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Research article

Analysis of temporal and spatial dynamics and driving factors in the aquaculture industry of Fuding City, China

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ABSTRACT

Background: The sustainable development of aquaculture is a crucial determinant of food security, the well-being of aquaculture practitioners, and economic growth within coastal regions. Considering the existing gap in research regarding spatial and temporal development of aquaculture, this study investigates the progression of aquaculture practices over time and across various locations in Fuding City, China.

Methods: We retrospectively collected temporal and spatial data on aquaculture, as well as demographic, social, and economic data for Fuding City from 2010 to 2020. By employing 3D kernel density analysis, we illustrated the temporal and spatial changes in aquaculture. Furthermore, we utilized Ordinary Least Squares regression to investigate the driving factors behind the spatial changes in the aquaculture industry.

Results: Over the past decades, we observed that in Fuding City, both the number of fishing rafts and aquaculture households initially decreased and then increased. The spatial distribution of aquaculture experienced a shift from the west (inner bay area) to the east (coastal area). Additionally, the type of fishing rafts also varied by region, with traditional rafts dominating the western inner bay and plastic rafts prevalent in the eastern offshore areas. Analysis of driving factors revealed that at least six factors have a significant positive correlation with the eastward shift of the aquaculture industry's center, including the proportion of migrant population, proportion of aquaculture to total fishery output, average temperature, investment in aquaculture technology, total fish sales, and GDP of Fuding City.

Conclusion: This study examines the spatial and temporal dynamics of aquaculture in Fuding City from 2010 to 2020, proposing an innovative approach to spatial optimization that integrates both horizontal and vertical strategies. These insights aim to guide the development of coastal aquaculture policies and support sustainable regional development, fostering a balanced coexistence between human activities and marine environments.

1. Introduction

The coastal zone constitutes a profoundly interlinked interface encompassing land, ocean, and atmosphere [1]. Within this domain, there is a frequent exchange of matter and energy, with human activities playing a notably active role [2]. Nevertheless, the relentless encroachment of human endeavors upon coastal regions poses considerable challenges to the sustainable socio-economic development

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of these areas. Of particular significance is the impact of aquaculture, a pivotal social and economic pursuit within the coastal zone, on the sustainable trajectory of regional development [3]. The overexploitation of marine fishery resources has led to a decline in the productivity of marine fish stocks. Concurrently, the escalating human demand for fish products has positioned aquaculture as a principal contributor to the global fish supply [4]. However, the expansive growth of aquaculture has precipitated a range of environmental predicaments. Noteworthy examples include the pollution of water bodies through fishery bait and the environmental degradation resulting from the deposition of discarded fishing rafts [5].

China's coastline spans approximately 32,000 km, with the mainland covering 18,400 km from the Yalu River at the China-Korea border to the China-Vietnam border [6]. Aquaculture, a pivotal social and economic activity within China's coastal zone, significantly influences the natural environment of this region. The coastal zone of China stands as a preeminent nexus where population, economy, environment, and resources intersect [7]. However, the relentless progression of urbanization and industrialization has engendered a pronounced decline in the environmental quality of China's coastal zone [8]. Currently, the retention rate of China's natural coastline is below 40 %, with artificial coastline constituting over 60 % [9]. Alterations in the ecological spatial pattern of the coastal zone have precipitated substantial transformations in the spatial distribution of aquaculture [10].

Since the commencement of the 21st century, a substantial body of scholarly research in the domain of marine sustainable development has been devoted to the relationship between local marine environmental knowledge and the spatiotemporal evolution of ocean space [11]. Presently, heightened scholarly attention is directed towards the examination of the impact exerted by fishermen's customs and their associated knowledge systems on local cognitive frameworks and the evolutionary trajectories of regional fisheries [12]. In a study elucidating fish habitat patterns in South America, fishermen in the southeastern region of Puerto Rico demonstrated a discerning correlation of ecological coefficients—such as substrate, salinity, season, and turbidity—with the spatial distribution of

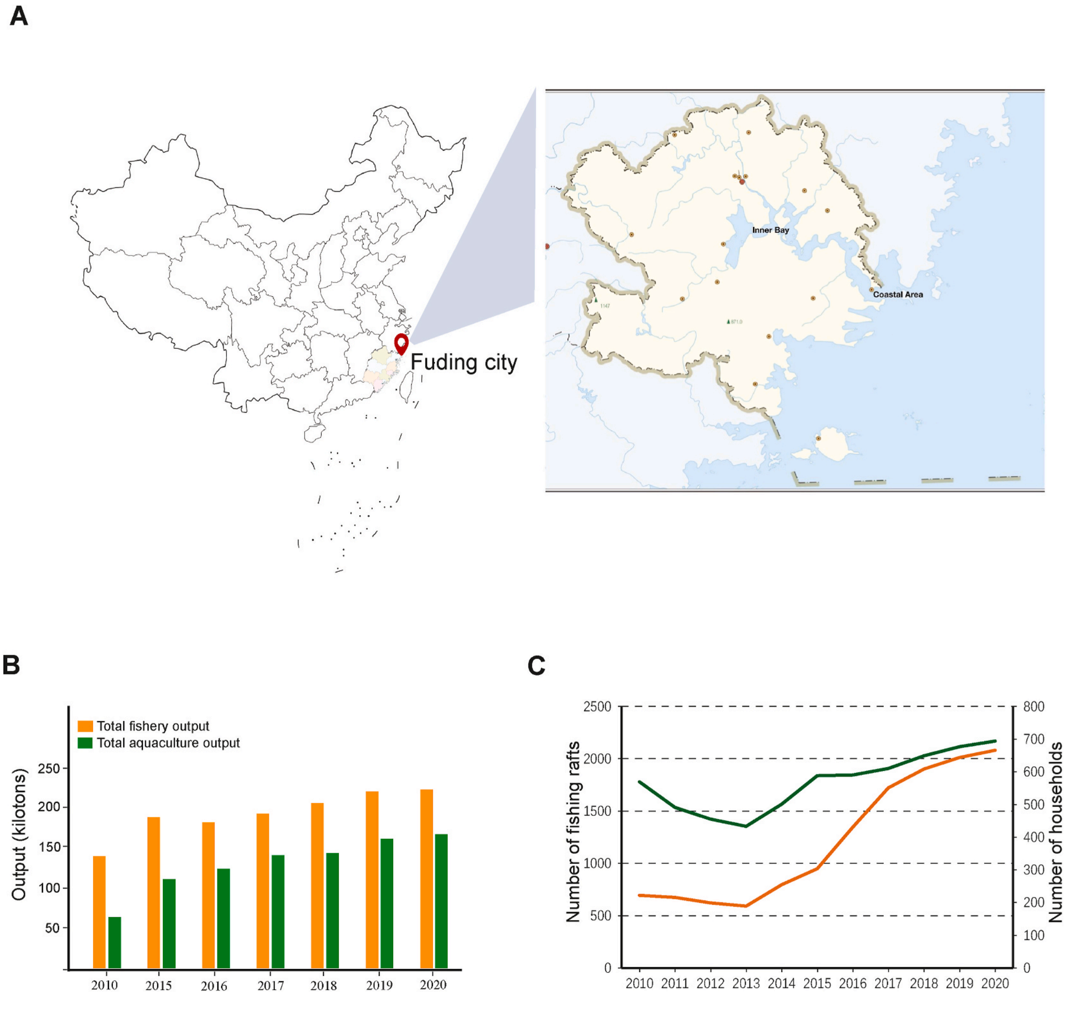

Fig. 1. Overview of the Geographical and Economic Landscape of Fuding City
A, Geographical Overview of Fuding City; B, Changes in the total fishery output and total aquaculture output from 2010 to 2020; According to Fuding Statistical Yearbook, relevant data from 2011 to 2014 has not been collected; C, Changes in the number of fishing rafts (orange line) and aquaculture households (green line) from 2010 to 2020.

aquaculture, strategically addressing concerns about resource replenishment [13].

With the development of technology, some scholars have used advanced techniques to analyze the spatiotemporal evolution of fishery aquaculture. For example, Prasad et al. used sentinel-1 synthetic aperture radar (SAR) data with a spatial resolution of 10 m to analyze the extraction and distribution patterns of pond aquaculture for the entire coastal zone of India [14]. Wang et al. introduced the method of edge overlap degree to further improve the accuracy of interpretation [15]. Kang et al. analyzed marine aquaculture's spatial and temporal distribution information from 2000 to 2018 in Liaoning Province by using remote sensing [16]. Liu et al. examined the spatiotemporal evolution of crab aquaculture in China since the 2000s and evaluated the environmental and economic characteristics along its life-cycle stages [17].

While existing scholarship has extensively explored the sustainable development of aquaculture, there is a dearth of discourse concerning the spatial patterns and evolutionary processes inherent in the development of both the aquaculture environment and industry. There are inadequacies in the exploration of principles governing spatiotemporal evolution and the identification of associated driving factors. Therefore, it is essential to conduct extensive research into the temporal and spatial dynamics of aquaculture and to understand the factors that drive these changes. This study focuses on Fuding City, China, examining the evolution of fishery aquaculture over the past decade through an analysis of its temporal and spatial fluctuations. The findings of this study are expected to provide a theoretical foundation for governmental decision-making concerning the sustainable development of the aquaculture industry.

2. Results

2.1. Economic and aquaculture overview of Fuding City

Fuding (福鼎), officially known as Fuding City, is a county-level city situated in the northeastern region of Fujian Province, China. With a population of approximately 600,850, Fuding serves as a vital coastal city, strategically positioned close to the economic spheres of Zhejiang and Fujian provinces (Fig. 1A). In 2020, Fuding reported a total aquatic product output of 225 Kilotons, marking a 1.20 % increase from the previous year. Of this total, marine products accounted for 216,000 tons (96 %), with freshwater products contributing 9000 tons (4 %). Between 2010 and 2020, the overall fishery output in Fuding escalated from 141 Kilotons to 225 Kilotons, accounting for an increase from 12.41 % to 15.86 % of the city's GDP. Meanwhile, the output of aquaculture production grew from 45 % to nearly 75 % of the total aquatic output (Fig. 1B). This significant growth underscores the vital role of aquaculture in driving the city's economic expansion.

In the study area, aquaculture practices differ significantly between the inner and outer harbors of Fuding City, influenced by variations in environmental conditions. The outer harbor, characterized by its higher wave intensity and salinity levels, predominantly supports corporate aquaculture operations focusing on the cultivation of species such as large yellow croaker (Larimichthys crocea), which thrive in these harsher conditions. These operations employ advanced deep-water large net cage technologies. Conversely, the inner harbor experiences lower wave intensity and reduced salinity, making it suitable for a diverse range of species including bass, spring carp, and red snapper. Aquaculture here combines traditional wooden raft techniques with modern environmentally friendly materials, following an integrated approach involving corporations, bases, and local farmers to ensure high-quality, eco-friendly, and safe aquaculture practices.

From 2010 to 2020, the number of fishing rafts in Fuding City displayed a volatile trend, initially experiencing a decline followed by a subsequent increase (Fig. 1C). The period between 2011 and 2013 witnessed escalated aquaculture density, leading to water pollution and the outbreak of fish white spot disease. In response, a lack of proficiency in disease prevention and treatment prompted the withdrawal of numerous fishermen from the aquaculture industry, thereby resulting in a marked reduction in the number of fishing rafts during this period. Subsequently, the expansion of the global seafood market and the unequivocal delineation of sea area ownership and usage rights by the Chinese government stimulated an influx of laborers into the aquaculture industry. Consequently, post-2013 witnessed a swift ascent in the number of fishing rafts in Fuding City. Similarly, the number of aquaculture households in the Fuding region exhibited a pattern of initial decline succeeded by subsequent augmentation. Notably, in direct comparison, the proliferation rate of aquaculture fishing rafts surpassed that of aquaculture households during this temporal trajectory.

2.2. Spatial evolution analysis of aquaculture

The economic and demographic center of Fuding City has notably migrated eastward, transitioning from the western inland bay to the more expansive outer bay areas. This shift is a direct consequence of ongoing urbanization efforts. Specifically, urbanization has driven the younger and middle-aged workforce to relocate to the Shacheng and Long'an industrial zones in the east. This demographic transition is reflected within the aquaculture sector through the eastward relocation of activities and fishing rafts from the congested inner bay to the coastal regions.

Fuding's terrain is characterized by hilly landscapes to its north and south, with human activity predominantly concentrated along the coastal areas, stretching from the inner bay's west coast to the east coast. From 2010 to 2020, there was a significant transformation in the spatial organization of aquaculture, moving from a dense concentration in the inner bay area to a pronounced focus on the eastern coastal regions (Fig. 2). Initially, in 2010, aquaculture clusters were primarily located in the Bachimen and Zhujiabi sea areas within the inner bay. However, over the decade, in 2020, a strategic realignment saw these activities shift to the Shacheng eastern sea area, resulting in a notable decrease in aquaculture density in the inner bay and an emergence of five principal clusters in the east, indicating a marked evolution in the spatial distribution of aquaculture in response to shifting economic and environmental pressures.

2.3. Analysis of spatial evolution across different types of fishing rafts

Different types of fishing rafts serve varied functions in aquaculture, and over the past decade, changes in the aquaculture industry have been observed through the temporal and spatial distribution shifts of raft types. The evolution of fishing rafts, especially those constructed from wood and plastic, has revealed distinct patterns over time and space. By 2020, plastic fishing rafts were predominantly situated in the offshore areas of Shacheng, Xiaguan, and Yanpu, areas characterized by their harsh wind and wave conditions (Fig. 3A). The need for durable rafts that can withstand events like typhoons has led to a preference for plastic rafts over wooden ones, despite the increased costs. This preference is influenced by economic considerations and the need to meet environmental protection standards, with plastic rafts endorsed by the government becoming the go-to choice for new aquaculture projects.

Conversely, wooden fishing rafts in 2020 were mainly found in the more sheltered inner bays of Bachimen and Zhujiabi, where the environmental conditions are less severe (Fig. 3B). The suitability of wooden rafts in these calmer waters reduces the demand for the more costly plastic alternatives. This pattern of raft distribution showcases a deliberate choice of materials, tailored to the environmental conditions and specific requirements of each location, reflecting strategic adaptations within the aquaculture industry.

2.4. Driving factors of spatiotemporal evolution

To accurately determine the driving factors behind the shift in the aquaculture industry's center of gravity, we analyzed the relationship between up to ten economic and social factors and the shift in the aquaculture industry's focal point using enhanced OLS regression models (Table 1). Six factors—migrant population proportion, proportion of aquaculture to total fishery output, average temperature, investment in aquaculture technology, total fish sales, and Fuding City's GDP—show a significant positive correlation with the eastward shift of the aquaculture industry's center. In contrast, four other factors—sewage treatment rate, number of typhoons, total population, and number of licenses for sea area use—hinder the outward movement of the aquaculture industry.

3. Discussion

The aquaculture mechanism and the resulting social, economic, and cultural externalities are an important part of optimizing aquaculture development in coastal areas in the era of globalization. These factors significantly impact the sustainable development of food security, biodiversity, and livelihoods in coastal areas. However, current research lacks a comprehensive understanding of aquaculture's spatial dynamics, particularly in terms of its evolution over time and space and the underlying driving factors. This study

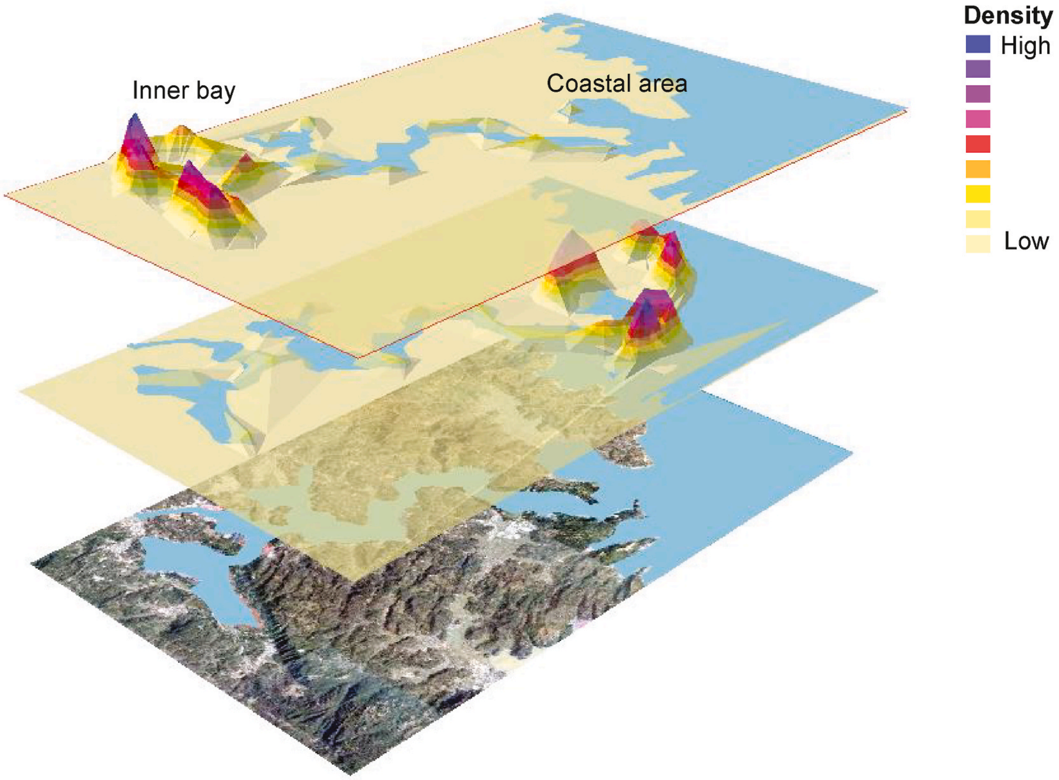

Fig. 2. 3D kernel density spatial analysis for aquaculture.

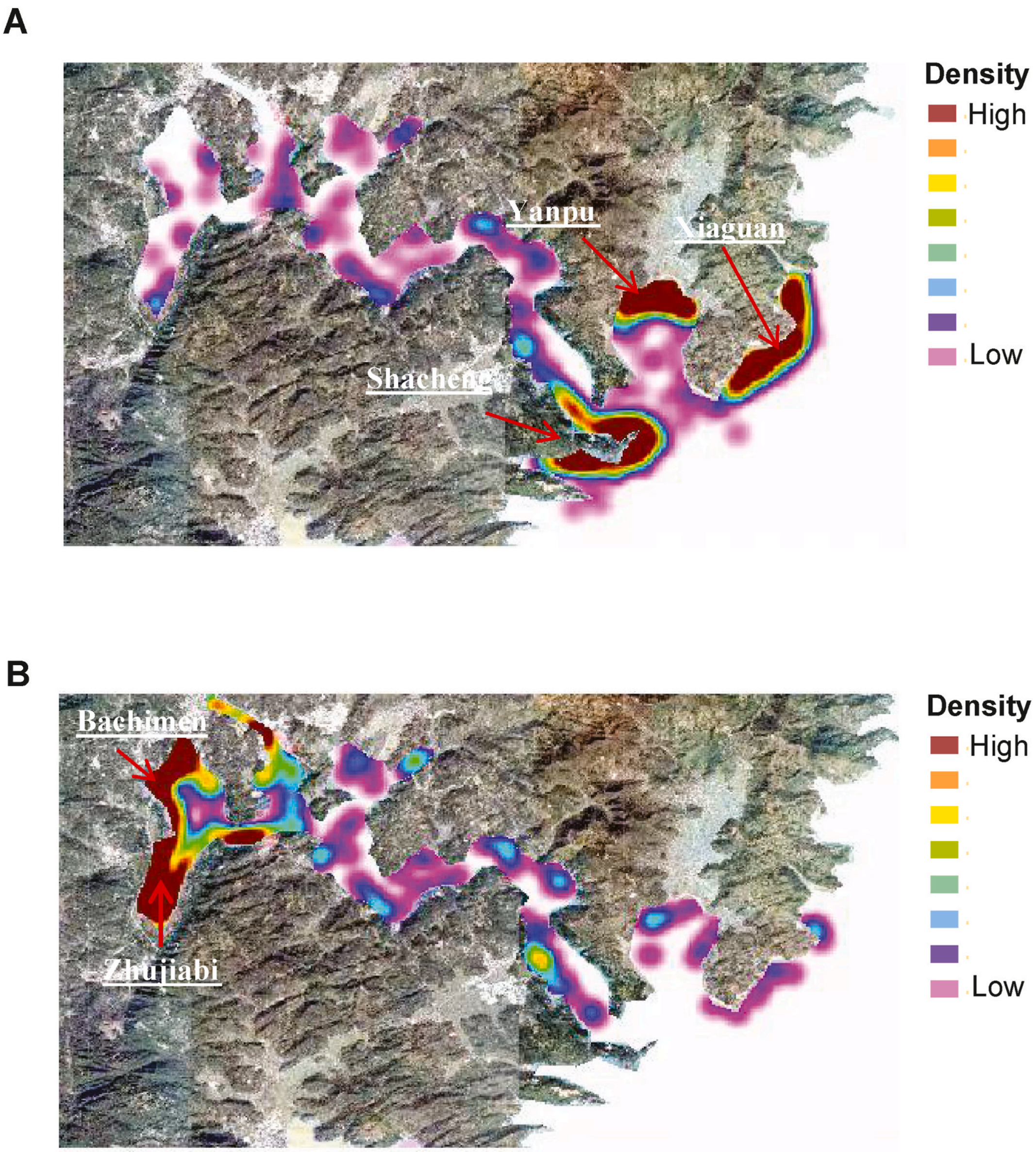

Fig. 3. Spatial density distribution of fishing rafts
A, Spatial density distribution of plastic fishing rafts in 2020; B, Spatial density distribution of wooden fishing rafts in 2020.

focuses on Fuding, a coastal city in China, retrospectively analyzing aquaculture data from 2010 to 2020 along with corresponding economic and social data. Through this analysis, we examine the temporal and spatial evolution patterns and driving factors of aquaculture to propose optimization policies for aquaculture planning, aiming to ensure the industry's positive development trajectory.

During the decade from 2010 to 2020, significant transformations occurred in the aquaculture sector of Fuding City, characterized by a fluctuating trend in the number of fishing rafts, a migration from the inner harbor to the open sea, and a material transition from wooden to plastic in raft construction. These shifts, as elucidated through model analysis, are primarily driven by increasing market demand for seafood, technological advancements, increasing environmental pollution, changes in labor force, greater industrial concentration, and the establishment of clear sea area usage rights.

The escalating demand for seafood has significantly influenced the density and spatial distribution of fishing rafts in the study area, driven by local markets in Fujian, such as Fuzhou and Ningde, as well as larger urban centers including Hangzhou, Wenzhou, Ningbo, and Shanghai. Seafood consumption in China experienced a dramatic increase from 8 kg per person in 2010 to 26 kg by 2020, tripling the demand and consequently elevating seafood prices, thereby enhancing the profitability of aquaculture. Advances in technology and improved aquaculture techniques have significantly increased the industry's resilience to environmental changes, facilitating the

Table 1
Comparative analysis of driving factors using different ordinary least squares (OLS) regression models.

Variable	Model 1: OLS	Model 2: orthogonalized OLS		Model 3: enhanced OLS	
	Unstandardized coefficient	Unstandardized coefficient	Standardized coefficient	Unstandardized coefficient	Standardized coefficient
C					
X_1	8.76034	8.229317*	0.9931688*	8.760514**	6.1979186227952**
X_2	11.01726**	0.4421818**	0.0533654**	11.01746***	3.2497445131716***
X_3	−64.63032	−0.2976767	−0.0359256	−64.62566***	−0.30951099039167***
X_4	638.3237**	0.4960152*	0.0598624*	638.432***	2.4664053963854***
X_5	75.85564	−0.1545481	−0.0186519	75.8553*	0.11919646543147*
X_6	−0.1326197*	−0.1169248 **	−0.0141113**	−0.1326238**	−1.0470158621055**
×7	−0.0027592*	−0.1124978*	−0.013577*	−0.0027592***	−2.7078388620519***
×8	0.0000423*	0.2079969	0.0251024	0.0000423*	4.6098566414079*
×9	−1.449715	0.3161848	0.0381593	−1.449728**	−0.31883388604668**
×10	11.58482*	0.4595563**	0.0554624**	11.58483**	1.036273706707**
Higher order terms					
$X_1 \times X_1$				0.0000034	0.0000132
$X_2 \times X_2$				−0.0000103	−0.00000461
$X_3 \times X_3$				−0.0025232	−0.000000375
$X_4 \times X_4$				−0.1718809	0.0000307
$X_5 \times X_5$				0.0119984	−0.00000658
$X_6 \times X_6$				0.0000000104	0.00000201
Adjusted R-squared	0.6127	0.6574		0.85673	
Rest test *p*-value	0.2149	0.2149		0.8508	
White test *p*-value	0.3971	0.3971		0.3971	
DW test	2.431189	2.431189		2.484473	
F-statistics (Prob.)	99999.0 (<0.001)	99999.0 (<0.001)		99999.0 (<0.001)	

viability of distant, large-scale operations. Originally, fishing rafts in sheltered inner bays were simple in structures, incorporating basic elements like sinkers and floats suited for calmer waters. However, modern designs have evolved to more complex hexahedral shapes that offer enhanced stability and flexibility, utilizing lightweight and durable Polyethylene materials instead of traditional bamboo and wood. These materials and design innovations have enabled the development of fishing rafts further from shore, shifting their spatial distribution from protected inner bays to open coastal areas.

Pollution from high-density farming, industrial activities in harbors, wastewater discharge, plastic waste, and typhoon debris has necessitated a shift in aquaculture practices toward the eastern coast, in search of cleaner and more sustainable environments. The interactive relationship between marine pollution and the evolution of marine spatial patterns remains a critical topic in the sustainable development of the ocean. For instance, studies have examined the ecological resource crisis caused by aquaculture-induced pollution in regions such as Ecuador and Nigeria, focusing on the resulting spatial transformation in aquaculture and the associated human rights implications for local fishermen [18]. Moreover, microplastic pollution significantly impacts the aquaculture industry, as it serves both as a source of plastic entering the marine environment (e.g., through lost fishing gear) and as a potential victim of its consequences [19]. Stephen Kneel et al. explore the awareness, knowledge, attitudes, and behaviors of the Irish fishing community regarding environmental issues such as microplastics, plastic pollution, and recycling. They identified that barriers to recycling used fishing plastics most often stem from a lack of knowledge or the absence of adequate facilities [20]. Additionally, microplastic pollution affects multiple stakeholders in the aquaculture industry, including aquaculture organisms, consumers, and practitioners. For example, the detection of microplastic debris in seafood may prompt consumers to shift toward alternative food sources to avoid such pollutants [21]. Furthermore, scholarly investigations have scrutinized the broad impacts of aquaculture pollution on social public opinion, environmental resilience, and social psychology [22].

Labor redistribution and the influx of migrant populations into Fuding have significantly influenced the spatial organization of aquaculture. Concurrently, the industry's clustering effect in the eastern coastal areas has facilitated the relocation of fishing rafts from the inner bays to the more exposed coastal regions. Additionally, the clarification of sea area usage rights has emerged as a pivotal driver of this migration, highlighting the necessity for robust policy and regulatory frameworks to support sustainable development in the sector. These findings contribute to the ongoing discussion about optimizing aquaculture practices, emphasizing the critical role of environmental, economic, and regulatory considerations in shaping the future of coastal aquaculture in Fuding City.

In essence, the exploration of territoriality in historical and contemporary marine common property and open-access systems, encompassing a wide range of local spatial and fishery governance frameworks, constitutes a longstanding tradition within the scholarly discourse on sustainable development in coastal areas. For instance, Karl C. Norman's research using the Torres Strait as a paradigmatic case study, provides a detailed examination of the practices employed by indigenous fishermen. These practices, developed through interactions with local marine communities, have proven effective not only in preserving the marine ecosystem but also in fostering the development of the Strait community [23]. Further extending the analysis, Jeffrey Wescott explored the effectiveness of the 'Kastom' system in Melanesia, devised by local ethnic groups for the equitable allocation of fishery production spaces [24]. These studies provide an important humanistic insight into the role of sea area use rights in marine spatiotemporal evolution.

This study proposes strategies for optimizing aquaculture space in Fuding City through horizontal expansion and vertical utilization. Horizontally, it emphasizes careful planning of fishing raft arrangements and advancing eco-friendly aquaculture technologies to protect marine ecosystems. Vertically, it addresses the challenge of utilizing deep-sea spaces by recommending strategic species organization and the development of equipment for deep-sea aquaculture.

Policy recommendations highlight the necessity for precise fishing raft site selection, the clarification of sea area usage rights, and the exploration of the sea's vertical dimension. Optimizing site selection entails establishing sustainability objectives, formulating inclusive rules to prevent conflicts, and employing scientific methods for site selection. Clarifying sea area use rights requires enhancing registration and management systems to resolve ownership disputes and align departmental views of these rights, guided by principles of historical respect, sustainable development, social stability, and legal consistency. Furthermore, the study suggests adopting layered sea usage approaches and 3D planning techniques to effectively manage the sea's vertical spaces. Collectively, these strategies and policy recommendations aim to enhance the sustainable development of aquaculture, ensuring environmental compatibility and resource efficiency.

4. Conclusions

This study explores the spatial and temporal dynamics of aquaculture in Fuding City over a decade, suggesting an innovative approach to optimizing aquaculture space through both horizontal and vertical strategies. It offers recommendations for improving fishing raft placement, clarifying marine use rights, and implementing a tiered approach to sea area usage rights. The objective is to guide coastal aquaculture policy and promote sustainable growth, ensuring harmony between aquaculture practices and the marine ecosystem.

5. Materials and methods

5.1. Study area description and data collection

Fuding (福鼎市), is a coastal city located in the northeastern part of Fujian Province, China. Geographically, the city benefits from a diverse landscape that includes both inner and outer harbors. Aquaculture practices differ significantly between the inner and outer harbors due to different environmental conditions. The outer harbor, with its rougher conditions, focuses on cultivating species like the large yellow croaker using advanced technologies. Meanwhile, the inner harbor, which is calmer and less saline, supports a variety of species including bass, spring carp, and red snapper, using traditional and environmentally friendly methods.

This study retrospectively collected spatial, demographic, and economic data related to fishery aquaculture in Fuding City (福鼎市), China, from 2010 to 2020 (Table S1). In this study, "fishery aquaculture" refers specifically to the structured and systematic efforts to cultivate both marine and freshwater species under diverse environmental conditions in Fuding. This term encompasses the differentiation between outer harbor and inner harbor aquaculture practices based on natural conditions such as wave intensity and salinity levels. Outer harbor aquaculture in Fuding is characterized by high salinity and strong wave action, primarily supporting the cultivation of species like the large yellow croaker using advanced technologies such as large, deep-water, anti-wave cages. These conditions result in fish with firmer flesh and superior quality, which commands higher market prices. Conversely, inner harbor aquaculture is influenced by lower salinity due to freshwater dilution and calmer waters, allowing for a diversified range of species such as bass, tilapia, and red snapper. Traditional wooden fish rafts with small cages are typically used in these areas. The study examines how these spatial and temporal variations in aquaculture practices are influenced by both natural factors and human interventions, including environmental regulations and marine ecological restoration efforts. Specifically, the Fuding government has regulated the management of sea area use right and designated distinct zones for marine aquaculture, limited aquaculture, and prohibited aquaculture to balance economic development with environmental sustainability. Spatial data include the location, area, and number of fishing rafts, while demographic and economic data encompass total population, immigrant population, GDP, fish sales, investment in aquaculture technology, proportion of aquaculture to total fishery output, the number of sea area use certificates issued, and the number of typhoons [25]. Spatial vector data for 2017–2020 were obtained through Fuding City's aquaculture grid management system, and data for 2010–2016 were provided by government departments. Population and economic data from 2010 to 2020 were sourced from the Fuding City Statistical Yearbook. To further verify the reliability of the data, field surveys were conducted, including questionnaires to local fishermen about the distribution of fishing rafts over the years, thereby corroborating the accuracy of the publicly available data.

5.2. 3D kernel density analysis

We utilized the 3D kernel density analysis method (ArcGIS v.10.0) to analyze the temporal and spatial evolution of aquaculture in Fuding City from 2010 to 2020. Kernel density estimation (KDE), a method of kernel smoothing used in statistics for estimating probability densities, was applied in our analysis [26]. We utilized ArcScene software to visualize the kernel density in 3D, so as to better explore the laws of space-time changes.

5.3. Geometric center of gravity analysis

The Center of Gravity Model was utilized to calculate the aquaculture density's center of gravity, measured through the 3D kernel density analysis method. The geometric center of gravity method, a standard approach for assessing the spatial distribution of economic and environmental attributes, was employed [27]. This method measures the center of gravity of aquaculture density by calculating the geometric center of the region and using the spatial phenomenon within the sub-region as weight to compute the spatial mean. A significant deviation of the spatial mean from the geometric center indicates an uneven distribution, or "deviation of the center of gravity".

5.4. Driving factors analysis by Ordinary Least Squares regression model

The Ordinary Least Squares (OLS) regression model is a statistical method employed to examine the relationship between one dependent variable and one or more independent variables. It seeks to establish the linear relationship between the dependent variable and independent variables, by minimizing the sum of the squared errors between the actual values and the predicted values. The OLS regression model is defined by the following equation:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_k X_k + \varepsilon$$

In this context, Y represents the dependent variable, which is the longitude of the center of gravity of aquaculture density in this study. A larger value of Y indicates a more easterly location of the center of gravity. The intercept is denoted by β_0, where $\beta_1, \beta_2, \dots, \beta_k$ represent the coefficients of the independent variables $X_1, X_2, \dots, X_k$, respectively. The error term ε, which represents the difference between the predicted and actual values of Y. The OLS regression model estimates the values of the coefficients $\beta_0, \beta_1, \beta_2, \dots, \beta_k$ by minimizing the residual sum of squares (RSS), which is the sum of squared errors. Once these coefficients have been estimated, the model can be used to predict the value of the dependent variable based on the independent variables. In this study, the independent variables include total fish sales (X_1), investment in aquaculture technology (X_2), sewage treatment rate (X_3), migrant population proportion (X_4), proportion of aquaculture to total fishery output (X_5), and the number of licenses of sea area use (X_6). Control variables are total population (X_7), GDP (X_8), number of typhoons (X_9), and average temperature (X_{10}).

The correlation analysis reveals that Y shares a significant linear relationship with all independent variables (X_1-X_{10}), with correlation coefficients above 0.6, suggesting the viability of a regression model for analysis. Particularly, Y shows a high correlation with X_1, X_2, X_4, X_5, X_6, X_7, and X_8, where coefficients exceed 0.9. However, high correlations among certain independent variables, such as between X_1 and X_2, X_1 and X_4, and X_2, and X_4, indicate potential multicollinearity, necessitating further examination (Fig. S1).

The correlation analysis shows variable associations ranging widely, affecting model choice and variable use. To tackle multicollinearity, three models were utilized (Table 1): a standard OLS regression (Model 1), an orthogonalized OLS to lessen collinearity (Model 2), and an enhanced OLS with higher-order terms for non-linear relations (Model 3). Model 1 faced autocorrelation and collinearity issues, affecting coefficient accuracy. Model 2 addressed collinearity, but not autocorrelation. Model 3, however, with significant coefficients ($p < 0.001$) and an R-squared of 0.85673, demonstrated strong predictive ability. The Durbin-Watson test indicated low autocorrelation, and the White and RESET tests suggested minimal concerns with heteroscedasticity and residual normality. Overall, Model 3 proved effective and reliable for prediction, showcasing superior statistical performance.

Data availability statement

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request. Should additional information be required, we encourage interested parties to contact the corresponding author directly.

CRediT authorship contribution statement

Yunhe Zhang: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Ting Yu:** Methodology, Investigation, Data curation. **Niandong Wang:** Methodology, Investigation, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Yunhe zhang reports financial support was provided by Zhejiang Federation of Humanities and Social Sciences. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e33972.

References

[1] A. Bevacqua, D. Yu, Y. Zhang, Coastal vulnerability: evolving concepts in understanding vulnerable people and places, Environ. Sci. Pol. 82 (2018) 19–29.

[2] F. Hamza, Impacts of human activities on diversity of wintering waterbirds: assessment in mediterranean coastal area, Ocean Coast Manag. 198 (2020) 105317.

[3] J.A.P. Agúndez, P. Raux, M.V. Pak, M. Cavallo, L. Lancelot, Top-level institutional policies and their implementation at regional level – a difficult equation. the example of the social acceptability of aquaculture development in Malaga, Spain, Aquaculture Reports 25 (2022) 101227.

[4] L. Recuero Virto, A preliminary assessment of the indicators for Sustainable Development Goal (SDG) 14 "Conserve and sustainably use the oceans, seas and marine resources for sustainable development", Mar. Pol. 98 (2018) 47–57.

[5] B.H. Buck, G. Krause, H. Rosenthal, Extensive open ocean aquaculture development within wind farms in Germany: the prospect of offshore co-management and legal constraints, Ocean Coast Manag. 47 (3) (2004) 95–122.

[6] J.M.Y. Chiu, B.H.K. Po, N. Degger, A. Tse, W. Liu, G. Zheng, D.-M. Zhao, D. Xu, B. Richardson, R.S.S. Wu, Contamination and risk implications of endocrine disrupting chemicals along the coastline of China: A systematic study using mussels and semipermeable membrane devices, Sci. Total Environ. 624 (2018) 1298–1307.

[7] C. Liu, M. Yang, Y. Hou, X. Xue, Ecosystem service multifunctionality assessment and coupling coordination analysis with land use and land cover change in China's coastal zones, Sci. Total Environ. 797 (2021) 149033.

[8] Z. Zheng, Z. Wu, Y. Chen, Z. Yang, F. Marinello, Exploration of eco-environment and urbanization changes in coastal zones: A case study in China over the past 20 years, Ecol. Indicat. 119 (2020) 106847.

[9] N. Xu, P. Gong, Significant coastline changes in China during 1991–2015 tracked by Landsat data, Sci. Bull. 63 (14) (2018) 883–886.

[10] Y. Tang, M. Wang, Q. Liu, Z. Hu, J. Zhang, T. Shi, G. Wu, F. Su, Ecological carrying capacity and sustainability assessment for coastal zones: A novel framework based on spatial scene and three-dimensional ecological footprint model, Ecol. Model. 466 (2022) 109881.

[11] A. Bastari, Y. Mascarell, M. Ortega, M. Coll, Local fishers experience can contribute to a better knowledge of marine resources in the Western Mediterranean Sea, Fish. Res. 248 (2022) 106222.

[12] Q. Hu, T. Zhang, Z. Jiao, Y. Duan, B.J. Dewancker, W. Gao, The impact of fishery industrial transformation on rural revitalization at village level: A case study of a Chinese fishing village, Ocean Coast Manag. 227 (2022) 106277.

[13] C.G. García-Quijano, Fishers' Knowledge of Marine species assemblages: bridging between scientific and local ecological knowledge in southeastern Puerto Rico, Am. Anthropol. 109 (2007) 529–536.

[14] K.A. Prasad, M. Ottinger, C. Wei, P. Leinenkugel, Assessment of coastal aquaculture for India from sentinel-1 SAR time series, Rem. Sens. 11 (2019) 357.

[15] J. Wang, L. Sui, X. Yang, Z. Wang, Y. Liu, J. Kang, C. Lu, F. Yang, B. Liu, Extracting coastal raft aquaculture data from landsat 8 OLI imagery, Sensors 19 (2019) 1221.

[16] J. Kang, L. Sui, X. Yang, Y. Liu, Z. Wang, J. Wang, F. Yang, B. Liu, Y. Ma, Sea surface-visible aquaculture spatial-temporal distribution remote sensing: a case study in liaoning province, China from 2000 to 2018, Sustainability 11 (2019) 7186.

[17] X. Liu, H. Wu, Y. Wang, Y. Liu, H. Zhu, Z. Li, P. Shan, Z. Yuan, Comparative assessment of Chinese mitten crab aquaculture in China: spatiotemporal changes and trade-offs, Environ. Pollut. 337 (2023) 122544.

[18] J. Ferguson, Seeing like an oil company: space, security, and global capital in neoliberal africa, Am. Anthropol. 107 (3) (2010) 377–382.

[19] C.J. Thiele, M.D. Hudson, A.E. Russell, M. Saluveer, G. Sidaoui-Haddad, Microplastics in fish and fishmeal: an emerging environmental challenge? Sci. Rep. 11 (2021) 2045.

[20] K. Stephen, G.S. Caroline, Alec Rolstonb, Suzanne Linnane , Examining awareness, attitudes and behaviours of stakeholders in Irish Fishing towards plastic, Resources, Environment and Sustainability 14 (2023) 1–15.

[21] N. Wootton, M. Nursey-Bray, P. Reis-Santos, B.M. Gillanders, Perceptions of plastic pollution in a prominent fishery: building strategies to inform management, Mar. Pol. 135 (2022) 104846.

[22] S. Jacobs, I. Sioen, S. De Henauw, Y. Rosseel, T. Calis, A. Tediosi, M. Nadal, A. Marques, W. Verbeke, Marine environmental contamination: public awareness, concern and perceived effectiveness in five European countries, Environ. Res. 143 (2015) 4–10.

[23] K.C. Norman. Grasping Adubad: Badulgal management, tenure, knowledge and harvest within the marine environment of the Torres Strait, University of Washington, Washington, 2007.

[24] J. Wescott, The Good Lake, the Possible Sea: Ethics and Environment in Northern Vanuatu, University of California, San Diego, 2012.

[25] You X., Fan M., Fuding Statistical Yearbook 2021, Fuding City Statistics Bureau, Fuding, 2021; You X., Fan M., Fuding Statistical Yearbook 2020, Fuding City Statistics Bureau, Fuding, 2020; You X., Fan M., Fuding Statistical Yearbook 2019, Fuding City Statistics Bureau, Fuding, 2019; You X., Fan M., Fuding Statistical Yearbook 2018, Fuding City Statistics Bureau, Fuding, 2018.

[26] Y. Ji, Y. Li, N. Yao, A. Biswas, X. Chen, L. Li, A. Pulatov, F. Liu, Multivariate global agricultural drought frequency analysis using kernel density estimation, Ecol. Eng. 177 (2022) 106550.

[27] J. Zhao, G. Ji, Y.L. Yue, Spatio-temporal dynamics of urban residential CO2 emissions and their driving forces in China using the integrated two nighttime light datasets, Appl. Energy 235 (2019) 612–624.