be developed for marine ecological environment pollution caused by sea-using enterprises?—A study based on evolutionary game theory. *Ocean Coast. Manag.* **2023**, *232* (Suppl. C), 106447. [CrossRef]
7. Zhang, K.; Tian, S.-Z.; Wu, Y.; Wu, J.; Liu, N.; Wang, D. Evaluation of China's maritime power construction index and policy textual analysis. *Mar. Econ. Manag.* **2023**, *6*, 59–71. [CrossRef]
8. Pata, U.K.; Erdogan, S.; Ozkan, O. Is reducing fossil fuel intensity important for environmental management and ensuring ecological efficiency in China? *J. Environ. Manag.* **2023**, *329* (Suppl. C), 117080. [CrossRef]
9. Yao, W.; Zhang, W.; Li, W. Promoting the development of marine low carbon through the digital economy. *J. Innov. Knowl.* **2023**, *8*, 100285. [CrossRef]
10. Péquin, B.; Cai, Q.; Lee, K.; Greer, C.W. Natural attenuation of oil in marine environments: A review. *Mar. Pollut. Bull.* **2022**, *176*, 113464. [CrossRef]
11. Ren, W.; Ji, J. How do environmental regulation and technological innovation affect the sustainable development of marine economy: New evidence from China's coastal provinces and cities. *Mar. Policy* **2021**, *128*, 104468. [CrossRef]
12. Kong, H.; Zhang, Y.; Zhang, Y.; Xu, Y.; Zhou, G.; Wang, S. Exploring Integrated Ocean Management Policy in China: Evolution, Challenges, and Prospects. *Water* **2024**, *16*, 1673. [CrossRef]
13. Hu, W.d.; Liu, J.; Ma, Z.; Wang, Y.; Zhang, D.; Yu, W.; Chen, B. China's marine protected area system: Evolution, challenges, and new prospects. *Mar. Policy* **2020**, *115*, 103780. [CrossRef]
14. Li, Y. Legislation and Policy on Pollution Prevention and the Control of Marine Microplastics. *Water* **2022**, *14*, 2790. [CrossRef]
15. Zou, W.; Yang, Y.; Yang, M.; Zhang, X.; Lai, S.; Chen, H. Analyzing efficiency measurement and influencing factors of China's marine green economy: Based on a two-stage network DEA model. *Front. Mar. Sci.* **2023**, *10*, 1020373. [CrossRef]

16. Allen, C.; Metternicht, G.; Wiedmann, T. National pathways to the Sustainable Development Goals (SDGs): A comparative review of scenario modelling tools. *Environ. Sci. Policy* **2016**, *66*, 199–207. [CrossRef]
17. Schoenenberger, L.; Schmid, A.; Tanase, R.; Beck, M.; Schwaninger, M. Structural Analysis of System Dynamics Models. *Simul. Model. Pract. Theory* **2021**, *110*, 102333. [CrossRef]
18. Perry, R.I.; Cury, P.; Brander, K.; Jennings, S.; Möllmann, C.; Planque, B. Sensitivity of marine systems to climate and fishing: Concepts, issues and management responses. *J. Mar. Syst.* **2010**, *79*, 427–435. [CrossRef]
19. Wu, Y.; Li, H.; Gu, Y.; Hu, H.; Zhou, G.; Yuan, Q. How can the lead industry improve sustainability based on the resource-economy-carbon nexus system? *Sustain. Prod. Consum.* **2024**, *49*, 82–91. [CrossRef]
20. Zhang, Y.; Zhu, T.; Guo, H.; Yang, X. Analysis of the coupling coordination degree of the Society-Economy-Resource-Environment system in urban areas: Case study of the Jingjinji urban agglomeration, China. *Ecol. Indic.* **2023**, *146* (Suppl. C), 109851. [CrossRef]
21. Xu, Y.; Chen, B.; Wu, J.; Dan, S.F.; Zhang, X.; Lu, D.; Duan, K. Comparative assessment of the environmental pollution and marine economic growth of Guangxi and China by using the environmental Kuznets curve fitting mode. *Environ. Sci. Pollut. Res. Int.* **2023**, *30*, 119406–119418. [CrossRef] [PubMed]
22. Jin, Y.; Xie, K.; Liu, G.; Peng, Y.; Wan, B. Nonlinear dynamics modeling and analysis of a marine buoy single-point mooring system. *Ocean Eng.* **2022**, *262*, 112031. [CrossRef]
23. Shao, Q.; Guo, G.; Junjie, K.; Kang, P. Environmental response to growth in the marine economy and urbanization: A heterogeneity analysis of 11 Chinese coastal regions using a panel vector autoregressive model. *Mar. Policy* **2021**, *124*, 104350. [CrossRef]
24. Noble, M.M.; Harasti, D.; Pittock, J.; Doran, B. Linking the social to the ecological using GIS methods in marine spatial planning and management to support resilience: A review. *Mar. Policy* **2019**, *108*, 103657. [CrossRef]
25. dos Santos, L.C.T.; Giannetti, B.F.; Agostinho, F.; Liu, G.; Almeida, C.M. A multi-criteria approach to assess interconnections among the environmental, economic, and social dimensions of circular economy. *J. Environ. Manag.* **2023**, *342*, 118317. [CrossRef]
26. Jing, Z.; Wang, J. Sustainable development evaluation of the society–economy–environment in a resource-based city of China:A complex network approach. *J. Clean. Prod.* **2020**, *263*, 121510. [CrossRef]
27. Wang, Y.; Song, C.; Cheng, C.; Wang, H.; Wang, X.; Gao, P. Modelling and evaluating the economy-resource-ecological environment system of a third-polar city using system dynamics and ranked weights-based coupling coordination degree model. *Cities* **2023**, *133*, 104151. [CrossRef]
28. Liu, F.; Huang, Y.; Zhang, L.; Li, G. Marine environmental pollution, aquatic products trade and marine fishery Economy—An empirical analysis based on simultaneous equation model. *Ocean Coast. Manag.* **2022**, *222*, 106096. [CrossRef]
29. Sun, J.; Miao, J.; Mu, H.; Xu, J.; Zhai, N. Sustainable development in marine economy: Assessing carrying capacity of Shandong province in China. *Ocean Coast. Manag.* **2022**, *216*, 105981. [CrossRef]
30. Guo, J.; Yuan, X.; Song, W. Driving forces on the development of China's marine economy: Efficiency and spatial perspective. *Ocean Coast. Manag.* **2022**, *224*, 106192. [CrossRef]
31. Bao, C.; Wang, H.; Sun, S. Comprehensive simulation of resources and environment carrying capacity for urban agglomeration: A system dynamics approach. *Ecol. Indic.* **2022**, *138*, 108874. [CrossRef]
32. Xing, L.; Xue, M.; Hu, M. Dynamic simulation and assessment of the coupling coordination degree of the economy–resource–environment system: Case of Wuhan City in China. *J. Environ. Manag.* **2019**, *230*, 474–487. [CrossRef]
33. Chen, X.; Yu, Z.; Liang, C.; Di, Q. Where Is the Path to Sustainable Marine Development? Evaluation and Empirical Analysis of the Synergy between Marine Carrying Capacity and Marine Economy High-Quality Development. *Water* **2024**, *16*, 394. [CrossRef]
34. Shao, W.; Xiong, Y.; Shi, D.; Xu, X.; Yue, W.; Soomro, M.A. Time dependent analysis of lateral bearing capacity of reinforced concrete piles combined with corrosion and scour. *Ocean Eng.* **2023**, *282*, 115065. [CrossRef]
35. Yao, W.; Zhang, W.; Li, W.; Li, P. Measurement and Evaluation of Convergence of Japan's Marine Fisheries and Marine Tourism. *Sustainability* **2022**, *14*, 9108. [CrossRef]
36. Lebdioui, A. The political economy of moving up in global value chains: How Malaysia added value to its natural resources through industrial policy. *Rev. Int. Political Econ.* **2022**, *29*, 870–903. [CrossRef]
37. Wang, S.; Lu, B.; Yin, K. Financial development, productivity, and high-quality development of the marine economy. *Mar. Policy* **2021**, *130*, 104553. [CrossRef]
38. Ababouch, L.; Nguyen, K.A.T.; de Souza, M.C.; Fernandez-Polanco, J. Value chains and market access for aquaculture products. *J. World Aquacult. Soc.* **2023**, *54*, 527–553. [CrossRef]
39. Huyen, N.T.T.; Hoa, T.T.M.; Ha, L.T. The Role of Knowledge-Sharing in Improving Marine Living Resources Towards Sustainable Blue Economy. *J. Knowl. Econ.* **2024**, 195. [CrossRef]
40. Zhong, H. Exploitation and utilization of marine resources and protection of marine ecology. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *369*, 012009. [CrossRef]
41. Iyiola, A.O.; Akinrinade, A.J.; Ajayi, F.O. Effects of Water Pollution on Biodiversity Along the Coastal Regions. In *Biodiversity in Africa: Potentials, Threats and Conservation*; Springer: Singapore, 2022; pp. 345–367.
42. Kibria, G.; Nugegoda, D.; Rose, G.; Haroon, A.Y. Climate change impacts on pollutants mobilization and interactive effects of climate change and pollutants on toxicity and bioaccumulation of pollutants in estuarine and marine biota and linkage to seafood security. *Mar. Pollut. Bull.* **2021**, *167*, 112364. [CrossRef] [PubMed]
43. Qi, X. The conceptual framework of the national blue economic system: A multiagent perspective. *Mar. Policy* **2022**, *145*, 105287. [CrossRef]

44. Restrepo-Gómez, D.C.; Zetina-Rejón, M.J.; Zepeda-Domínguez, J.A. Trends in marine fisheries social-ecological systems studies. *Ocean Coast. Manag.* **2022**, *220* (Suppl. C), 106076. [CrossRef]
45. Kedong, Y.; Liu, Z.; Zhang, C.; Huang, S.; Li, J.; Lv, L.; Su, X.; Zhang, R. Analysis and forecast of marine economy development in China. *Mar. Econ. Manag.* **2022**, *5*, 1–33. [CrossRef]
46. Li, L.; Wu, B.; Patwary, A.K. RETRACTED ARTICLE: How marine tourism promote financial development in sustainable economy: New evidences from South Asia and implications to future tourism students. *Environ. Sci. Pollut. Res.* **2022**, *29*, 1155–1172. [CrossRef]
47. Cochrane, K.L. Reconciling sustainability, economic efficiency and equity in marine fisheries: Has there been progress in the last 20 years? *Fish Fish.* **2021**, *22*, 298–323. [CrossRef]
48. Andrews, N.; Bennett, N.J.; Le Billon, P.; Green, S.J.; Cisneros-Montemayor, A.M.; Amongin, S.; Gray, N.J.; Sumaila, U.R. Oil, fisheries and coastal communities: A review of impacts on the environment, livelihoods, space and governance. *Energy Res. Soc. Sci.* **2021**, *75*, 102009. [CrossRef]
49. Xu, Y.; Lin, J.; Yin, B.; Martens, P.; Krafft, T. Marine fishing and climate change: A China's perspective on fisheries economic development and greenhouse gas emissions. *Ocean Coast. Manag.* **2023**, *245*, 106861. [CrossRef]
50. Bölük, G.; Mert, M. Fossil & renewable energy consumption, GHGs (greenhouse gases) and economic growth: Evidence from a panel of EU (European Union) countries. *Energy* **2014**, *74*, 439–446. [CrossRef]
51. Guo, J.; Jiang, C.; Wang, Y.; Yang, J.; Huang, W.; Gong, Q.; Zhao, Y.; Yang, Z.; Chen, W.; Ren, H. Exploring ecosystem responses to coastal exploitation and identifying their spatial determinants: Re-orienting ecosystem conservation strategies for landscape management. *Ecol. Indic.* **2022**, *138*, 108860. [CrossRef]
52. Ward, D.; Melbourne-Thomas, J.; Pecl, G.T.; Evans, K.; Green, M.; McCormack, P.C.; Novaglio, C.; Trebilco, R.; Bax, N.; Brasier, M.J.; et al. Safeguarding marine life: Conservation of biodiversity and ecosystems. *Rev. Fish. Biol. Fish.* **2022**, *32*, 65–100. [CrossRef] [PubMed]
53. Zhou, Y.; Li, G.; Zhou, S.; Hu, D.; Zhang, S.; Kong, L. Spatio-temporal differences and convergence analysis of green development efficiency of marine economy in China. *Ocean Coast. Manag.* **2023**, *238*, 106560. [CrossRef]
54. Li, Y.; Li, Y.; Zhou, Y.; Shi, Y.; Zhu, X. Investigation of a coupling model of coordination between urbanization and the environment. *J. Environ. Manag.* **2012**, *98*, 127–133. [CrossRef] [PubMed]
55. Cheng, X.; Long, R.; Chen, H.; Li, Q. Coupling coordination degree and spatial dynamic evolution of a regional green competitiveness system—A case study from China. *Ecol. Indic.* **2019**, *104*, 489–500. [CrossRef]
56. Tang, S.; Zhu, Y.; Wang, F.; Shen, N. Can Marketization Improve Sustainable Development in Northeastern China? Evidence from the Perspective of Coupling Coordination Degree Model. *Discret. Dyn. Nat. Soc.* **2022**, *2022*, 1–12. [CrossRef]
57. Chen, X.; Zhou, F.; Hu, D.; Yi, G.; Cao, W. An improved evaluation method to assess the coordination between mineral resource exploitation, economic development, and environmental protection. *Ecol. Indic.* **2022**, *138*, 108808. [CrossRef]
58. Liu, T.-L.; Song, Q.-J.; Lu, J.; Qi, Y. An integrated approach to evaluating the coupling coordination degree between low-carbon development and air quality in Chinese cities. *Adv. Clim. Chang. Res.* **2021**, *12*, 710–722. [CrossRef]
59. Ma, P.; Ye, G.; Peng, X.; Liu, J.; Qi, J.; Jia, S. Development of an index system for evaluation of ecological carrying capacity of marine ecosystems. *Ocean Coast. Manag.* **2017**, *144*, 23–30. [CrossRef]
60. Barlas, Y. Formal aspects of model validity and validation in system dynamics. *Syst. Dynam. Rev.* **1996**, *12*, 183–210. [CrossRef]

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Financial Mechanism for Sustainable Development of the Marine Economy with Respect to Technology, Digitalization, and Low Carbonization

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Abstract: This study explores the impact of regional financial development on the sustainable growth of the marine economy across 14 coastal cities in Guangdong Province from 2004 to 2022. To assess this, a comprehensive index system was developed to measure marine economic sustainability, incorporating key factors such as capital investment, production efficiency, and processing and trade. The findings indicate that financial development significantly enhances the sustainable growth of the marine economy. However, the interaction between financial development, technology digitalization, and low-carbon initiatives leads to diminishing returns in terms of sustainability. Through the use of the Moran index and the spatial Durbin model, the analysis reveals a dual outcome: while financial development positively influences a city's marine economic sustainability, it exerts negative spillover effects on neighboring cities. Previous studies have primarily focused on the relationship between financial development and the marine economy at the national or provincial level, leaving a gap in understanding these dynamics at the city level. Furthermore, the coordination between financial development and marine economic sustainability across cities within the same region remains largely unexplored. This study addresses these gaps by investigating city-level dynamics and examining intercity coordination between financial development and marine economic growth. The results offer a novel perspective for policymakers, highlighting strategies to balance regional financing for the marine economy with targeted investments in science, technology, digitalization, and low-carbon initiatives. This approach seeks to optimize resource allocation and mitigate potential substitution effects. Ultimately, this research contributes to a more nuanced understanding of the complex interplay between financial development and the marine economy at both city and regional levels.

Keywords: financial development; sustainable development of the marine economy; technology; digitalization; low carbonization

1. Introduction

Protecting marine ecosystems is essential for fostering a prosperous and sustainable China, as a healthy ocean is a cornerstone of maritime strength. Globally, the emphasis on sustainable marine resource management has grown, particularly in coastal nations facing the consequences of resource depletion and environmental degradation. China's coastal regions, characterized by dense populations, concentrated industries, and high resource demand, are under significant environmental stress. These pressures have led to various ecological challenges, including marine pollution, the loss of biodiversity, and the deterioration of marine ecosystems, all of which have hindered the socioeconomic development of coastal areas. To ensure ecological security, it is critical to prioritize marine biodiversity and commit to the sustainable development of the marine economy.

Financial development plays a key role in facilitating resource allocation, contributing to the accumulation of both physical and human capital [1]. As financial development deepens and becomes more efficient, it enhances the productivity of the marine industry, thereby driving the growth of the marine economy [2]. In recent years, governments have increasingly embraced policies that promote green finance and industrial digitalization, leveraging efficient financial operations and capital allocation [3]. These efforts, coupled with modern technologies such as blockchain, big data, IoT, and AI, have advanced the integration of digitalization and low-carbon initiatives to support the development goals of the ocean economy [4,5].

To strengthen their marine economies, countries must first understand how financial development influences marine economic sustainability. Guangdong Province, which has led China's marine economy for nearly three decades, provides a compelling example. Through comprehensive development strategies, including the implementation of policies and action plans to build a robust marine province, Guangdong has made significant progress in areas such as aquaculture, marine engineering, and offshore wind power. Its focus on technology, digitalization, and low-carbon initiatives sets a benchmark for sustainable marine economic development. With its advanced marine economy and leadership in innovation, Guangdong offers an ideal context for analyzing these dynamics. This study seeks to examine the impact of financial development on the sustainable growth of the marine economy in the region. Utilizing panel data from 14 coastal cities in Guangdong between 2004 and 2022, the study employs econometric models to assess how financial development influences various aspects of marine economic sustainability, particularly in relation to technology integration, digital transformation, and low-carbon strategies. The insights gained from this research are intended to deepen the understanding of how financial development can foster sustainable growth in marine economies. By exploring the effects of technological advancements, digitalization, and low-carbon efforts, this study aims to contribute to the broader discourse on promoting sustainability in coastal marine economies.

In the following section, we address the limitations identified in the literature and propose improvements or extensions to overcome these challenges. First, traditional research methods have primarily focused on analyzing single variables, such as the growth rate of the marine economy. While this approach helps clarify trends in the overall scale of the marine economy, it lacks a comprehensive evaluation of its sustainable development capabilities. This study introduces a sustainable development index for the marine economy, providing a more nuanced and holistic assessment of the complexity and systemic nature of sustainable marine development. Second, previous research has predominantly examined relationships between individual or limited sets of variables. In contrast, this study takes a broader view by integrating regional science and technology, digitalization, and low carbonization. By employing a multidimensional analytical framework, this research offers a more detailed understanding of how financial development impacts the sustainable development of the marine economy through various channels. Third, most studies have focused on the relationship between financial development and the marine economy at the national or provincial level. Few studies have investigated these relationships at the city level or explored the coordinating effects of financial development and the marine economy among cities in the same region. To address this gap, we incorporate spatial externalities into our research framework, fully considering the unique characteristics of each city. By utilizing Moran's index and a spatial multi-objective model, we uncover patterns of marine economic development in this region, providing valuable samples and references for further research in other regions.

2. Literature Review and Hypotheses

2.1. Literature Review

Scholars have devoted considerable attention to the relationships between financial development and the ocean economy [2,6–8], technologization and the ocean economy [9–11], digitization and the ocean economy [12,13], and low carbonization and the ocean economy [14,15]. Previous studies have provided substantial empirical evidence from diverse perspectives for the sustainable development of the marine economy. A literature review revealed a linear or nonlinear correlation between financial development, science and technology, digitalization, low carbonization, and the marine economy.

Financial development is crucial for economic growth, with a strong demand–pull or supply–push relationship between the two [16]. Scholars have studied the impact of financial development on the marine economy, and most of the findings confirm that financial development contributes to the growth of the marine economy. Le [17] found significant positive effects of energy consumption, fixed asset investment, government expenditures, financial development, and trade openness on marine economic growth using data from 46 emerging markets and developing countries from 1990 to 2014. Nham and Ha [6] used 2009–2020 data from 24 European coastal countries to confirm that the development of financial markets and the efficiency of financial institutions positively affect marine economic growth. Wang, Lu, and Yin [2] highlighted a positive correlation between financial development and China's marine economic growth, driven mainly by deeper financial development and improved efficiency. Moreover, some studies have identified nonlinear relationships between financial development and marine economic growth. Song, Chen, Tao, Su, and Umar [7] demonstrated a U-shaped relationship in China, suggesting that financial development fosters marine economic growth only after surpassing a certain threshold. They also noted U-shaped and inverted U-shaped relationships between financial development and different sectors of the marine industry: a U-shaped relationship with the primary and tertiary sectors, and an inverted U-shaped relationship with the secondary sector. Xu and Cui [8] found an inverted U-shaped relationship between loan, bond, and stock financing and marine economic growth in China.

According to the Cobb–Douglas production theory, technology plays a vital role in economic growth. Economic growth is facilitated by financial institutions, which provide funding for research and development (R&D) investments and the purchase of equipment and machinery necessary for production. According to transaction cost theory, digitalization—a critical aspect of information and communication technology (ICT)—has been widely applied in production and marketing at lower costs, enhancing production efficiency and improving market transactions, thereby making a significant contribution to economic growth. Financial institutions also support ICT infrastructure investment, which increases digitalization technology and further contributes to economic growth. Environmental, social, and governance (ESG) theory underscores that environmental protection is a crucial issue in economic growth. Financial institutions offer financial backing for green technologies in production processes, which reduce pollution and contribute to sustainable development. Marine economic growth, innovative development of the marine economy, and resilience to the global water crisis are three pivotal factors for the sustainable development of the marine economy [18,19]. In recent years, governments have been actively promoting marine science, technology and innovation policies, digital transformation policies, and low-carbon development policies to promote the development of the marine economy.

According to the United Nations report "10 Years of Marine Science Promoting Sustainable Development (2021–2030)", marine science and technology innovation has also been clearly proposed as a key factor for the sustainable development of the marine economy in the future [20]. Marine science and technological innovation provide solutions to optimize the structure of the marine industry [21], enhance economic efficiency [22], and balance the relationship between ecology and development [23]. Furthermore, the development of the marine economy stimulates the demand for high-quality marine science and technology, attracting more funds and talent to invest in marine science and technology innovation, which in turn promotes the development of the marine economy. Some domestic scholars have confirmed the relationship between marine scientific and technological innovation and marine economic growth using data from coastal provinces in China, suggesting that strengthening marine scientific and technological innovation, personnel training, and marine intellectual property protection can drive the development of the marine economy [9,11].

Digitalization has proven effective in predicting demand within the marine economic chain, preventing excessive energy use and marine pollution, and driving the marine economy towards high-end, green, and integrated clustering [24]. Digitalization has proven effective in predicting demand within the marine economic chain, preventing excessive energy use and marine pollution, and driving the marine economy towards high-end, green, and integrated clustering [25,26]. Studies in the Baltic Sea region suggest that digital transformation can boost innovation and support the blue economy by investing in digital solutions and communication infrastructure, enhancing economic competitiveness and job creation [12]. Similarly, research in Saudi Arabia confirms that financial development and ICT positively affect economic growth, with a robust ICT environment amplifying the impact of financial development [27]. Specifically, the government can fully explore the potential of the "marine economy + digital economy" to increase the competitiveness of the marine economy [12,28].

Implementing low-carbon economic policies promotes a shift from traditional high-carbon models, encourages renewable energy use, reduces carbon emissions, and strengthens environmental protection [14,15]. These policies also aid in reducing marine pollution and environmental damage, fostering the sustainability of the marine economy. Studies in China and Central and Eastern European countries reveal that financial development can facilitate carbon emission reductions through clean-energy use, although short-term effects may vary [29,30]. The sustainable development of the marine economy requires a rational use of resources and a reduction in carbon emissions, which depends on substantial financial investments and technological improvements [17,31].

The literature underscores the complex interplay between financial development, technological and digital advancements, and marine economic growth. Financial support is a crucial factor in enabling innovation and economic development, but the outcomes of these interactions depend on contextual factors like technological progress and infrastructure development. This study aims to comprehensively examine the integration of financial development, marine scientific and technological innovation, digitalization, and low carbonization, considering their interactions and spatial characteristics. Emphasizing the importance of spatial factors provides a new perspective on sustainable marine economic development, influenced not only by local conditions but also by surrounding economic activities.

2.2. Hypotheses

2.2.1. Financial Development and Marine Economic Growth

Regional urban financial development plays a crucial role in providing the capital and financial tools necessary for the development of the marine economy [32]. The establishment and growth of financial markets create a more favorable trading and operating environment for the marine economy. This enables investors and enterprises to engage in trading and financing activities through financial markets, thereby increasing the feasibility and sustainability of marine economic projects [6,33].

As the economic hinterland of the Guangdong–Hong Kong–Macao Greater Bay Area, regional financial development in Guangdong Province serves as a platform for promoting ocean economic growth and international cooperation. Financial institutions not only offer cross-border transaction services but also provide financing support to ocean economic enterprises. Furthermore, regional financial development has led to an increase in professionals who can provide specialized services for the marine economic industry. Through these professional financial services, improvements in management levels are achieved along with the increased operational efficiency of marine economic enterprises, which ultimately contributes to their sustainable development [6].

On the basis of theoretical concepts and the literature, the following hypothesis is proposed in this study:

Hypothesis 1: *Regional financial development plays a pivotal role in fostering the sustainable advancement of the marine economy.*

2.2.2. Financial Development, Technologization, and Marine Economic Growth

With respect to the interaction between technology and financial development, two main viewpoints are studied: complementarity and substitution [21–23]. This view holds that the sustainable development of the marine economy has experienced a marginal benefit increase under the joint action of these two factors. In addition, technological advances, such as blockchain technology and smart contracts, can provide more efficient, safe, and reliable financial services. These innovations can reduce intermediation costs and transaction frictions within financial services while further promoting sustainable development within the marine economy. In addition, with the increase in technology, many funds are needed to support it. However, financial development can provide necessary financing and investment channels to propel high technological content and value appreciation within marine industry development.

On the other hand, an alternative view suggests that, owing to cost-effectiveness considerations, supporting marine industry growth with substantial capital investments may be necessary. This perspective argues that as technologization increases, so do marginal costs, ultimately resulting in diminishing marginal benefits for sustainable marine economic development [32,33]. Moreover, the rise in technological demands within the marine industry may lead to increased funding flows towards technological research and development (R&D) and innovation efforts. The investment of financial capital in other key areas of the marine economy is reduced, potentially inhibiting the positive relationship between financial development and sustainable development.

On the basis of theoretical concepts and the literature, the following hypothesis is proposed in this study:

Hypothesis 2: *The integration of technology and financial development synergistically enhances the sustainable development of the marine economy.*

Hypothesis 3: *The integration of technology and financial development synergistically restrains the sustainable development of the marine economy.*

2.2.3. Financial Development, Digitalization, and Maritime Economic Growth

With respect to the interaction between digitalization and financial development, prior studies have confirmed the complementary effects. Alimi and Adediran [34] used data from 2005–2016 from 13 economic communities of West African State member countries to construct an ICT index in terms of fixed-line telephony, mobile telephony, and the internet and reported that financial development and the degree of digitization can contribute to economic growth. Gheraia, Abid, Sekrafi, and Abdelli [27] confirmed that financial development and ICT in Saudi Arabia have a positive influence on economic growth and that when ICT is developed, both financial development and ICT can promote regional economic growth. On the basis of the above empirical evidence, the enhancement of digitalization promotes the formation of a digital financial ecosystem, win–win cooperation between industries, the coordinated development of different fields of the marine economy, and the digital transformation and enhancement of the whole industrial chain. Certainly, related research argues that there is a substitution effect between them. Digitalization is influenced by the stock of marine financial capital, and it has a U-shaped relationship with the development of the marine economy [13]. When digitalization reaches a certain level, enterprises and individuals can obtain funds and information more directly through digital platforms, thus reducing their dependence on traditional financial intermediaries. This may lead to a decrease in the participation of financial institutions in the marine economy, and the positive relationship between financial development and the sustainable development of the marine economy may be suppressed because of the weakening role of financial intermediaries, the diversion of funds, and the lag of financial service innovation.

On the basis of theoretical concepts and the literature, the following hypothesis is proposed in this study:

Hypothesis 4: *The integration of digitalization and financial development synergistically enhances the sustainable development of the marine economy.*

Hypothesis 5: *The integration of digitalization and financial development synergistically restrains the sustainable development of the marine economy.*

2.2.4. Financial Development, Low Carbonization, and Marine Economic Growth

In terms of the interaction between financial development and low carbonization, there are also two competing views. The supplementary view is that financial development plays an important role in low-carbon transformation and economic development, and financial institutions can support low carbonization by providing financial services such as credit and insurance [14,15,29]. The promotion of low carbonization can be driven by demand, policy, social responsibility and international cooperation, which can promote the sustainable development of the marine economy. However, the alternative view holds that low-carbon and financial development restrict the sustainable development of the marine economy [31,35]. Moreover, the development of low-carbon lending faces greater technical risks, market risks, and policy risks. These uncertainties may make financial institutions more cautious when providing financial support. If the government's policy guidance is insufficient and the corresponding incentives and constraints are lacking, financial institutions may lack motivation to support the sustainable development of the marine economy, and the positive role of financial development in the sustainable development of the marine economy may be inhibited [30].

On the basis of theoretical concepts and the literature, the following hypothesis is proposed in this study:

Hypothesis 6: *The integration of low carbonization and financial development synergistically enhances the sustainable development of the marine economy.*

Hypothesis 7: *The integration of low carbonization and financial development synergistically restrains the sustainable development of the marine economy.*

3. Model, Data, and Variables

3.1. Data and Sample

This study is underpinned by an analysis of 14 coastal cities in Guangdong Province, including Guangzhou, Shenzhen, Zhuhai, Shantou, Huizhou, Dongguan, Zhongshan, Yangjiang, Jiangmen, Shanwei, Zhanjiang, Maoming, Chaozhou, and Jieyang. The panel data were extracted from the Guangdong Provincial Statistical Yearbooks (2004–2022), the Guangdong Provincial Rural Statistical Yearbooks, and the Guangdong Provincial Market Supervision Administration.

3.2. Research Variables

3.2.1. Dependent Variable

The construction of an index system for the sustainable development of the marine economy aims to comprehensively evaluate its sustainability. Drawing on Wang, Tian, Geng, and Zhang's [36] three industrial chains of marine resources, this study seeks to establish three core dimensions for marine resources: capital investment, production efficiency, and processing and trade. Seven specific secondary indicators are selected to quantify these dimensions. The following provides an explanation of each dimension and its corresponding secondary indicators.

Data were sourced from the Guangdong Statistical Yearbook and the Guangdong Rural Statistical Yearbook.

Capital investment is a crucial metric for evaluating resource allocation and the economic foundation of marine economic activities. It reflects the industry's investment in expanding production capacity, improving technical capabilities, and enhancing market competitiveness. The three secondary indicators for this dimension are as follows:

- Marine fishing motorboats (tons): this measures the capital intensity and technical level of the fishing industry.
- Mariculture area (qing): the size of the aquaculture area directly reflects the scale of aquaculture activities and the level of capital investment.
- Part-time personnel in marine fishing and mariculture (persons): this indicates the availability of labor, reflecting both talent reserves and labor inputs in the industry.

Production efficiency is a key criterion for evaluating the efficient use of resources and output capacity in marine economic activities. High production efficiency indicates that greater output is achieved with the same level of resource input. Two secondary indicators for this dimension are as follows:

- Marine fishing cargo (tons): growth in fishing cargo typically signals improvements in fishing technology, better management, or resource recovery.
- Quantity of mariculture fish (tons): this reflects advancements in aquaculture technology, variety improvements, and enhanced management practices.

Processing and trade are crucial for assessing the extension of the marine economic industrial chain and the promotion of value-added activities. Through deep processing and expanded trade, the value of marine products can be enhanced, boosting industrial competitiveness. The secondary indicators for this dimension are as follows:

- Seawater processed products (tons): this measures the processing capacity for marine products and the extent of industrial chain development.
- Port cargo throughput (10,000 tons): as a critical hub for the maritime economy, growth in cargo throughput indicates prosperity in maritime trade and regional economic expansion.

All the aforementioned secondary indicators are logarithmically transformed, as shown in Table 1.

Table 1. Indicator system for sustainable development of the marine economy.

Indicators	Secondary Indicators	Orientations
Capital investment	Motorized marine fishing vessels (tons)	+
	Mariculture area (qing)	+
	Part-time staff specialized in marine fishing and mariculture (persons)	+
Production efficiency	Volume of marine capture fisheries (tons)	+
	Mariculture catch (tons)	+
Processing and trade	Processed seawater (tons)	+
	Port cargo throughput (10,000 tons)	+

3.2.2. Independent Variables

In the study of Nham and Ha [6], the financial development index was constructed with three levels of composite indicators: financial institution deepening, financial institution entry, and financial institution efficiency.

Data for this study were sourced from the Guangdong Statistical Yearbook and the Guangdong Provincial Market Supervision Administration.

Financial institution deepening measures the penetration and influence of financial institutions within the economy. Three secondary indicators are used to assess this:

- Ratio of loans to GDP: a higher ratio indicates that financial institutions provide a larger proportion of funding to the economy, reflecting a well-developed financial system.
- Ratio of deposits to GDP: a higher ratio suggests that the financial system effectively mobilizes savings, which can then be used for investment and economic growth.
- Depth of insurance: a greater depth reflects a more developed insurance sector, offering risk mitigation and financial security to individuals and businesses.

Financial institution entry evaluates the accessibility and availability of financial services. Two secondary indicators are used:

- Ratio of financial institutions to the permanent population: a higher ratio suggests that financial services are more accessible, making it easier for individuals and businesses to obtain loans, savings accounts, and other financial products.
- Ratio of employees in financial institutions to the permanent population: a higher ratio can indicate a more developed financial system with specialized services, though this depends on employee efficiency.
- Insurance density: This measures the extent to which insurance services are utilized by the population. A higher density implies greater awareness and adoption of insurance products.

Financial institution efficiency assesses how effectively financial institutions operate:

- Savings mobilization: efficient mobilization of savings is essential for economic growth, as it provides the capital needed for investment in infrastructure, businesses, and other productive activities.

In total, seven secondary indicators were selected to measure financial development, all of which are positive indicators, as shown in Table 2.

Table 2. Indicator system for the financial development index.

Indicators	Secondary Indicators	Orientations
Deepening of financial institutions	Ratio of loans to GDP (-)	+
	Ratio of deposits to GDP (-)	+
	Depth of insurance (premium income/GDP) (-)	+
Entry of financial institutions	Ratio of financial institutions to the permanent population (-)	+
	Ratio of employees in financial institutions to the permanent population (-)	+
	Insurance density (premium income/resident population) (-)	+
Efficiency of financial institutions	Savings mobilization (loans from financial institutions/deposits from financial institutions) (-)	+

3.2.3. Moderating Variables and Control Variables

Moderating variables include technology, digitalization, and low carbonization. In the studies of Le [17], economic development (gdppc), fixed-asset investment (fai), industrial development (indp), foreign direct investment (fdi), openness (open), and government intervention (gov) are added as control variables. The specific research variables are shown in Table 3.

Table 3. Research variables.

Variant	Variable Name	Nicknames	Measure
implicit variable	sustainable development of the marine economy	MES index	Index of sustainable development of the marine economy
independent variable	financial development	FD index	Financial development Index
moderator variable	technology	tech	Number of patents granted/employment
	digitization	digital	Number of cell phone subscribers/resident population Total telecommunications business turnover/GDP
	low carbonization	carbon	Carbon emissions per capita
control variable	economic development	gdppc	Natural logarithm of GDP per capita
	fixed-asset investment	fai	Total investment in fixed assets/GDP
	industrial development	indp	(Primary sector output × 1 + secondary sector output × 2 + tertiary sector output × 3)/GDP
	overseas foreign direct investment (OFDI)	fdi	Amount of FDI/GDP
	openness	open	Total import/export trade/GDP
	government intervention	gov	Government budget expenditure/GDP

3.3. Index Construction Methodology

The variables of this study, sustainable development of the marine economy, financial development, and degree of digitization, are measured via the entropy index, which is processed in the following steps.

The first step is to standardize the above secondary indicator factors in the following way: If the secondary factor is positive, Equation (1) is used; if the secondary factor is negative, Equation (2) is used.

$$X_{ij} = \frac{X_{ij} - \min(Xij)}{\max(X_{ij}) - \min(X_{ij})} \quad (1)$$

$$X_{ij} = \frac{\max(Xij) - X_{ij}}{\max(X_{ij}) - \min(X_{ij})} \quad (2)$$

The second step calculates the *j*-factor weight for each city according to the formula below. $\sum_{i=1}^{m} X_{ij}$ is the *j* indicator for city *i* with m cities.

$$P_{ij} = \frac{X_{ij}}{\sum_{i=1}^{m} X_{ij}} \quad (3)$$

The entropy value of factor *j* for each city *i* is calculated according to the following formula, where the constant value $K = 1/\text{m}$ is the reciprocal of the number of cities:

$$e_j = -K * \sum_{i=1}^{m} P_{ij} ln P_{ij} \quad (4)$$

Next, the coefficient of variation is calculated. The coefficient of variation g_j is expressed as $1 - e_j$:

$$g_j = 1 - e_j \quad (5)$$

Next, the evaluation index weights are calculated, with ω_j representing the weight of g_j:

$$\omega_j = \frac{g_j}{\sum_{j=1}^{n} g_j} \tag{6}$$

Ultimately, the combined factor is scored. S is the combined per-factor score for factor j for each city i.

$$S = \sum_{j=1}^{n} P_{ij} * \omega_j \tag{7}$$

3.4. Research Model

A fixed effects model is employed to examine the proposed research hypotheses.

$$be_{it} = \alpha_0 + \alpha_1 fd_{it} + \sum Control_{it} + \mu_{it} + v_{it} + \varepsilon_{it} \tag{8}$$

$$be_{it} = \beta_0 + \beta_1 fd_{it} + \beta_2 tech_{it} + \beta_3 fd_{it} \times tech_{it} + \sum Control_{it} + \mu_{it} + v_{it} + \varepsilon_{it} \tag{9}$$

$$be_{it} = \gamma_0 + \gamma_1 fd_{it} + \gamma_2 digital_{it} + \gamma_3 fd_{it} \times digital_{it} + \sum Control_{it} + \mu_{it} + v_{it} + \varepsilon_{it} \tag{10}$$

$$be_{it} = \theta_0 + \theta_1 fd_{it} + \theta_2 carbon_{it} + \theta_3 fd_{it} \times carbon_{it} + \sum Control_{it} + \mu_{it} + v_{it} + \varepsilon_{it} \tag{11}$$

3.5. Descriptive Analysis

Table 4 shows the descriptive analysis results, which can be used to understand the data characteristics of each variable. The dependent variable of the marine economic sustainable development index (MES index) lies between 0.000 and 0.891, with a standard deviation of 0.234, indicating that there are slight differences in the sustainable development of the marine economy of coastal cities in Guangdong. The independent variable of the financial development index (FD index) lies between 0.002 and 0.879, with a standard deviation of 0.256, indicating that there is a significant difference in the financial development of coastal cities in Guangdong. In terms of technology, digitalization, and low carbonization, some cities have a greater degree of difference in technology and digitalization, which reflects the imbalance of urban development in the Bay Area (such as Guangzhou and Shenzhen) as well as non-Bay Area cities (such as Yangjiang and Zhanjiang).

Table 4. Descriptive analysis.

Variable	Sample Size	Maximum	Minimum	Mean	Standard Deviation
MES index	266	0.891	0.000	0.258	0.234
FD index	266	0.879	0.002	0.394	0.256
tech	266	231.081	0.362	35.443	43.199
digital	266	1.000	0.000	0.383	0.297
carbon	262	35.690	2.088	10.603	6.658
gdppc	266	12.119	8.851	10.654	0.735
fai	266	10.381	0.170	3.474	2.612
indp	266	2.709	2.135	2.387	0.135
fdi	266	0.555	0.000	0.017	0.036
open	266	2.397	0.012	0.558	0.549
gov	266	0.279	0.015	0.102	0.060

3.6. Correlation Analysis

Table 5 shows the results of the correlation analysis. The VIF values of the independent variables, moderating variables, and control variables are all greater than 1, and the average VIF is less than 10, indicating that there is no correlation and that any variable can independently explain the dependent variable.

Table 5. Correlation analysis.

Var.	VIF	1/VIF
FD index	7.82	0.1279
tech	6.36	0.1571
digital	6.06	0.1651
carbon	5.21	0.1920
gdppc	4.98	0.2009
fai	4.00	0.2501
indp	2.59	0.3861
fdi	1.99	0.5028
open	1.50	0.6654
gov	1.23	0.8162
Mean VIF	4.17	

4. Results and Discussion

4.1. Regression Analysis of the Fixed Effects Model of FD and MES

We use a fixed effects model to make a preliminary judgment on the relationship between financial development (FD index) and marine economic sustainable development (MES index). R^2 is the coefficient of determination, which indicates the proportion of the variation in Y that can be explained by the variation in X. R^2 is a measure of how closely the regression line fits each observation. When $R^2 = 1$, it indicates a perfect fit; when $R^2 = 0$, it indicates that there is no linear relationship between X and Y. The higher the value of R^2 is, the better the fit. In this paper, R^2 is close to 1, which indicates a good fit and a linear relationship. F is used to test whether the regression relationship is significant. This paper takes $p < 0.10$ as more significant, $p < 0.05$ as significant, and $p < 0.01$ as very significant. All the models in this paper passed the F test, and all the regression relationships were significant.

Table 6 shows the results of this test. The empirical results of Model 1 show that the regression coefficient of financial development (FD index) is 0.177, which is significant at the $p < 0.01$ level, indicating that financial development has a positive effect on the sustainable development of the marine economy and supporting Research Hypothesis 1. The sustainable development of the marine economy is likely limited by the scale of capital and the efficiency of capital allocation, and as regional financial development progresses, the scale of capital gradually increases capital allocation efficiency to enhance the provision of financial services, effectively promoting the sustainable development of the marine economy. When regional financial development progresses, the scale of capital gradually increases, the efficiency of capital allocation improves, and the financial services provided can effectively promote the sustainable development of the marine economy.

Our regression analysis reveals a negative coefficient of −0.001 for the cross-multiplier term (FD index_tech) associated with the interplay between financial development and technology, yielding a significant result at the $p < 0.05$ threshold. This shows that when the degree of technology is improved, the improvement in the financial development level will not increase the marginal income of the sustainable development of the marine economy. This finding corroborates the presence of a substitution effect between the extent of technology and financial development, underpinning Hypothesis 3. This is likely due to the enhancement of the autonomy and competitiveness of the marine industry due to the improvement in the technological level, which reduces the demand for financial support. In this case, financial development may play a more auxiliary and supporting role. The positive impact of financial development on the sustainable development of the marine economy has been inhibited by an increase in the degree of technologization.

Table 6. Benchmark regression results.

Variable Name	Model 1	Model 2	Model 3	Model 4
FD index	0.177 ***	0.209 ***	0.232 ***	0.116 ***
	(0.042)	(0.044)	(0.049)	(0.044)
tech		0.001 ***		
		(0.000)		
FD index_tech		−0.001 **		
		(0.000)		
digital			0.111 **	
			(0.046)	
FD index_digital			−0.163 **	
			(0.073)	
carbon				−0.003 ***
				(0.001)
FD index_carbon				0.005 ***
				(0.001)
gdppc	0.001	0.031	0.002	0.030
	(0.018)	(0.022)	(0.018)	(0.019)
ffi	−0.002	−0.002	−0.002	−0.004 *
	(0.002)	(0.002)	(0.002)	(0.002)
indp	0.055	0.083	0.058	0.027
	(0.052)	(0.052)	(0.052)	(0.059)
fdi	−0.024	−0.011	−0.009	−0.022
	(0.051)	(0.050)	(0.051)	(0.049)
open	−0.030 ***	−0.026 ***	−0.027 ***	−0.026 ***
	(0.009)	(0.009)	(0.009)	(0.008)
gov	−0.498 ***	−0.516 ***	−0.470 ***	−0.474 ***
	(0.101)	(0.099)	(0.101)	(0.097)
Constant	0.092	−0.285	0.043	−0.084
	(0.227)	(0.267)	(0.230)	(0.246)
Observations	266	266	266	266
R-squared	0.276	0.312	0.294	0.338
Number of years	19	19	19	19
city FE	YES	YES	YES	YES
year FE	YES	YES	YES	YES

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; *p* values are in parentheses.

In addition, our regression analysis reveals a negative coefficient of −0.163 for the cross-multiplier term (FD index_digital) associated with the interplay between financial development and digital capital, yielding a significant result at the $p < 0.05$ threshold. This finding suggests that as the marine economy becomes more digitized, the increase in financial development does not augment the marginal benefits of sustainable development. This finding corroborates the presence of a substitution effect between the extent of digitalization and financial development, underpinning Hypothesis 5. Digitalization can mitigate resource wastage and environmental degradation, bolstering efficiency and curtailing costs, thereby diminishing the reliance on financial capital. In the wake of digitalization driving innovation as a primary impetus for marine economy advancement, the influence of financial development is relatively mitigated. Practically, it is imperative to consider the interplay between the degree of digitalization and financial development holistically, ensuring a balance and synergy in their progression to foster sustainable development within the marine economy.

Finally, our regression analysis reveals a positive coefficient of 0.005 for the cross-multiplier term (FD index_carbon) associated with the interplay between financial development and low carbonization, yielding a significant result at the $p < 0.01$ threshold. Since low carbonization is a negative indicator, a higher value indicates higher carbon emissions, and a lower value indicates lower carbon emissions and a higher degree of low carbonization. This finding corroborates the presence of a substitution effect between the extent of low carbonization and financial development, underpinning Hypothesis 7.

Low carbonization implies a reduced dependence on fossil fuels and a more efficient use of energy, which contributes to the reduction in carbon emissions from marine economic activities. When policy guidance and market demand shift towards low-carbon industries, financial capital may flow from traditional marine industries to emerging decarbonized industries. Financial institutions usually consider the profitability and risk of projects when evaluating them, which may lead them to choose to reduce investment in marine economy-related projects when faced with the economic costs of the transition and the uncertainty of technological transformation.

4.2. Spatial Econometric Modeling Analysis

The Moran index is used to assess whether the sustainable development of the dependent marine economy is spatially correlated. Building upon the fixed effects model, the LM test results are analyzed to determine whether the model should incorporate spatial lag dependent variables or spatial error terms. On the basis of the LM test results, an appropriate spatial econometric model for the panel data is selected from among the spatial lag model (SLM), spatial error model (SEM), and spatial Durbin model (SDM).

The Moran index reflects the degree of similarity in observation values among adjacent spatial units. It assesses the overall spatial correlation within the research area, indicating whether the spatial distribution shows a pattern of clustering or dispersion, and evaluates the strength and significance of this pattern. Thus, the Moran index enables an exploration of the spatial correlation characteristics of the degree of coordination. The specific formula for calculating the Moran index is as follows:

$$\text{Moran's I} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(x_i - \overline{x})^2} \quad (12)$$

In the context of spatial econometric analysis, let n denote the number of coastal cities in Guangdong Province. The Moran index is calculated via the spatial weight matrix, where W_{ij} represents the element in the i-th row and j-th column. The variable x_j denotes the value of the j-th regional variable x, and the average value of x is the mean of all the urban variables x. The term $(x_i - \overline{x})^2$ represents the variance of all the urban variables x. The Moran index ranges from -1 to 1, where a value close to 1 indicates a positive spatial correlation (i.e., high or low clustering), a value close to -1 signifies a negative spatial correlation (i.e., high or low dispersion), and a value near 0 implies a random spatial distribution.

To assess local spatial correlation in terms of the degree of coordination, a Moran scatter plot is constructed via the local spatial autocorrelation model. In the Moran scatter plot, each data point corresponds to a spatial unit, and the points are categorized into one of four quadrants on the basis of the relative magnitude of the unit's value and that of its neighboring units. These quadrants represent different spatial autocorrelation patterns:

First quadrant: this represents positive spatial autocorrelation, where spatial units with high values tend to be adjacent to other high-value units.

Second quadrant: indicates negative spatial autocorrelation, where units with low values are typically adjacent to units with high values.

Third quadrant: denotes positive spatial autocorrelation, with low-value units being adjacent to other low-value units.

Fourth quadrant: reflects negative spatial autocorrelation, where high-value units are generally adjacent to low-value units.

According to the global spatial autocorrelation model, we can calculate Moran's I. As shown in Table 7, from 2004–2022, Moran's I was significantly positive at the 1% or 5% level. This indicates that there is significant positive autocorrelation in the sustainable development of the regional marine economy, suggesting that a spatial econometric model should be considered for analysis.

Table 7. Global geographic distance as measured by Moran's I index (2004–2022).

Year	W	
	Moran's I	Z Value
2004	0.138 **	2.345
2005	0.139 ***	2.362
2006	0.131 ***	2.380
2007	0.107 **	2.162
2008	0.112 **	2.256
2009	0.127 **	2.342
2010	0.127 ***	2.321
2011	0.129 ***	2.363
2012	0.130 ***	2.380
2013	0.133 ***	2.407
2014	0.136 ***	2.417
2015	0.142 ***	2.489
2016	0.139 ***	2.539
2017	0.139 ***	2.522
2018	0.135 ***	2.500
2019	0.149 ***	2.514
2020	0.149 ***	2.628
2021	0.149 ***	2.630
2022	0.129 **	2.288

Note: ***, ** denote significance at the 1%, 5% levels, respectively, and W represents the geographic distance matrix.

The global Moran's I index captures only the overall spatial autocorrelation of the data and does not capture the spatial agglomeration of specific regions. To visualize the spatial correlation of different regions more intuitively, a Moran's I scatter diagram is drawn on the basis of the spatial autocorrelation model. The diagonal line typically represents the trend line of spatial positive correlation. The scatter points, on the other hand, represent the relative positional relationship between the observed values of individual cities (or spatial units) and the average observed values of their neighboring areas. In this diagram, quadrants I and III have positive spatial correlations, whereas quadrants II and IV have negative spatial correlations. Figure 1 shows that more points fall into quadrants I, II, and III, indicating that coordination is characterized mainly by high–high homogeneous aggregation and low–low homogeneous clustering, with some low–high heterogeneous clustering.

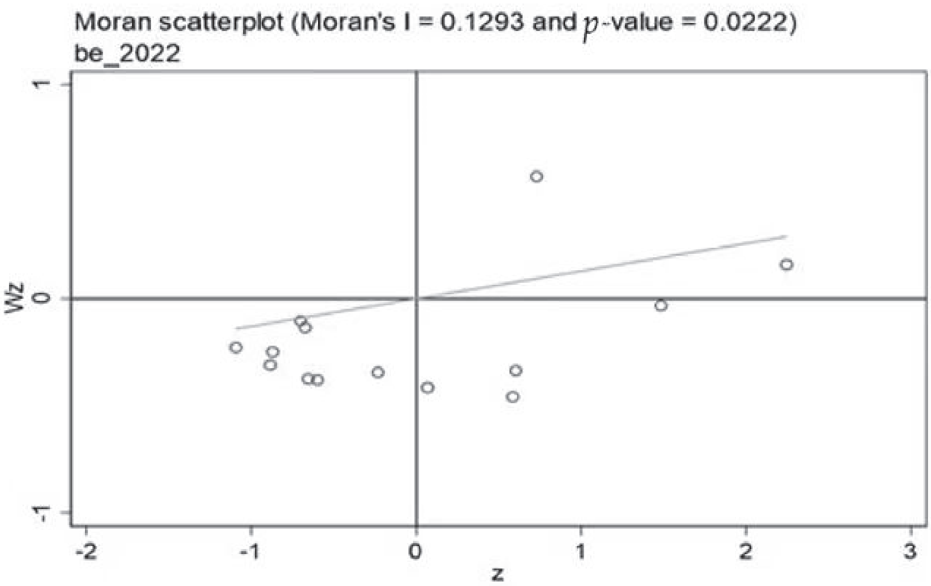

Figure 1. Scatter plot of the Moran index of sustainable development of regional marine economy.

The results of the Lagrange multiplier (LM) or robust Lagrange multiplier (robust-LM) tests, which were applied to examine the presence of spatial autocorrelation of the dependent variable and spatial autocorrelation of the error term in the underlying regression model, are shown in Table 8. The test results of the LM-lag and robust-LM-lag tests using the geographic distance matrix under the individual and time two-way fixed model rejected the original hypothesis of no spatial autocorrelation of the dependent variable and supported the spatial lag model (SLM). Second, the LM error statistic and robust-LM error statistic also support the spatial error model (SEM).

Table 8. LM test model selection results under the spatial weight matrix.

	W		
	Individual Fixed	**Time Fixed**	**Individual and Time Fixed**
LM-error	0.0473	1.058	7.666 ***
Robust-LM-error	7.035 ***	7.285 ***	5.541 ***
LM-lag	0.539	4.474 **	11.058 ***
Robust-LM-lag	7.526 ***	10.701 ***	8.933 ***

Note: ***, ** indicate significance at the 1%, 5% levels, respectively, and W represents the geographic distance matrix.

In addition to considering the spatial autocorrelation of the dependent variable and the error term, the spatial autocorrelation between the independent variables can also be considered; therefore, this study uses the likelihood ratio (LR) to conduct a retest to verify whether the spatial Durbin model can be degraded to a spatial lag model and a spatial error model. Table 9 shows the spatial measurement regression results after adding the geographic distance matrix, in which the LR test-related statistics test results and the statistics of the LR test under the geographic distance matrix passed the 1% significance test, indicating that the spatial Durbin model does not degenerate into a spatial lag model and a spatial error model under the geographic distance weighting matrix, which shows that the spatial Durbin model for the regression analysis is applicable to this study. In addition, the original hypothesis of being subject to random effects is rejected, as the Hausman test statistic passes the 1% significance test, and the final analysis is conducted via the fixed effects model of the spatial Durbin model. The regression coefficient of financial development (FD index) is 0.077, which is significant at the $p < 0.10$ level, which indicates that financial development in this city has a significant effect on the development of the marine economy in this city and supports Hypothesis 1.

Table 10 shows the empirical results of the direct, indirect, and total effects of the spatial Durbin model. The total effect of financial development (FD index) on the sustainable development of the marine economy is −0.397, the direct effect is 0.160, the indirect effect is −0.557, and it is significant at the $p < 0.01$ level. These findings indicate that the financial development of this city has a significant positive effect on the sustainable development of the marine economy in this city and that the financial development of this city has a significant negative spatial spillover effect on the sustainable development of the marine economy in neighboring cities.

The specific reasons may be as follows: First, there is competition for resources. As a whole, the focus of industrial development in coastal cities is on the tertiary, secondary, and primary sectors, but in terms of individual cities, there is uneven development; for example, the financial development of the Bay Area cities in Guangdong Province (e.g., Guangzhou, Shenzhen, etc.) tends to attract a large amount of financial resources and investment, which may result in the loss of resources in surrounding non-Bay Area cities (e.g., Yangjiang, Zhanjiang, etc.). The concentrated use of these resources will cause neighboring cities to face competitive pressure in the development of the marine economy and find it difficult to obtain adequate financial support, thus affecting their sustainable development. The second is the financial center effect. The Bay Area cities in the PRD tend to have strong economic and financial agglomeration effects. When a city becomes a financial center, more financial institutions and enterprises set up headquarters and branches in that city, leading to growth in consumption and employment, further strengthening the city's financial advantages. In contrast, neighboring cities may be unable to enjoy the same development opportunities due to a lack of financial resources and institutional support. Third, with respect to the industrial agglomeration effect, financial development may promote the industrial agglomeration of Bay Area cities, attracting more enterprises and talent to the region. This industrial agglomeration effect may further widen the development gap with neighboring cities, making neighboring cities face greater development resistance in the field of sustainable development of the marine economy.

Table 9. Regression results of the spatial measurement models.

	Fixed Effect	Stochastic Effect
	MES Index	**MES Index**
FD index	0.077 *	0.186 ***
	(0.043)	(0.042)
gdppc	−0.013	−0.015
	(0.016)	(0.018)
ffi	−0.005 ***	−0.002
	(0.002)	(0.002)
indp	0.076	0.001
	(0.047)	(0.047)
fdi	−0.071	−0.029
	(0.048)	(0.049)
open	−0.026 ***	−0.032 ***
	(0.007)	(0.009)
gov	−0.390 ***	−0.448 ***
	(0.093)	(0.095)
W_fd	−0.825 ***	−0.236 **
	(0.186)	(0.114)
W_gdppc	0.009	−0.012
	(0.053)	(0.025)
W_ffi	−0.008	0.006
	(0.006)	(0.005)
W_indp	0.341 **	−0.131
	(0.169)	(0.096)
W_fdi	−0.223	0.001
	(0.240)	(0.157)
W_open	0.036	0.009
	(0.035)	(0.021)
W_gov	0.014	0.463 **
	(0.528)	(0.206)
ρ	−0.880 ***	−0.077
	(0.166)	(0.127)
Hausman	101.14 ***	
LR-lag	28.17 ***	
LR-error	34.10 ***	
Wald-lag	30.23 ***	
Wald-error	37.84 ***	

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; *p* values are in parentheses; W represents the geographic distance matrix.

Table 10. Spatial Durbin model direct, indirect, and total effects.

	W		
Variables	**Direct**	**Indirect**	**Total**
FD index	0.160 ***	−0.557 ***	−0.397 ***
	(0.044)	(0.108)	(0.116)
gdppc	−0.016	0.016	−0.000
	(0.019)	(0.036)	(0.027)
ffi	−0.004 **	−0.002	−0.006 *
	(0.002)	(0.004)	(0.003)
indp	0.051	0.168 *	0.218 **
	(0.047)	(0.094)	(0.098)
fdi	−0.057	−0.087	−0.144
	(0.045)	(0.146)	(0.146)
open	−0.031 ***	0.036 *	0.005
	(0.008)	(0.021)	(0.018)
gov	−0.424 ***	0.217	−0.207
	(0.092)	(0.319)	(0.309)

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; *p* values are in parentheses; W represents the geographic distance matrix.

5. Conclusions and Policy Recommendations

On the basis of the empirical results and discussion, this study draws the following conclusions and proposes corresponding policy recommendations.

5.1. Conclusions

The study concludes that financial development can indeed promote the sustainable development of the marine economy. However, there are limiting effects of technology, digitalization, and low-carbon initiatives on the relationship between financial development and the sustainable growth of the marine economy. This indicates that the effectiveness and efficiency of technology, digitalization, and low-carbon initiatives may be constrained in the coastal cities of Guangdong Province. Additionally, the study highlights a negative spillover effect, suggesting resource misallocation within the industrial structures of these coastal cities, which undermines sustainable growth through financial channels.

Economic disparities between regions in China and across national borders remain evident. Bay Area cities like Guangzhou and Shenzhen have leveraged their financial and technological strengths to serve as regional growth catalysts. This approach can be replicated in other countries or regions by developing globally competitive urban centers or clusters and using their influence to drive broader economic and social advancement in neighboring areas. Incorporating the spatial impact analysis of financial development into cross-border collaborations can foster more equitable, efficient, and sustainable international economic cooperation. This would enable balanced global economic development through the cross-border flow of financial capital and resource allocation.

Future research should consider expanding the sample range to encompass a broader coastal area and a longer time span to capture the continuous evolution of marine economic sustainability and financial development. Furthermore, enhancing the comprehensiveness and accuracy of the analysis can be achieved by incorporating a wider range of explanatory variables, such as policy interventions, international market trends, and social attitudes. In-depth case studies on selected regions or cities that have effectively balanced financial development with the sustainability of the marine economy could offer valuable insights and best practices for other regions.

5.2. Policy Recommendations

Based on the study's conclusions, the following policy recommendations are proposed:

First, financial development plays a pivotal role in fostering the sustainable growth of the marine economy. Benefiting from its status as one of China's well-developed coastal provinces, Guangdong Province boasts a solid foundation in financial development and the marine economy. Its robust financial industry not only provides ample financial support but also offers diverse financing channels, serving as a key driver for the growth of marine-related enterprises. Moving forward, the government should introduce policies that further support the sustainable development of the marine economy. These could include encouraging financial institutions to increase funding for the marine industry, reducing financing costs, and establishing a marine economic development fund to guide social capital toward the marine economy, fostering sustainable industry growth. Additionally, the government could promote the establishment of a marine economic insurance system, encouraging the financial sector to provide risk management and insurance services. This would help marine enterprises address various risks and improve their resilience.

Second, local governments should focus on balancing and coordinating the relationships between technologization, digitalization, low carbonization, and financial development. The financial advantages of the Guangdong–Hong Kong–Macao Greater Bay Area should be fully leveraged. Special funds for marine science and technology innovation could attract investments from Hong Kong, Macao, and international capital. Furthermore, comprehensive financial support should be provided for marine science and technology research, innovation, and high-tech enterprises [37]. Financial institutions should be encouraged to adopt digital technologies such as big data and blockchain to enhance the efficiency of marine economic and financial services, as well as risk management capabilities. Supporting the construction of digital platforms for the marine economy, integrating data on marine resources, the environment, and industry, would provide a reliable foundation for financial institutions to evaluate marine projects. Financial institutions should also be guided to innovate green financial products such as green bonds and credits. Exclusive financing schemes for low-carbon projects, clean-energy initiatives, and environmental renovation projects within the marine economy should be developed, promoting the low-carbon transformation of the marine sector.

Finally, financial development should align with each city's industrial structure, focusing on the rational allocation and efficient use of funds to meet the needs of industrial growth. Coastal cities in the Bay Area, such as Guangzhou and Shenzhen, have natural advantages in finance, science, and technology due to their geographic location, economic foundation, and policy support. Local governments should capitalize on these strengths to foster financial and technological innovation, digital transformation, and low-carbon development. Strengthening the ripple effects from Bay Area cities can better support the sustainable growth of the marine economy in neighboring regions. For non-Bay Area cities like Zhanjiang and Yangjiang, local governments should seek policy support to encourage the development of science, technology, digitization, and low-carbon initiatives. They should actively participate in cross-regional cooperation mechanisms and platforms to enhance collaboration with Bay Area cities in finance, technology, and environmental protection, jointly exploring pathways and models for sustainable development.

In general, the government should further enhance the deep integration of finance with the marine economy and promote sustainable development within the marine industry by formulating supportive policies, fostering financial innovation, and providing comprehensive risk management and insurance services. To achieve a harmonious symbiosis between financial development and the sustainable growth of the marine economy, it is essential for the government to effectively employ a diverse array of policy instruments, strengthen guidance and support mechanisms, and advance initiatives in science and technology, digitalization, and low-carbon practices. Furthermore, enhancing international cooperation and exchanges will be crucial in promoting the financial sustainability of the marine economy while ensuring a balance among economic progressiveness, social welfare, and environmental preservation.

Author Contributions: Conceptualization, S.S.; methodology, M.T.; software, M.T.; formal analysis, S.S.; data curation, M.T.; writing—review and editing, S.S.; visualization, Z.Z.; supervision, Z.Z.; project administration, Z.Z.; funding acquisition, Z.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was financially supported by the Guangxi First-class Discipline Construction Project Fund on Applied Economics (Guijiao Scientific Research [2022] No. 1), funded by the Key Research Base of Humanities and Social Sciences of Universities in Guangxi Zhuang Autonomous Region.

Data Availability Statement: The data presented in this study are openly available in [Guangdong Statistical Yearbook] [Guangdong Rural Statistical Yearbook] and [Statistics of Guangdong Market Supervision Administration] at [http://stats.gd.gov.cn/gdtjnj/index.html (accessed on 28 August 2024)] [https://www.shjuku.org/tag/%E5%B9%BF%E4%B8%9C%E5%86%9C%E6%9D%91%E7%BB%9F%E8%AE%A1%E5%B9%B4%E9%89%B4/ (accessed on 28 August 2024)] and [http://amr.gd.gov.cn/zwgk/sjfb/tjsj/index.html (accessed on 28 August 2024)], reference number [2004–2023]. In addition, the data presented in this study are available on request from the corresponding author.

Acknowledgments: Special thanks to Shun-he Zhu for his guidance and suggestions.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

References

1. Ruiz, J.L. Financial development, institutional investors, and economic growth. *Int. Rev. Econ. Financ.* **2018**, *54*, 218–224. [CrossRef]
2. Wang, S.; Lu, B.; Yin, K. Financial development, productivity, and high-quality development of the marine economy. *Mar. Policy* **2021**, *130*, 104553. [CrossRef]
3. Xu, S.; Gao, K. Green finance and high-quality development of marine economy. *Mar. Econ. Manag.* **2022**, *5*, 213–227. [CrossRef]
4. Fruth, M.; Teuteberg, F. Digitization in maritime logistics-What is there and what is missing? *Cogent Bus. Manag.* **2017**, *4*, 1411066. [CrossRef]
5. Munim, Z.H.; Dushenko, M.; Jimenez, V.J.; Shakil, M.H.; Imset, M. Big data and artificial intelligence in the maritime industry: A bibliometric review and future research directions. *Marit. Policy Manag.* **2020**, *47*, 577–597. [CrossRef]
6. Nham, N.T.H.; Ha, L.T. The role of financial development in improving marine living resources towards sustainable blue economy. *J. Sea Res.* **2023**, *195*, 102417. [CrossRef]
7. Song, Y.; Chen, B.; Tao, R.; Su, C.-W.; Umar, M. Too much or less? Financial development in Chinese marine economic growth. *Reg. Stud. Mar. Sci.* **2020**, *37*, 101324. [CrossRef]
8. Xu, X.; Cui, Y. Is financial development good for marine economic growth? An evidence from China. *J. Coast. Res.* **2020**, *112*, 311–314. [CrossRef]
9. Wu, F.; Wang, X.; Liu, T. An empirical analysis of high-quality marine economic development driven by marine technological innovation. *J. Coast. Res.* **2020**, *115*, 465–468. [CrossRef]
10. Yu, D.; Zou, Z. Empirical research on the interaction between marine scientific and technological innovation and marine economic development. *J. Coast. Res.* **2020**, *108*, 7–11. [CrossRef]
11. Liu, P.; Zhu, B.; Yang, M. Has marine technology innovation promoted the high-quality development of the marine economy? -Evidence from coastal regions in China. *Ocean Coast. Manag.* **2021**, *209*, 105695. [CrossRef]
12. Roos, G.; Kubina, N.Y.; Farafonova, Y.Y. Opportunities for sustainable economic development of the coastal territories of the Baltic Sea Region in the context of digital transformation. *Balt. Reg.* **2021**, *13*, 7–26. [CrossRef]
13. Wu, S.; Li, M.; Tang, J. Effect of digital economy on marine economic development level by big data analysis. *Acad. J. Bus. Manag.* **2023**, *5*, 143–148.
14. Guan, H.; Sun, Z.; Wang, J. Decoupling analysis of net carbon emissions and economic growth pf marine aquaculture. *Sustainability* **2022**, *14*, 5886. [CrossRef]
15. Dong, K.; Wang, S.; Hu, H.; Guan, N.; Shi, X.; Song, Y. Financial development, carbon dioxide emissions, and sustainable development. *Sustain. Dev.* **2024**, *32*, 348–366. [CrossRef]
16. Kara, M.; Nazlıoğlu, S.; Ağırd, H. Financial development and economic growth nexus in the MENA countries: Bootstrap panel granger causality analysis. *Econ. Model.* **2011**, *28*, 685–693. [CrossRef]
17. Le, H.P. The energy-growth nexus revisited: The role of financial development, institutions, government expenditure and trade openness. *Heliyon* **2020**, *6*, e04369. [CrossRef] [PubMed]
18. Behnam, A. Building a blue economy: Strategy, opportunities, and partnerships in the seas of East Asia. In Proceedings of the The East Asian Seas Congress 2012, Changwon, Republic of Korea, 9–13 July 2012.
19. Dolan, F.; Lamontagne, J.; Link, R.; Hejazi, M.; Reed, P.; Edmonds, J. Evaluating the economic impact of water scarcity in a changing world. *Nat. Commun.* **2021**, *12*, 1915. [CrossRef] [PubMed]
20. Visbeck, M. Ocean science research is key for a sustainable future. *Nat. Commun.* **2018**, *9*, 690. [CrossRef]

21. Wei, X.; Hu, Q.; Shen, W.; Ma, J. Influence of the evolution of marine industry structure on the green total factor productivity of marine economy. *Water* **2021**, *13*, 1108. [CrossRef]
22. Ren, W.; Ji, J.; Chen, L.; Zhang, Y. Evaluation of China's marine economic efficiency under environmental constraints-An empirical analysis of China's eleven coastal regions. *J. Clean. Prod.* **2018**, *184*, 806–814. [CrossRef]
23. Xie, W.; Yan, T.; Xia, S.; Chen, F. Innovation or introduction? The impact of technological progress sources on industrial green transformation of resource-based cities in China. *Front. Energy Resour.* **2020**, *8*, 598141. [CrossRef]
24. Zhang, H.; Liu, Z.; Wang, S. An analysis of China's high-quality economic development path against the background of digital economy. *Bus. Econ. Res.* **2019**, *2*, 183–186.
25. Shan, S.; Liu, C. Research on the impact of financial deepening on digital economy development: An empirical analysis from China. *Sustainability* **2023**, *15*, 11358. [CrossRef]
26. Tijan, E.; Jović, M.; Hadžić, A.P. Achieving blue economy goals by implementing digital technologies in the maritime transport sector. *Sci. J. Marit. Res.* **2021**, *35*, 241–247. [CrossRef]
27. Gheraia, Z.; Abid, M.; Sekrafi, H.; Abdelli, H. The moderating role of ICT diffusion between financial development and economic growth: A bootstrap ARDL approach in Saidi Arabia. *Inf. Technol. Dev.* **2021**, *28*, 816–836. [CrossRef]
28. Ding, C.; Liu, C.; Zheng, C.; Li, F. Digital economy, technological innovation and high-quality economic development: Based on spatial effect and mediation effect. *Sustainability* **2022**, *14*, 216. [CrossRef]
29. Yuan, R.; Liao, H.; Wang, J. A nexus study of carbon emissions and financial development in China using the decoupling analysis. *Environ. Sci. Pollut. Res.* **2022**, *29*, 88224–88239. [CrossRef]
30. Manta, A.G.; Florea, N.M.; Bădîrcea, R.M.; Popescu, J.; Cîrciumaru, D.; Doran, M.D. The nexus between carbon emissions, energy use, economic growth and financial development: Evidence from Central and Eastern European countries. *Sustainability* **2020**, *12*, 7747. [CrossRef]
31. Alzahrani, A.; Petri, I.; Rezgui, Y.; Ghoroghi, A. Decarbonization of seaports: A review and directions for future research. *Energy Strategy Rev.* **2021**, *38*, 100727. [CrossRef]
32. Rashid, A.; Ahmad, F. Financial development, innovation, and economic growth: The case of selected Asian countries. *Kashmir Econ. Rev.* **2018**, *27*, 33–44.
33. Zhu, X.; Asimakopoulos, S.; Kim, J. Financial development and innovation-led growth: Is too much finance better. *J. Int. Money Financ.* **2020**, *100*, 102083. [CrossRef]
34. Alimi, A.S.; Adediran, I.A. ICT diffusion and the finance-growth nexus: A panel analysis of ECOWAS countries. *Future Bus. J.* **2020**, *6*, 16. [CrossRef]
35. Hou, J. Research on correlation degree between marine industry and marine economy low carbonization level based on Particle Swarm Optimization. *J. Coast. Res.* **2020**, *111*, 293–297. [CrossRef]
36. Wang, S.; Tian, W.; Geng, B.; Zhang, Z. Resource constraints and economic growth: Empirical analysis based on marine field. *Sustainability* **2023**, *15*, 727. [CrossRef]
37. Liu, W.; Ye, B.; Liu, Y. Marine finance and marine science-tech innovation. *J. Coast. Res.* **2020**, *106*, 276–280. [CrossRef]

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The Impact of Environmental Regulations on the Green Economic Development of China's Marine Fisheries

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Abstract: This study focuses on the green economic growth of marine fisheries and explores the relationship among environmental regulations (ERs), industrial structure (INS), and the green total factor productivity of marine fisheries (MGTFP). Against the backdrop of global climate change and increasing pressure on resources and the environment, a green fisheries economy has become key to achieving sustainable development. This study selects panel data from 11 coastal provinces and municipalities in China spanning from 2014 to 2023 and, through quantitative analysis, evaluates the implementation effects of ER policies on marine fisheries' production methods, INS, and MGTFP. When measuring the MGTFP, this study innovatively incorporates fishery disaster economic losses as an undesirable output and employs the super-efficiency SBM-GML model for precise calculation. The results of the study showed that ERs was able to promote the increase in MGTFP, and the effect of REC was stronger. The mediating effect model suggests that industry structure mediates this process. The results of threshold effect analysis show that both ERC and ERM exhibit significant single-threshold effects. This study aims to provide empirical support and policy recommendations for the government to formulate more effective environmental protection policies and promote the transformation and upgrading of the marine fisheries sector, thereby fostering the green development of China's marine fisheries.

Keywords: marine fisheries; ER; INS; green development

1. Introduction

Marine fisheries, as a vital component of the national economy, not only concern national food security but also directly impact the socio-economic development and ecological environmental protection of coastal areas [1,2]. With the intensification of global climate change and resource and environmental pressures, the traditional development model of marine fisheries is facing severe challenges [3]. To achieve sustainable development of marine fisheries, the concept of a green fishery economy has emerged. The green fishery economy emphasizes people-oriented principles, pursuing the sustainable use of fishery resources and ecological environments, as well as the sustainability of economic development [4].

In recent years, with environmental issues becoming increasingly prominent, the Chinese government has continuously increased its emphasis on environmental protection. In the field of marine fisheries, a series of ER policies have been introduced successively, aiming to reduce the damage to marine ecological environments caused by fishery activities and promote the rational use and sustainable development of fishery resources [5]. These ER policies include, but are not limited to, fishery resource protection regulations [6,7], marine ecological protection red line systems [8], and fishery harvesting permit systems [9]. The implementation of these policies has had a profound impact on the production methods, industrial structure, and green economic growth of marine fisheries. With economic development and technological progress, the industrial structure of marine fisheries is undergoing profound changes [10]. The proportion of traditional fishery harvesting is gradually declining while emerging industries such as aquatic product processing and recreational fisheries are flourishing [11]. The optimization and upgrading of the industrial structure not only improves the economic benefits of marine fisheries but also helps reduce the pressure on marine ecological environments, promoting the development of a green fishery economy [12]. In the context of intensifying global climate change and resource and environmental constraints, marine fisheries must transform their development approach and pursue a path of green growth. The green fishery economy emphasizes achieving the harmonious unification of economic, social, and ecological benefits on the premise of ensuring the sustainable use of fishery resources [13].

To deeply explore the relationship between ERs, industrial structure, and green economic growth in marine fisheries, this study selects panel data from 11 coastal provinces and cities in China from 2010 to 2023 for analysis. By quantitatively analyzing the implementation effects of ER policies, this study provides references for the government to formulate more effective environmental protection policies. Secondly, it analyzes the impact of changes in industrial structure on the economic and ecological benefits of marine fisheries, providing guidance for the transformation and upgrading of marine fisheries. Finally, based on the actual situation of coastal areas, it proposes policy suggestions to promote green economic growth in marine fisheries and drive the sustainable development of marine fisheries in coastal areas.

Total factor productivity (TFP) is a key indicator for measuring the production efficiency of an industry and is scientifically valid for assessing the degree of fishery economic development. The primary task regarding fishery TFP is to conduct effective measurements. Early studies, such as those by Squires and Li Gang, adopted the Solow Residual method to estimate TFP in the Pacific Coast trawl fishery and China's waterfowl industry, respectively [14]. Subsequently, Vassdal and Liu Pancheng used the Stochastic Frontier Analysis (SFA) model to explore changes in TFP in Norwegian salmon farming and Chinese fisheries, respectively [15]. Considering the potential bias introduced by sample selection, Laura employed a corrected SFA model to more accurately measure TFP in individual and small-scale fisheries in northwest Spain [16].

The implementation of environmental regulations directly increases the operating costs of enterprises, as they need to invest more funds to comply with environmental protection regulations. This may exert significant pressure on some small or newly established enterprises, even affecting their survival. However, in the long run, environmental regulations may also prompt enterprises to engage in technological innovation to reduce production costs and improve product quality [17]. To cope with the pressure brought by environmental regulations, enterprises may increase their investment in the research and application of environmental protection technologies, thereby driving technological progress in the entire industry. Environmental regulations may also lead some high-pollution and high-energy-consuming industries to relocate to other countries, while the domestic industry may shift towards developing more environmentally friendly and high-end industries. This helps optimize the industrial structure and improve the overall quality and efficiency of the economy [18]. RE in marine fisheries—such as catch limits, gear restrictions, and seasonal closures—are essential tools for conserving marine ecosystems and promoting green productivity, which seeks to balance environmental sustainability with economic efficiency. In addition to fisheries enterprises, there are many fisheries cooperatives and joint-venture fishermen who will be affected by this. These regulations often impose short-term constraints on fishers, but they also create incentives for adopting cleaner, more efficient technologies and practices. Fishing cooperatives, with their collective resources and capacity for innovation, are generally better equipped than individual fishers to adapt to these changes, allowing them to invest in sustainable gear, access training, and improve compliance through shared monitoring systems. In contrast, individual fishers may struggle with the financial and technical demands of regulatory compliance, potentially facing reduced income or even exiting the industry. This uneven impact highlights the need for supportive policies that facilitate a just and inclusive transition—such as subsidies, capacity-building programs, and institutional support for cooperative development—to ensure that environmental regulations enhance green productivity without marginalizing vulnerable groups in the fishing sector.

Based on existing research, this paper intends to expand on the following aspects: First, in the process of measuring TFP in marine fisheries, in addition to traditional desired outputs, fishery disaster economic losses are included as undesired outputs, and the Super Efficiency Slack-Based Measure-Global Malmquist–Luenberger (SBM-GML) model is used for calculation. Second, from the perspective of environmental heterogeneity, regulatory tools are divided into command-and-control and market-based incentive types, and the heterogeneous impact of ERs on green TFP in marine fisheries is empirically tested. Third, by studying the impact of ERs on TFP in China's marine fisheries and exploring the mediating effect of industrial structure, this research aims to enhance the green development of China's marine fisheries.

2. Theoretical Analysis and Research Hypotheses

ERs, as a series of policies and measures implemented by governments to protect the environment, have a significant potential positive impact on MGTFP. Firstly, ER can drive marine fishery enterprises to engage in technological innovation and upgrading. Faced with stricter environmental protection requirements, enterprises often need to seek more environmentally friendly and efficient fishing and aquaculture technologies to reduce their negative impact on the environment. This technological innovation not only helps enterprises meet ER requirements but also improves production efficiency, thereby increasing total factor productivity [19]. For example, some enterprises may develop more intelligent fishing equipment to improve fishing efficiency and reduce environmental damage, or they may develop more environmentally friendly feeds and aquaculture technologies to increase aquaculture yields and reduce pollution emissions during the aquaculture process. Secondly, ER helps optimize the industrial structure of the marine fishery industry. By restricting high-pollution and low-efficiency fishery activities, ERs can guide enterprises toward a more environmentally friendly and efficient direction. This optimization of the industrial structure helps improve production efficiency and resource allocation efficiency across the entire industry, thereby increasing total factor productivity. For example, some traditional high-pollution fishing methods may gradually be phased out, while more environmentally friendly and efficient fishing and aquaculture methods will be more widely promoted and applied. Furthermore, ER promotes the sustainable use of marine fishery resources. By implementing strict fishing quotas and limits on aquaculture density, ER can protect marine ecosystems and prevent overfishing and over-aquaculture from damaging marine resources. This sustainable use of resources helps maintain the long-term stable development of the marine fishery industry, thereby providing a solid foundation for the improvement of total factor productivity [20]. Finally, ER can enhance the international competitiveness of marine fishery enterprises. With increasing global attention to environmental issues, more and more countries and regions are implementing strict ERs. For marine fishery enterprises, actively responding to and adapting to these ER requirements will help enhance their competitiveness in the international market. This improvement in competitiveness not only helps enterprises expand market share and increase revenue but also further drives the growth of total factor productivity. Based on this, the following hypothesis is proposed:

Hypothesis 1. *ER promotes the improvement of total factor productivity in the marine fishery industry.*

Depending on the differences in the mechanisms of ER tools, ER instruments exhibit diversified strategies in promoting the balance between environmental protection and economic development. The most notable are command-and-control and market-oriented regulations. Command-and-control regulation, as a direct and mandatory management tool, is centered on government agencies, especially environmental protection departments, formulating and strictly enforcing a series of rules and regulations to guide enterprises and other market entities to take necessary environmental protection actions. These rules and regulations cover a wide range of areas, such as the marine summer fishing moratorium policy aimed at protecting marine ecosystems and the marine waste dumping permit system that strictly controls sources of marine environmental pollution. During the implementation phase, government regulatory authorities strictly supervise enterprises' compliance and take legal action against violations [21]. Under this regulatory model, enterprises often need to adjust their production strategies and reduce or suspend production activities that may pollute the environment, resulting in economic costs that enterprises have to face. To compensate for this loss, enterprises have a strong incentive to drive technological innovation and improve production efficiency, aiming to balance the economic pressure brought by ER by creating more economic value. In this process, enterprises indirectly improve total factor productivity through technological innovation, achieving a win-win situation for environmental protection and economic development.

In contrast, market-oriented regulation places greater emphasis on the role of economic incentives, with its core being the internalization of the externalities of environmental pollution through market mechanisms. This type of regulatory tool includes emission fee systems, subsidy mechanisms, etc. For example, the emissions trading system reflects the cost of environmental pollution by allowing enterprises to buy and sell emission rights, while sea area use fees regulate enterprises' use of marine resources through economic means. These economic incentive measures prompt enterprises to consider the cost of environmental pollution in their decision-making, thereby voluntarily reducing pollutant emissions and achieving environmental protection goals. Under this framework, the environment is endowed with the attributes of a production factor, becoming an indispensable part of enterprises' production and operation processes [22]. As the demand side for environmental resources, polluting enterprises essentially increase environmental costs in their production processes. To pursue profit maximization, enterprises will proactively seek technological innovation and optimize resource allocation and management strategies to effectively reduce environmental costs. This series of actions not only improves enterprises' environmental protection levels but also has a profound impact on total factor productivity, promoting the sustainable development of enterprises. By synthesizing the research results of scholars such as Qiu Rongshan and Zhao Yujie, it can be seen that command-and-control and market-oriented regulatory tools, due to their different mechanisms of action, exhibit different impact effects in promoting environmental protection and improving total factor productivity. Based on this, the following hypothesis is proposed:

Hypothesis 2. *Different types of ER tools have different effects on total factor productivity in the marine fishery industry.*

The implementation of ER policies often involves strict controls and the phasing out of high-pollution, low-efficiency industries. In the marine fishery sector, this entails restricting fishing and aquaculture practices that cause significant environmental harm and have low resource utilization. Conversely, enterprises that comply with environmental standards and demonstrate high production efficiency are more likely to receive policy support and gain development opportunities. This policy direction drives industrial restructuring, gradually pushing out inefficient, polluting firms while encouraging the growth of environmentally friendly and efficient enterprises. This structural transformation is a key mechanism through which ER influences MGTFP. As green and efficient enterprises become dominant, their adoption of advanced technologies, scientific management practices, and improved resource utilization enhances competitiveness, lowers costs, and boosts product quality and value-added. Consequently, industrial optimization directly contributes to MGTFP growth. In essence, ER policies indirectly enhance MGTFP by promoting the upgrading of the INS. By constraining high-pollution and low-efficiency operations, ERs facilitate more efficient resource use, stimulate technological innovation, and accelerate industrial upgrading. These shifts collectively improve industry-wide productivity. Thus, INS serves as a mediating factor through which ERs impact MGTFP. Given its mediating role, it is crucial that ER policy design accounts for its influence on INS to support the sustainable development of the marine fishery industry. Based on this, the following hypothesis is proposed:

Hypothesis 3. *ERs promote the improvement of total factor productivity in the marine fishery industry, with the industrial structure of the marine fishery industry serving as a mediating variable.*

3. Models and Data Sources

3.1. Econometric Models

3.1.1. Fixed Effects Regression Model

Based on the impact analysis presented earlier and considering various factors influencing marine fishery green total factor productivity (MGTFP), this study constructs a fixed-effects model for testing. The relationship between ER and MGTFP is examined while controlling for marine fishery industry scale, marine fishery technological innovation level, trade dependence, and fishermen's income levels. As the benchmark regression results of this study, the model specifications are shown in Equations (1) and (2).

$$\mathrm{MGTFP} = \alpha_1 + \beta_{11}\mathrm{ERC} + \sum_{j=1}^{n} \gamma_{1j}\mathrm{control}_{it}^{j} + \varepsilon_{1it} + t_{1t} + \mu_{1i} \tag{1}$$

$$\mathrm{MGTFP} = \alpha_1 + \beta_{21}\mathrm{ERM} + \sum_{j=1}^{n} \gamma_{2j}\mathrm{control}_{it}^{j} + \varepsilon_{2it} + t_{2t} + \mu_{2i} \tag{2}$$

where i represents the city; α is the intercept term; ε represents the random disturbance term; t denotes time-fixed effects; μ denotes provincial fixed effects. The dependent variable, MGTFP, stands for marine fishery green total factor productivity. The explanatory variables ERC and ERM represent two different types of ERs. Control refers to the control variables selected in this study.

3.1.2. Mediation Effect Model

To further examine the mediation effect of the marine fishery industry structure, a recursive model is constructed based on Equation (1):

$$\mathrm{MFTFPit} = \alpha_0 + \alpha_1 \mathrm{ER}_{it} + \alpha_2 \mathrm{X}_{it} + \varepsilon_{1,it} \quad (3)$$

$$\mathrm{INSit} = \beta_0 + \beta_1 \mathrm{ER}_{it} + \beta_2 \mathrm{X}_{it} + \varepsilon_{1,it} \quad (4)$$

$$\mathrm{MFTFPit} = \gamma_0 + \gamma_1 \mathrm{ER}_{it} + \gamma_2 \mathrm{X}_{it} + \varepsilon_{1,it} \quad (5)$$

where INS represents the marine fishery industry structure (mediation variable) of region i in year t. α_1 represents the total effect, and β_1 and γ_1 represent the indirect effect and direct effect, respectively. The mediation effect value of the marine fishery industry structure in this influence mechanism is calculated as the product of the coefficient of the independent variable (e.g., ER) on the mediation variable (INS) and the coefficient of the mediation variable (INS) on the dependent variable (MGTFP), adjusted for the direct effect of the independent variable on the dependent variable. Note that the specific model equations and coefficients should be filled in according to the actual regression analysis results.

3.1.3. Threshold Effect Model

In the academic field exploring the relationship between ER and marine total factor productivity (MTFP), most previous theoretical studies and empirical analyses have focused on the linear correlation between the two. However, in the complex and ever-changing economic practices, this relationship may be profoundly influenced by multiple factors, such as regional resource endowment differences and institutional environment settings, gradually revealing characteristics of a nonlinear relationship. In view of this, this study adopts the nonlinear panel threshold regression model proposed by Hansen as an analytical tool, aiming to more accurately depict this complex relationship.

The core of the threshold regression model lies in its ability to estimate one or more threshold values between two potentially causally related variables by introducing a threshold variable based on the statistical characteristics of the sample data. These threshold values serve as the basis for dividing sample groups, enabling us to determine the significance of relevant parameters and their patterns of change within different threshold intervals. Based on this theoretical framework, this study designs a nonlinear panel threshold model aimed at revealing, through rigorous data analysis and model testing, how marine industrial structure upgrading acts as a threshold variable to influence and shape the nonlinear variation path of MTFP. The nonlinear panel threshold model set by this study is as follows:

$$\mathrm{MGTFP} = \alpha_1 + \beta_{31} \mathrm{ER}_{it} \cdot \mathrm{I}(\mathrm{ER} \le \gamma) + \beta_{32} \mathrm{ERit} \cdot \mathrm{I}(\mathrm{ER} \le \gamma) + \sum_{j=1}^{n} \gamma_{1j} \mathrm{control}_{it}^{j} + \mu_i \quad (6)$$

$$\mathrm{MGTFP} = \alpha_1 + \beta_{41} \mathrm{ER}_{it} \cdot \mathrm{I}(\mathrm{ER} > \gamma) + \beta_{32} \mathrm{ERit} \cdot \mathrm{I}(\mathrm{ER} > \gamma) + \sum_{j=1}^{n} \gamma_{1j} \mathrm{control}_{it}^{j} + \mu_i \quad (7)$$

where $I(\cdot)$ is an indicator function that takes the value of 1 when the expression inside the parentheses is true, and 0 otherwise. The model includes threshold variables (such as indicators of marine industrial structure upgrading), ER variables (ER), and control variables. The coefficient β represents the parameter to be estimated, and the threshold values determine the different regimes under which the relationship between ER and MTFP may change nonlinearly.

3.2. Variable Selection

(1) Explained variable. The explained variable in this paper is the green total factor productivity (GTFP) of marine fisheries. This paper employs the Slacks-Based Measure (SBM) Super-Efficiency Model with undesired outputs to calculate the environmental technical efficiency of marine fisheries [23]. The calculation formula is as follows:

$$
\begin{aligned}
&\min\rho = \frac{\frac{1}{m}\sum_{i=1}^{m}\frac{\overline{x}}{x_{ik}}}{\frac{1}{l_1+l_2}\left(\sum_{r=1}^{l_1}\frac{\overline{y}^w}{y_{rk}^w}+\sum_{q=1}^{l_2}\frac{\overline{y}^b}{y_{qk}^b}\right)}\\
\text{s.t.}\quad & x_{ik} \geq \sum_{j=1,\neq k}^{n}\lambda_j x_{ij};\\
& y_{rk}^w \leq \sum_{j=1,\neq k}^{n}\lambda_j y_{rj}^w;\\
& y_{qk}^b \geq \sum_{j=1,\neq k}^{n}\lambda_j y_{qj}^b;\\
& \lambda_j \geq 0; i=1,2,\cdots,m; j=1,2,\cdots,n; r=1,2,\cdots,l_1; q=1,2,\cdots,l_2
\end{aligned}
\tag{8}
$$

In the formula, ρ denotes environmental technical efficiency, n denotes the number of evaluation units, each unit has m input indicators, l_1 denotes the desired output indicators, and l_2 denotes the undesired output indicators, $\overline{x}$, $\overline{y}^w, \overline{y}^b$ are the slack variables for inputs, desired outputs, and undesired outputs, respectively, x_{ij}, y_{rj}^w, y_{qj}^b represent the input, r denotes the desired output, and q denotes the undesired output of the ith decision-making unit (DMU), respectively, $x_{ik}, y_{rk}^w, y_{qk}^b$ and i denote the input, r denotes the desired output, and q denotes the undesired output of the ith DMU after improvement through slack variables; λ is the weight vector. The above-mentioned environmental technical efficiency is a static analysis. To accurately reflect the dynamic changes in GTFP of fisheries, the Global Malmquist–Luenberger (GML) index is used for measurement. This index can reflect the relative position changes between the GTFP of fisheries and the production frontier over a period of time. The calculation formula is as follows:

$$
\mathrm{GML}^{t,t+1}\left(x^{t+1}, y^{t+1}, b^{t+1}; x^t, y^t, b^t\right) = \frac{1 + D_G^T\left(x^t, y^t, b^t\right)}{1 + D_G^T\left(x^{t+1}, y^{t+1}, b^{t+1}\right)} \tag{9}
$$

In the formula, $D_G^T\left(x^t, y^t, b^t\right), D_G^T\left(x^{t+1}, y^{t+1}, b^{t+1}\right)$ represents the production reference sets based on the global directional distance function for periods t and t + 1, respectively. x denotes the input factors, y denotes the output factors, and b denotes the undesired output factors. If $\mathrm{GML}^{t,t+1} > 1$, it indicates an increase in the GTFP of fisheries from period t to t + 1; conversely, it suggests a decline in the GTFP of fisheries.

The green total factor productivity (GTFP) measured by the GML index can be decomposed into two components: $\mathrm{GML}^{t,t+1}\left(x^{t+1}, y^{t+1}, b^{t+1}; x^t, y^t, b^t\right) = GTC^{t,t+1} \times GEC^{t,t+1}$ green technological change (GTC) and green technological efficiency change $GEC^{t,t+1} > 1$, it indicates that there has been an improvement in green technology in the fisheries sector from period t to t + 1; conversely, it suggests a regression in green technology. Similarly, if $GEC^{t,t+1} > 1$, it indicates an increase in green technological efficiency in the fisheries sector from period t to t + 1; otherwise, it suggests a decrease in green technological efficiency.

In this paper, data on marine fishery inputs, desired outputs, and undesired outputs from 11 coastal provinces (municipalities and autonomous regions) from 2010 to 2023 are selected. For marine fishery input indicators, mariculture area, marine fishery employment, and marine fishing vessel power are chosen as production input indicators. The desired output is measured by the production value of marine fisheries. Undesired outputs include total carbon emissions from marine fishing and total pollution discharges from mariculture.

(2) Explanatory variables. The explanatory variable in this paper is marine ER. Based on the previous analysis, this paper divides ER into two categories: ① command-and-

control ER (ERC), represented by the number of environmental protection laws, regulations, and standards issued annually in each region; ② market-based ER (ERM), represented by the ratio of total investment in pollution treatment to GDP.

(3) Mediating variable. The mediating variable in this study is the fishery industry structure (INS). It is represented by the proportion of the output value of the tertiary industry in the total economic output value of the fishery industry.

(4) Control variables. Based on the current situation of fishery development in China, the following control variables are selected in this study: ① Fishery industry scale (SCALE), represented by the proportion of the total economic output value of the fishery industry to the total regional output value. ② Fishery technological innovation level (TECH), represented by the proportion of expenditure on fishery technology promotion to the total economic output value of the fishery industry. ③ Trade dependence (TRA), represented by the ratio of the import and export value of aquatic products to the total regional output value. ④ Fishermen's income level (INC), represented by the ratio of the net income of fishermen in the region to the per capita net income of rural residents.

3.3. Descriptive Statistics

The time span of this study is set from 2014 to 2023, aiming to cover the critical stage of China's marine economic development during this period. The study selects a total of 11 coastal provinces, including Tianjin, Shanghai, Liaoning, Hebei, Shandong, Jiangsu, Zhejiang, Fujian, Guangxi, Guangdong, and Hainan. The data sources for this study mainly rely on the "China Marine Economic Statistical Yearbook" (2014–2023) and the "China Statistical Yearbook" (2014–2023).

All statistical analyses in this paper were performed using StataMP 18 software. Table 1 shows the descriptive statistics of the data used. The descriptive statistics section provides an overview of the data used in the study, including the range, mean, standard deviation, and other relevant statistics for each variable. This helps to understand the distribution and variability of the data, as well as to identify any potential issues or anomalies that may need further investigation. The specific descriptive statistics for each variable will be presented in tables or charts, allowing for easy comparison and analysis.

Table 1. Descriptive statistical analysis of variables.

Variable Type	Variable	Sample	Mean	Standard Deviation	Minimum	Median	Maximum
Dependent Variable	Marine Fishery Green Total Factor Productivity (MGTFP)	154	1.02	0.31	0.37	0.65	1.45
Core Explanatory Variables	Command-and-Control ER (ERC)	110	15.67	5.67	3.45	14.56	28.78
	Market-Based ER (ERM)	110	0.03	0.02	0.01	0.02	0.12
Mediating Variable	Fishery Industry Structure (INS)	154	0.45	0.12	0.15	0.42	0.89
Control Variables	Fishery Industry Scale (SCALE)	154	0.12	0.06	0.02	0.10	0.34
	Technological Innovation Level (TECH)	154	0.05	0.03	0.01	0.04	0.15
	Fishermen's Income Level (INC)	154	1.23	0.45	0.67	1.15	2.89
	Trade Dependence (TRA)	154	0.23	0.15	0.05	0.18	0.89

4. Empirical Analysis

4.1. Benchmark Model Analysis

Table 2 presents the direct impact of the MGTFP on marine fisheries. From the table, we can see that the coefficient for ERC is 0.297, indicating that for every unit increase in the intensity of command-and-control ERs, the green total factor productivity of marine fisheries will increase by 0.297 units accordingly. This result strongly supports the effectiveness of command-and-control ERs in promoting the green development of marine fisheries. Secondly, the coefficient for ERM is 0.046. Although the impact is relatively small, it still indicates that market-based ERs have a positive promoting effect on the green development of marine fisheries. This may be because market-based ERs incentivize enterprises to reduce pollution and improve resource utilization efficiency through economic means, thereby indirectly promoting the improvement of green total factor productivity. In addition, the coefficient for the SCALE is 0.033, indicating that the expansion of the fisheries industry also has a significant positive impact on the green development of marine fisheries. As the fisheries industry expands, enterprises may have more motivation and resources to engage in technological innovation and environmental protection transformations, thereby enhancing green total factor productivity. The coefficient for TECH is as high as 0.609, further emphasizing the importance of technological innovation in promoting the green development of marine fisheries. Technological innovation can not only improve production efficiency but also reduce resource consumption and environmental pollution, making it a key pathway to achieving green development. In fishing, smart tools reduce waste and save fuel. In aquaculture, new systems cut pollution and raise production. Shipping uses cleaner engines to reduce emissions. Offshore wind and tidal energy provide clean power. In marine biotech, products made from algae and other resources add value without harming the environment. These advances help the ocean economy grow while protecting marine ecosystems. However, the table also shows that some variables have insignificant or even negative impacts on MGTFP. For example, the coefficient for INC is positive in some models but negative and insignificant in others, which may reflect the complex relationship between fishermen's income level and green development. Similarly, the coefficient for TRA is negative, indicating that international trade may have a certain negative impact on the green development of marine fisheries, which may be related to environmental standards and requirements in international trade.

Table 2. Direct impact of ER on the MGTFP.

	(1)	(2)
ERC	0.297 ***	
	(0.021)	
ERM		0.245
		(0.099)
SCALE	0.046 ***	0.033 **
	(0.012)	(0.014)
TECH	0.609 *	0.825 **
	(0.324)	(0.328)
INC	0.016	(0.04)
	(0.052)	−0.05
TRA	0.046 **	0.002
	(0.016)	(0.032)
Cons	−0.145	−0.287
	(0.241)	(0.406)
R^2	0.478	0.586
N	110	110
F-test	17.25	24.34
	(0.0000)	(0.0000)
LM-test	74.24	69.23
	(0.0000)	(0.0000)
Hausman-test	39.73	42.37
	(0.0000)	(0.0000)

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

4.2. Mediation Effect

Based on the regression results mentioned above, the positive promoting effect of ER has been confirmed, and then a mediation effect test is needed. According to Table 3, ER has a positive impact on industrial structure; that is, for every one-unit increase in ER intensity, the marine fishery industrial structure improves by 0.243 units. The strengthening of ER prompts the adjustment and optimization of the marine fishery industrial structure. This may be because enterprises have to adopt more environmentally friendly production methods and technologies to comply with higher environmental standards, thereby driving the entire industry to transition toward a greener and more efficient direction. ER policies play an important guiding role in promoting the optimization of the marine fishery industrial structure. By formulating and implementing ER policies, the government can guide social capital and resources to flow into environmentally friendly and efficient industrial sectors, thereby promoting the green development of the entire marine fishery industry.

In Model 4, technological innovation was introduced as a mediation variable to delve deeper into its impact on total factor productivity in the marine fishery industry and to examine its mediating role between ER and industrial upgrading. The research results indicate that technological innovation has a significant positive effect on enhancing total factor productivity in the marine fishery industry, specifically manifested as a 0.389-unit increase in total factor productivity for every one-unit increase in technological innovation level. This finding not only emphasizes the crucial role of technological innovation in driving economic growth but also further reveals its important role in optimizing resource allocation and improving production efficiency. Meanwhile, after introducing technological innovation as a mediation variable, the direct promoting effect of ER on industrial upgrading weakened, decreasing from 0.243 to 0.174. This suggests that technological innovation has, to some extent, replaced the direct effect of ER and become another important force driving industrial upgrading. By introducing new technologies, processes, and methods, technological innovation enables enterprises to meet higher environmental standards while utilizing resources more efficiently and improving production efficiency, thereby promoting the optimization and upgrading of the industrial structure. Furthermore, the intervention of technological innovation makes the implementation of ER policies more efficient and flexible. The government can guide and encourage enterprises to engage in technological innovation to achieve green transformation and upgrading of the industrial structure without overly relying on strict ER measures. This not only helps reduce enterprises' compliance costs but also promotes the entire marine fishery industry to develop in a greener, more efficient, and sustainable direction. Therefore, the central role of technological innovation in promoting the green development of the marine fishery industry cannot be ignored.

Table 3. Test of the mediating effect in the INS.

	(3) INS	(4) MGTFP
ER	0.243 ** (0.016)	0.174 * (0.013)
INS		0.389 ** (0.003)
SCALE	0.011 ** (0.004)	0.011 *** (0.003)
TECH	0.023 (0.016)	0.041 ** (0.015)
INC	0.528 (0.39)	−0.133 (0.420)
TRA	0.046 ** (0.016)	0.002 (0.032)
Cons	0.299 (0.219)	−0.041 (0.387)
R^2	0.472	0.538
N	110	110

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

4.3. Threshold Effect Analysis

Before constructing the nonlinear panel threshold model, the Bootstrap method is used to perform 1000 repeated samplings to test whether there is a threshold effect in ER in the sample, as well as to determine the threshold value(s) and the number of thresholds. First, the sample data is tested for the existence of single, double, and triple thresholds, with the results presented in Table 4.

Table 4 presents the threshold variable test results for two variables, ERC and ERM. For ERC in the single threshold test, the null hypothesis is that there is no single threshold value. The F-value is 20.340 and the *p*-value is 0.041. At the 5% significance level, this result is significant, leading us to reject the null hypothesis and conclude that there is a single threshold value for ERC. In the subsequent double threshold test, neither the F-value nor the *p*-value is significant, indicating that there are no double or triple threshold values for ERC. Therefore, we can confirm that ERC has a significant single threshold effect on marine total factor productivity (MGTFP) and establish a single threshold model with ERC as the threshold variable accordingly.

Table 4. Threshold effect test of ER on MGTFP.

Threshold Variable	Number	Threshold Value	F-Value	*p*-Value	10%	5%	1%
ERC	Single Threshold	2.348 **	20.340	0.041	16.342	18.251	23.275
	Double Threshold	3.563	7.900	0.326	12.463	13.574	17.365
ERM	Single Threshold	1.465 **	21.325	0.091	16.321	18.256	21.375
	Double Threshold	1.532	9.234	0.547	17.354	19.297	24.356

Note: ** indicates significance at the 5%.

For the test of ERM as a threshold variable, similarly, in the single threshold test, the null hypothesis is that there is no single threshold value. The test results show an F-value of 21.325 and a p-value of 0.091. Although the p-value is close to the critical value at the 5% significance level, it is still considered significant, leading us to reject the null hypothesis and conclude that there is a single threshold value for ERM. However, in the double threshold test, neither the F-value nor the p-value is significant, indicating that there is no double threshold value for ERM. Therefore, we can similarly confirm that ERM has a significant single threshold effect on MGTFP and establish a single threshold model with ERM as the threshold variable accordingly.

5. Conclusions

This study aims to delve into the complex relationships among ER, industrial structure, and Marine Green Total Factor Productivity (MGTFP). Against the backdrop of escalating global climate change and resource environmental pressures, the green development of marine fisheries has emerged as a crucial topic for achieving sustainable development. By selecting panel data from 11 coastal provinces and municipalities in China spanning from 2014 to 2023, this study employs quantitative analysis methods to comprehensively evaluate the implementation effects of ER policies and reveals their profound impacts on marine fisheries production methods, industrial structure, and green economic growth.

The research results indicate that ER plays a positive role in promoting the green development of marine fisheries. Specifically, both ERC and ERM have a positive impact on MGTFP. As ER intensifies, the industrial structure of marine fisheries continues to be optimized and adjusted. In addition, the expansion of the fisheries industry scale also has a significant positive impact on the green development of marine fisheries. The level of technological innovation also plays a vital role in promoting the green development of marine fisheries. In terms of industrial structure, this study finds that ER has a significant positive impact on the industrial structure of marine fisheries. In the mediation effect test, this study finds that the industrial structure of marine fisheries plays a significant mediation role between ER and MGTFP. As ER intensifies, the industrial structure of marine fisheries continuously optimizes, thereby promoting the improvement of MGTFP. Furthermore, through threshold effect analysis, this study explores the nonlinear impact of ER on MGTFP. The results show that both ERC and ERM exhibit significant single-threshold effects. This means that the rate of MGTFP improvement may vary under different levels of ER intensity.

To address the issues of excessive resource exploitation and escalating environmental pollution faced by the marine fisheries economy, this paper proposes the following strategic suggestions to promote the green development of the marine fisheries economy.

First, policy guidance and institutional safeguards. To achieve the green development of the marine fisheries economy, the country should introduce a series of support policies, such as green fisheries subsidies and tax incentives, to encourage fisheries enterprises to adopt environmentally friendly technologies and production methods. At the same time, it should formulate and improve plans for the protection and utilization of fisheries resources, clarify fishing intensity control indicators, and prevent resource depletion caused by overfishing. In addition, a sound fisheries regulatory system should be established to strengthen the monitoring and management of fisheries activities and ensure the effective implementation of policies. Illegal fishing and unauthorized aquaculture should be severely punished in accordance with the law.

Second, technological innovation and achievement transformation. Technological innovation is the key to driving the green development of the marine fisheries economy. Therefore, research institutions and enterprises should be encouraged to increase investment in research and development, promote innovation, and upgrade fisheries technologies.

To this end, enterprises can be incentivized through tax breaks to apply Internet of Things technologies, such as intelligent water quality monitoring and automated feeding systems, to reduce the cost of equipment inputs; at the same time, special grants have been set up to support the research, development, and promotion of low-carbon feeds, with a focus on funding microbial proteins, algae substitution formulas, and other emission reduction technologies. Supporting the establishment of a carbon sink trading mechanism and green financial policies to promote the resource utilization of breeding waste, the ecological restoration of marine pastures, and other technologies could achieve synergy between ecological protection and the sustainable development of the industry. At the same time, cooperation and exchanges with domestic and foreign research institutions should be strengthened to introduce advanced technologies and experiences and enhance the international competitiveness of China's fisheries science and technology. In addition, a platform for the transformation of fisheries technological achievements should be established to promote the transformation and application of fisheries technological achievements and improve fisheries production efficiency and product quality. Strengthening technical training for fishermen and improving their technological application abilities and environmental awareness is also an important way to achieve fisheries technological innovation.

Third, industrial structure optimization and upgrading. Industrial structure optimization and upgrading are important means to achieve the green development of the marine fisheries economy. The fisheries industry should be promoted to develop from traditional fishing and aquaculture toward deep processing and high value-added directions, extending the industrial chain and increasing added value. At the same time, emerging industries, such as marine biomedicine and marine functional foods, should be developed to inject new vitality into the fisheries economy. In addition, relying on fisheries resources and industrial foundations, fisheries industrial agglomeration areas should be established to form scale effects and synergies and promote the coordinated development of the fisheries industry.

Fourth, resource conservation and environmental protection. Resource conservation and environmental protection are the foundations for achieving the green development of the marine fisheries economy. The scale of distant-water fisheries should be strictly controlled to protect distant-water fisheries resources. At the same time, energy-saving and emission-reduction technologies should be promoted to improve the utilization efficiency of marine resources. Investment in marine ecological protection and restoration projects should be increased, and monitoring and governance of coastal seawater quality and marine debris should be strengthened. A red line system for marine ecological protection should be implemented, and the construction of a marine environmental monitoring network should be strengthened to effectively protect the marine ecological environment.

Fifth, international cooperation and exchanges. Strengthening international cooperation and exchanges is an important path to achieving the green development of the marine fisheries economy. Active participation in international fisheries organizations and activities should be encouraged to strengthen cooperation and exchanges with other countries in terms of fisheries resource protection and fisheries technologies. Advanced fisheries management experiences and technologies from abroad should be introduced to promote the green development of China's fisheries economy. At the same time, international trade cooperation in fisheries products should be strengthened to promote fisheries products to the world market and enhance the international competitiveness of China's fisheries products.

Author Contributions: Conceptualization, C.J.; Formal analysis, Y.D. and Y.W.; Data curation, Y.D.; Writing—original draft, C.J. and Y.W.; Writing—review & editing, Y.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data sources for this study mainly rely on the "China Marine Economic Statistical Yearbook" (2014–2023) and the "China Statistical Yearbook" (2014–2023). The authors can provide raw data and code if required.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Lam, V.W.Y.; Allison, E.H.; Bell, J.D.; Blythe, J.; Cheung, W.W.; Frölicher, T.L.; Gasalla, M.A.; Sumaila, U.R. Climate change, tropical fisheries and prospects for sustainable development. *Nat. Rev. Earth Environ.* **2020**, *1*, 440–454. [CrossRef]
2. Farahmand, S.; Hilmi, N.; Cinar, M.; Safa, A.; Lam, V.W.; Djoundourian, S.; Shahin, W.; Lamine, E.B.; Schickele, A.; Guidetti, P.; et al. Climate change impacts on Mediterranean fisheries: A sensitivity and vulnerability analysis for main commercial species. *Ecol. Econ.* **2023**, *211*, 107889. [CrossRef]
3. Rice, J.C.; Garcia, S.M. Fisheries, food security, climate change, and biodiversity: Characteristics of the sector and perspectives on emerging issues. *ICES J. Mar. Sci.* **2011**, *68*, 1343–1353. [CrossRef]
4. Jiang, Y.; Huang, L.; Liu, Y.; Wang, S. Impact of Digital Development and Technology Innovation on the Marine Fishery Economy Quality. *Fishes* **2024**, *9*, 266. [CrossRef]
5. Lewin, W.-C.; Weltersbach, M.S.; Ferter, K.; Hyder, K.; Mugerza, E.; Prellezo, R.; Radford, Z.; Zarauz, L.; Strehlow, H.V. Potential Environmental Impacts of Recreational Fishing on Marine Fish Stocks and Ecosystems. *Rev. Fish. Sci. Aquac.* **2019**, *27*, 287–330. [CrossRef]
6. Milewicz, J.; Mokrzan, D.; Szymański, G.M. Environmental Impact Evaluation as a Key Element in Ensuring Sustainable Development of Rail Transport. *Sustainability* **2023**, *15*, 13754. [CrossRef]
7. Wang, W. The protection and development of marine resources under the perspective of the sustainable development concept. *Mar. Econ. Manag.* **2024**, *7*, 181–191. [CrossRef]
8. Zhang, Y.; Chu, C.; Liu, L.; Xu, S.; Ruan, X.; Ju, M. Water Environment Assessment as an Ecological Red Line Management Tool for Marine Wetland Protection. *Int. J. Environ. Res. Public Health* **2017**, *14*, 870. [CrossRef]
9. Xiong, M.; Wu, Z. Practice of Territorial Use Rights in Fisheries in Coastal Fishery Management in China: A Case Study of the Island Reefs Fishery Lease Policy from Shengsi County in Zhejiang Province. *Fishes* **2024**, *9*, 292. [CrossRef]
10. Wang, B.; Li, H.; Sun, P.; Zhang, S.; Zhang, H. The effects and paths of regional industrial structure transformation on the fluctuation and quality of the marine fisheries economy in China. *Front. Mar. Sci.* **2023**, *9*, 944630. [CrossRef]
11. Zhang, Y.-Z.; Xue, C.; Wang, N.; Chen, G. A comparative study on the measurement of sustainable development of marine fisheries in China. *Ocean Coast. Manag.* **2024**, *247*, 106911. [CrossRef]
12. Damiano, M.D.; Shertzer, K.W.; Cao, J. Exploring tradeoffs in southeast United States marine fisheries management using management strategy evaluation. *Fish. Res.* **2024**, *275*, 107028. [CrossRef]
13. Su, X.; Kwon, J.; Huang, S.; Zhang, M. Impact of Green Supply Chain Management on Cost Stickiness of Chinese Fishery Enterprises. *J. Coast. Res.* **2023**, *116*, 403–407. [CrossRef]
14. Squires, D. Productivity Measurement in Common Property Resource Industries: An Application to the Pacific Coast Trawl Fishery. *RAND J. Econ.* **1992**, *23*, 221–236. [CrossRef]
15. Vassdal, T.; Holst, H.M.S. Technical Progress and Regress in Norwegian Salmon Farming: A Malmquist Index Approach. *Mar. Resour. Econ.* **2011**, *26*, 329–341. [CrossRef]
16. García-De-La-Fuente, L.; Fernández-Vázquez, E.; Ramos-Carvajal, M.C. Sample selection bias in fisheries technical efficiency studies using stochastic frontiers; presence and correction for an artisanal fishery in Northwest Spain. *Ocean Coast. Manag.* **2020**, *198*, 105319. [CrossRef]
17. Takyi, R.; Addo, C.; El Mahrad, B.; Adade, R.; ElHadary, M.; Nunoo, F.K.E.; Essandoh, J.; Chuku, E.O.; Iriarte-Ahon, F. Marine fisheries management in the Eastern Central Atlantic Ocean. *Ocean Coast. Manag.* **2023**, *244*, 106784. [CrossRef]
18. Seung, C.K.; Kim, D.-H.; Yi, J.-H. Does Rationalization Improve Economy-Wide Welfare? A General Equilibrium Analysis of a Regional Fishery in a Developed Country. *Environ. Resour. Econ.* **2024**, *87*, 1713–1759. [CrossRef]
19. Chen, X.; Sun, Z.; Di, Q.; Liang, C. Marine fishery carbon emission reduction and changing factors behind marine fishery eco-efficiency growth in China. *Ecol. Inform.* **2024**, *80*, 102478. [CrossRef]
20. Li, L.C.; Jiang, S.; Lin, Y.T. The Impact of the Digital Economy on Sustainable Fisheries: Insights from Green Total Factor Productivity in China's Coastal Regions. *Sustainability* **2025**, *17*, 2673. [CrossRef]
21. Nguyen, T.V.; Hoang, N.K. How economic policies and development impact marine fisheries: Lessons learned from a transitional economy. *Ecol. Econ.* **2024**, *225*, 108314. [CrossRef]
22. Yang, W.; Chen, X.; Liu, Y. Recent developments in building sustainable marine fisheries in China: Reflections on the 2023 Revision of the Marine Environmental Protection Law. *Mar. Policy* **2025**, *171*, 106439. [CrossRef]

23. Shu, T.; Liao, X.; Yang, S.; Yu, T. Towards sustainability: Evaluating energy efficiency with a super-efficiency SBM-DEA model across 168 economies. *Appl. Energy* **2024**, *376 Pt A*, 124254. [CrossRef]

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ISBN 978-3-7258-4680-1