



OPEN Multi-objective scenarios analysis for optimizing mariculture spatial allocation: a case study of Lianyungang, China

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Optimizing the spatial allocation of fishery production is crucial for implementing the China's "Blue Granary" strategy and achieving sustainable utilization of fishery resources. An optimization framework was constructed from three objectives dimensions: demand, pattern, and efficiency. Taking the sea area of Lianyungang in Jiangsu Province as a case study, compound annual growth rate models were used to predict the mariculture output in 2030. The spatial pattern was optimized through spatial identification of protected area and fishery resource, environmental suitability assessment, and spatial use compatibility analysis. Subsequently, an adaptation matrix aligning spatial zones and aquaculture mode was established, proposing multi-scenario mariculture spatial layouts. The results were as follows: 1) Based on 2018 and 2022 as reference years, the predicted mariculture outputs for Jiangsu in 2030 are 1.1375 million tonnes and 1.0658 million tonnes, respectively, with the study area contributing 173,200 tonnes and 158,800 tonnes; 2) Spatial analysis identified 891.7 km² of fishery conservation zones and 1,853.8 km² of suitable aquaculture areas within the study region, including 1,205.4 km² suitable for deep-water aquaculture and 648.4 km² for shallow-water aquaculture, of which 188.3 km² are multifunctional three-dimensional spaces; 3) Four scenarios were simulated based on predicted yields and per-unit-area productivity, with spatial layouts optimized using method-specific spatial parameter matching. The spatial ranges for the four aquaculture methods under different scenarios are as follows: deep-water cage culture requires 3,715–4,035 cubic meters of water space, raft culture necessitates 1,755–2,165 hectares of marine area, suspended cage culture occupies 295–725 hectares of operational range, and bottom sowing requires 1,280–1,855 hectares of seabed area. This study presents a methodological framework for mariculture spatial optimization that may contribute to sustainable marine fisheries development.

Keywords Spatial allocation, Mariculture production, Production mode, Spatial matching, Multi-objective

With the continuous advancement of Chinese modernization, the quality of life for the population has significantly improved, accompanied by an optimized dietary structure. As aquatic products serve as a vital source of high-quality animal protein, domestic demand for these products has markedly increased in China¹. The Dietary Guidelines for Chinese Residents (2022) emphasize the nutritional importance of fish and other aquatic foods, recommending an intake of 300–500 g (or two servings) per week, which translates to an annual consumption of approximately 28.8–48 kg per capita². Based on China's fishery development status and referencing dietary transition trends in developed countries, Xin³ projected sustained growth in aquatic product consumption through 2030. Similarly, Yuan⁴ used apparent consumption data to predict that China's demand for aquatic products will continue to rise beyond 2030. However, according to China's National Bureau of Statistics, the per capita consumption of aquatic products in 2022 remained at only 13.9 kg/year—far below the recommended level. This substantial demand, juxtaposed with limited fishery resources, has intensified the supply-demand imbalance, suggesting that the strain on aquatic product availability will persist in the long term.

With the implementation of "Blue Granary" strategy, China has progressively intensified marine fishery resources protection efforts and promoted sustainable, high-quality fishery resources production practices, leading to a significant phase-out of traditional coastal aquaculture and small-scale, high-pollution operations in

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favor of modern approaches like multi-tiered aquaculture and marine ranching. In response to these challenges, scholarly research has coalesced around two critical dimensions of fishery resource management. The first dimension examines fishery species conservation through the lens of holistic ecosystem effects^{5,6}, investigating the adaptive responses of various fishery populations to environmental changes^{7,8}, and assessing the carrying capacity of critical fishery habitats such as spawning grounds, feeding areas, and migratory corridors^{9,10}. Second, as marine ranching and multi-tiered aquaculture emerge as innovative models for marine resource development, growing research has explored how to optimize natural productivity to create spatial configurations that balance ecological protection with intensive resource use^{11,12}.

Optimizing spatial configuration can effectively reconcile conflicts between ecological conservation and resource utilization, as well as among various development activities. Existing research has extensively evaluated the spatial suitability of fisheries based on habitat carrying capacity and the exclusivity of aquaculture activities. However, few studies have systematically examined how spatial arrangements interact with fishery production efficiency and yield requirements, which may constrain the practical implementation of optimization schemes. Building upon established research on land use potential^{13,14} and agricultural productivity enhancement^{15,16}, this study develops an optimization framework for the spatial configuration of fishery resource conservation and utilization. Grounded in an analysis of marine aquatic product demand, the framework is guided by three core principles: safeguarding food security, conserving fishery resources, and promoting sustainable development. The study focuses on optimizing three key dimensions: mariculture production, spatial distribution, and production modes. The aim of the study is to advance the implementation of the “Blue Granary” strategy while ensuring national food security, facilitating territorial spatial optimization and achieving high-quality development in marine fisheries.

Methodology

Overview of the study area

The study area is located in the coastal waters of Lianyungang City, Jiangsu Province, China (119.21–120.42.21.42°E, 34.47–35.16°N), with a total area of 5,574 km². Characterized by significant seawater temperature variations and relatively low salinity levels, this biologically productive area supports diverse commercial fishes, crabs, shrimp, shellfishes and macroalgae, representing one of China’s eight major fishing grounds¹⁷. Designated as a national marine pasture demonstration zone, this region functions as a base for sustainable marine fish production.

Technical approach

This study establishes a multi-scenario spatial optimization framework based on three key objectives: “demand,” “pattern,” and “efficiency.” The demand objective refers to fishery resource requirements, which are estimated through compound growth rate method by integrating data on recent mariculture products, supply-demand relationships, regional characteristics, and policy directives. The pattern objective focuses on the spatial distribution of fishery resources, involving spatial identification of protected area and fishery resource, environmental suitability assessment, and spatial use compatibility analysis to delineate conservation zones, production areas, and multifunctional spatial configurations. The efficiency objective evaluates production capacity across different aquaculture methods, serving as a practical driver for optimal sea space utilization; this is achieved by analyzing historical spatial yield variations to establish optimal pairings between spatial units and aquaculture methods. Building upon these individual system evaluations, the study interlinks all three-dimensional objectives to develop four distinct scenarios for spatial planning of fishery resource conservation and utilization (Fig. 1).

Statistical analysis

Mariculture products demand prediction model

This study analyzes and determines the trends in mariculture yields at both the national level and the Jiangsu regional level from 2014 to 2022, as well as the dynamics of fishery import and export values. The growth rate of aquaculture yields and the projected annual output are calculated by the compound annual growth rate (CAGR) model¹⁸. The formulas are as follows:

$$CAGR = \left(\left(\frac{V_n}{V_o} \right)^{\frac{1}{n}} - 1 \right) \times 100 \pm X \quad (1)$$

where:

- **CAGR** denotes the growth rate (%) of aquaculture yield in the projected year;
- **V_n** represents the output (in 10,000 tonnes) in the final year of the time series;
- **V_o** represents the output (in 10,000 tonnes) in the initial year of the time series;
- **n** denotes the time span (in years);
- **X** signifies the correction factor (%).

$$V_m = V_n \times (1 + CAGR)^{(m-n+1)} \quad (2)$$

where:

- **V_m** denotes the projected aquaculture yield (in 10,000 tonnes) for the target year;
- **CAGR**, **V_n**, and **n** retain the same definitions as in Eq. (1).

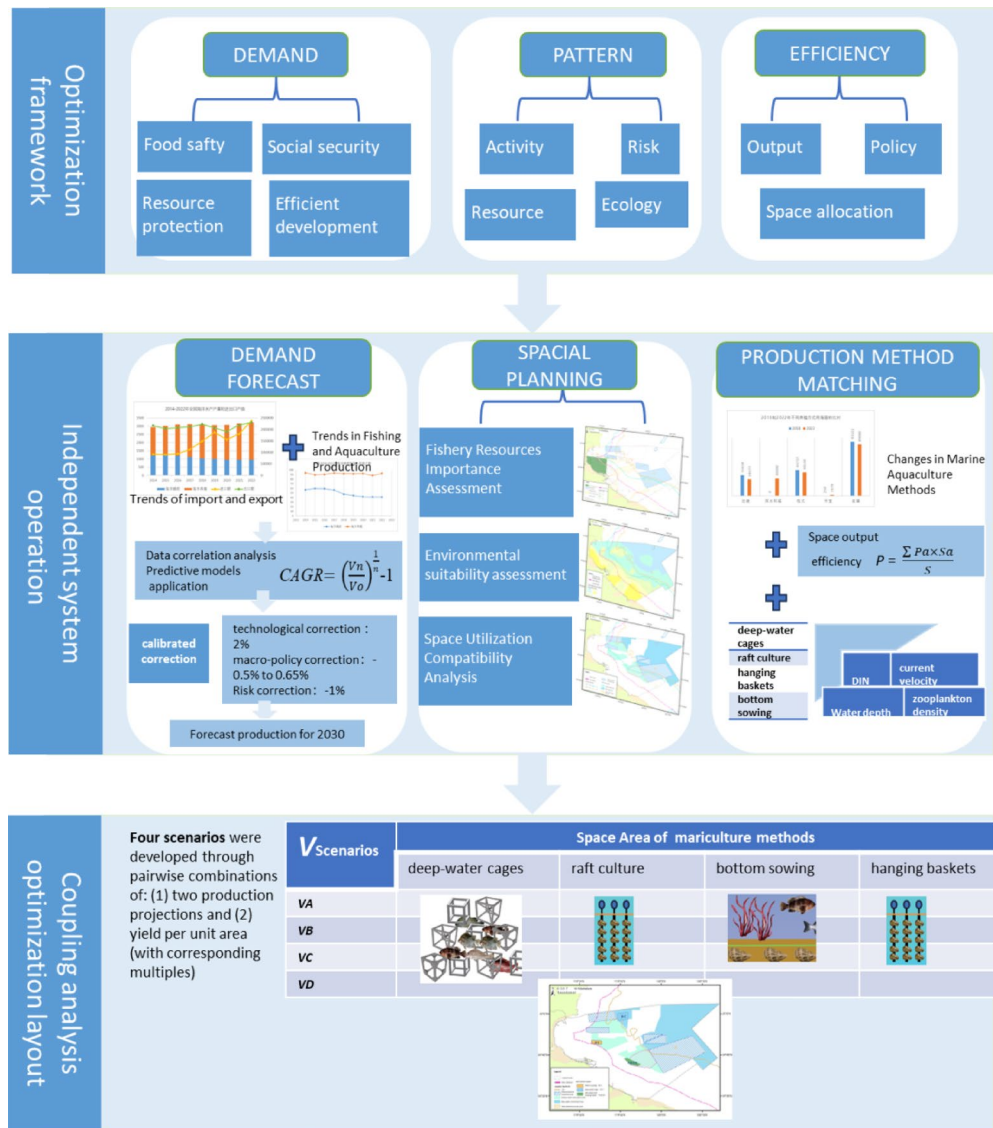


Fig. 1. Technological path for spatial layout of fishery resource protection and utilization (Generated by ArcGIS 10.2, <http://www.esri.com/software/arcgis/arcgis-for-desktop>).

Spatial Production Efficiency

The spatial production efficiency of aquaculture areas, defined as the mariculture yield per unit area, was calculated using the following formula:

$$P = \frac{\sum Pa \times Sa}{S} \tag{3}$$

where:

- **P** represents the mariculture yield per unit area (tonnes/hectare);
- **Pa** denotes the yield per unit area (or volume) for a specific aquaculture method (kilograms/hectare or kilograms/cubic meter);
- **Sa** indicates the area (or volume) for a specific aquaculture method (hectares or cubic meters);
- **S** is the total aquaculture area (hectares).

Spatial parameter matching for different aquaculture methods

The main aquaculture methods in the study area were identified based on the China Fishery Statistical Yearbook. An adaptation matrix between aquaculture methods and spatial parameters was established through literature review^{24–28}(Table 1). Spatial matching was performed in ArcGIS, where the spatial extents for different aquaculture methods were extracted after coordinate transformation.

Mariculture methods	Mariculture products	DIN	current velocity	Water depth	zooplankton density	Yield per unit area
		/mg·L ⁻¹	/cm·s ⁻¹	m	/ind·m ⁻³	
deep-water cages	commercial fish	< 0.5	30–90	> 15	> 10	35/t·m ⁻³
raft culture	macroalgae	0.4–0.6	20–35	10–20	> 5	8.5/t·ha ⁻¹
	shellfish	< 0.5	30–50			
hanging baskets	crabs, shellfish	< 0.5	30–50	10–20	> 5	8.5/t·ha ⁻¹
bottom sowing	sea cucumber	< 0.5	20–35	10–20	> 5	6/t·ha ⁻¹

Table 1. Spatial parameter adaptation matrix and unit yield for different aquaculture methods. Note: The environmental parameter thresholds are primarily derived from existing literature on the ecological suitability of different aquaculture modes (e.g., references^{24–28}, and are also informed by the classification standards for seawater quality outlined in China's Technical Specifications for Marine Environmental Quality Assessment (HJ1300-2023).

Based on predicted production values (V_m) under four scenarios, the optimization of aquaculture spatial allocation was conducted. Linear regression analysis ($R^2=0.95$) was applied to production and area data of different aquaculture methods at both national and regional levels in 2018 and 2022, yielding the production per unit area for each method (Table 1). The objective function for optimizing aquaculture space was formulated as follows:

$$V_m = 35S_{cage} + 8.5S_{raft} + 6S_{sowing} + 8.5S_{basket} \quad (4)$$

where:

- V_m represents predicted aquaculture production (10,000 tonnes).
- S_{cage} , S_{raft} , S_{sowing} , and S_{basket} denote deep-water cage aquaculture volume (m³), raft culture area (ha), bottom sowing aquaculture area (ha), and hanging-basket aquaculture area (ha) respectively.

Spatial analysis

Based on marine spatial elements and fishery resource conditions, this study optimizes the spatial configuration for fishery conservation and utilization in the study area. The optimization methodology comprises three key components^{19–21}: (i) Spatial identification of protected area and Fishery resources (ii) evaluation of environmental suitability, and (iii) analysis of spatial use compatibility.

- **Spatial identification of protected areas and fishery resources** focuses on identifying marine protected areas (MPAs), germplasm reserves, and critical habitats, including spawning grounds, feeding grounds, wintering grounds, and migratory corridors.
- **Environmental suitability evaluation** examines the spatiotemporal distribution of key parameters such as seawater quality (nutrients, dissolved oxygen (DO), and chlorophyll-a), zooplankton biomass, and current velocity, which collectively determine optimal zones for aquaculture (Table 1).

Seawater quality parameters and zooplankton density data were processed using the Inverse Distance Weighting (IDW) interpolation method and projected coordinate transformation in ArcGIS software to generate 0.1° grid data. The indicator grid data classification was conducted according to the following standards: (1) For dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), DO, and chlorophyll-a concentrations, classification followed the Technical Specifications for China's Marine Environmental Quality Assessment (HJ1300-2023) with three grades: Grade 1 (excellent), Grade 2 (moderate), and Grade 3 (poor). (2) Zooplankton density was classified into three suitability levels using the natural breaks method: Grade 1 (abundant), Grade 2 (moderate), and Grade 3 (scarce).

The spatial suitability classification was determined through integrated assessment of these indicators: (1) Type 1 (Highly Suitable): Grids containing no Grade 3 indicators and at least two Grade 1 indicators; (2) Type 2 (Moderately Suitable): Grids containing no Grade 3 indicators and at least one Grade 1 indicator; (3) Type 3 (Marginally Suitable): Grids containing only Grade 2 indicators; (4) Type 4 (Less Suitable): Grids containing only zooplankton density as Grade 3; (5) Type 5 (Unsuitable): Grids containing two or more Grade 3 indicators.

All spatial data layers, including ecological protection zones, germplasm resource conservation areas, critical habitats (spawning/feeding/wintering grounds and migratory corridors), mariculture zones, port channels, and offshore wind farm areas, were integrated in ArcGIS using the China Geodetic Coordinate System 2000 (CGCS2000) as the unified spatial reference.

Spatial use compatibility analysis identifies potential conflicts between fishery production and other human activities^{22,23}. Marine spatial utilization efficiency can be improved through three-dimensional multi-functional zoning strategies (Appendix A).

Data Sources

This study utilized the following datasets: (1) Annual marine fishery statistics data from China Fishery Statistical Yearbooks (2014–2022), including: total and Jiangsu-specific marine product yields; marine capture and aquaculture production (national and Jiangsu provincial levels); national aquatic product import/export

values; aquaculture area statistics by zone and cultivation method (2018 and 2022). (2) Marine environmental monitoring data (2021–2022), including: seawater quality parameters (DIN, DIP, DO, chlorophyll-a) from multi-depth measurements during May, August and October (mean values in mg/L); zooplankton density (ind/m^3) from August surveys; bathymetric data (0.1° grid resolution) obtained from GEBCO (<https://www.gebco.net/>). (3) Marine spatial planning documents: Jiangsu Marine Functional Zoning, Jiangsu Coastal and Marine Spatial Planning, Lianyungang Aquaculture Zone Planning (extracted spatial information on MPAs, germplasm reserves, prohibited aquaculture zones, and shipping routes). (4) Marine usage data: authorized marine aquaculture and offshore wind farm seaward of the 0-meter isobath (including utilization types, spatial extents, and area measurements).

Results

Fishery production forecast

Changes in marine fishery production and mariculture methods

The total national output of marine aquatic products comprises marine capture production, mariculture production, and distant-water capture production. From 2014 to 2022, the total production increased from 31.1017 million tonnes to 34.5953 million tonnes. Notably, marine capture production exhibited a continuous decline, dropping from 12.0018 million tonnes to 9.5085 million tonnes, whereas mariculture production demonstrated steady growth, rising from 17.324 million tonnes to 22.757 million tonnes—a 31.4% increase over the eight-year period. During this period, the total import and export value of national marine aquatic products underwent significant changes. Imports experienced rapid growth, surging from USD 91.85838 billion in 2014 to USD 237.0646 billion in 2022, representing an increase of over 150%. In contrast, export values remained largely stable above USD 200 billion except for a pandemic-induced dip in 2020. The import-to-export ratio exhibited a pronounced upward trend, rising from 0.42 in 2014 to 1.03 in 2022 (Fig. 2).

Over the period from 2014 to 2022, Jiangsu Province exhibited a continuous decline in marine capture production, decreasing from 568,800 tonnes to 412,300 tonnes. Mariculture output peaked at 935,900 tonnes in 2014 but reached its lowest level in 2021 (881,100 tonnes) (Fig. 3). Concurrently, Jiangsu's proportion of national mariculture production steadily decreased from 5.4% to 4.1%. A comparative analysis of Jiangsu's mariculture spatial extent between 2018 and 2022 revealed an overall reduction of 7.7%. Water-surface aquaculture area declined from 48,900 to 47,500 hectares, while sea beach aquaculture decreased from 117,400 to 106,200 hectares. Among the five major mariculture methods, pond aquaculture area experienced the most significant contraction (−20%, from 35,700 to 28,600 hectares), followed by raft aquaculture (−9.4%) and bottom-sowing cultures (−4.7%). In contrast, the area of deep-water cage aquaculture and hanging-basket culture expanded by 3,000 m^3 and 1,400 hectares, respectively (Fig. 4).

Projection analysis of mariculture production in 2030

The years 2014 and 2018 were selected as the initial base years, with 2018 and 2022 as the terminal years. Using Eq. (1) with $X=0$, the calculated average value was 0.16%. When 2014, 2018, and 2021 were designated as the initial base years with 2022 as the terminal year, while holding a single correction variable constant, Eq. (1) yielded the following correction rates: the macro-policy factor (−0.5% to 0.65%), the technological improvement factor (2%) (Appendix B) and the risk factor (−1%). Based on these results, CAGR was calculated as 1.8%. Using 2018 and 2022 as the base years and applying Eq. (2), the projected marine aquaculture output for Jiangsu Province in 2030 was estimated at 1.1375 million tonnes and 1.0658 million tonnes, respectively.

Spatial analysis of fishery resource conservation and utilization in the study area

The study area contains marine protected areas (MPAs), conservation islands, and important fishery resource conservation zones (including spawning grounds and a shrimp germplasm reserve), covering a total area of

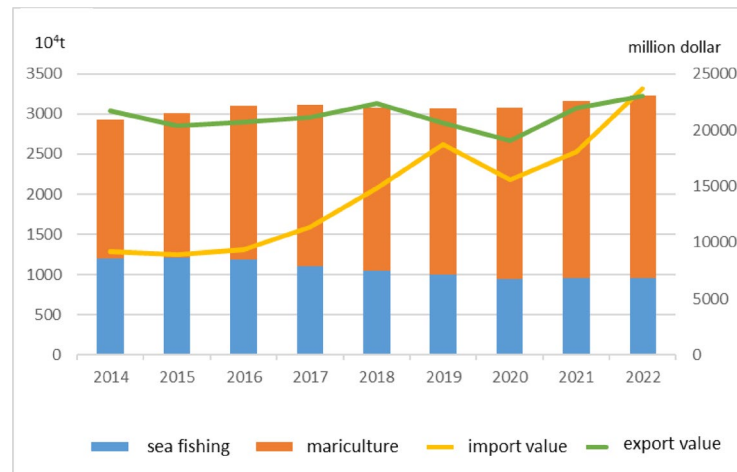


Fig. 2. Marine fisheries production and import-export value in China from 2014 to 2022.

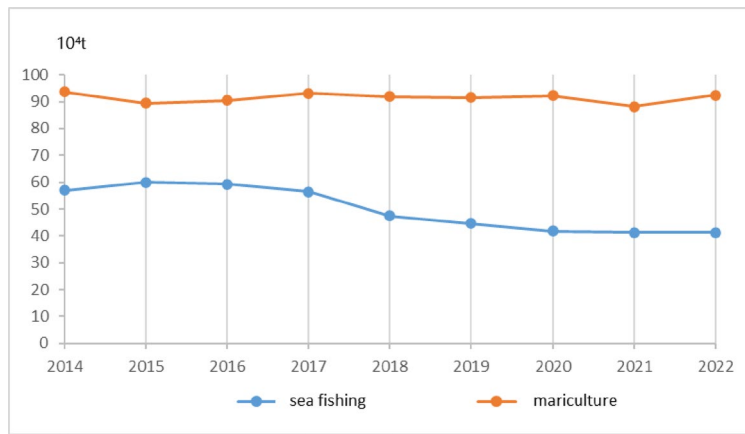


Fig. 3. Marine fishing production and marine aquaculture production in Jiangsu from 2014 to 2022.

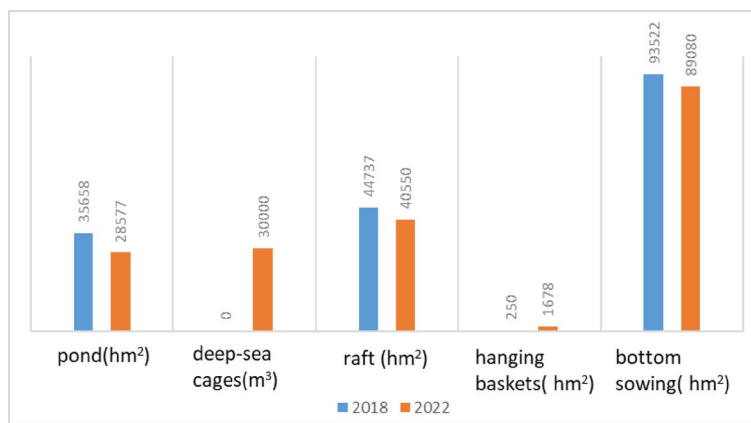


Fig. 4. Changes in aquaculture area for different aquaculture methods in 2018 and 2022.

correction factor	corrected value	impact effects (positive or negative)	impact description
macro- policy	-0.5%~0.65%	positive or negative	negative: Following China's 2018 implementation of ecological protection redlines, coastal wetland conservation policies, and reclamation controls, Jiangsu's mariculture area decreased by 17,600 ha compared to 2014 levels. positive: Deep-sea aquaculture expansion and three-dimensional spatial utilization as key policy-driven, the 3,000 m ³ increase in deep-water cage farming and 1,400 ha expansion of hanging baskets mariculture observed in Jiangsu between 2018 and 2022.
technological improvement	2%	positive	Between 2018 and 2022, the mariculture yield per unit area increased from 4.92 t/ha to 5.6 t/ha, due to technological advancements.
risk	-1%	negative	The 2021 outbreaks of green tide and sea ice events caused measurable reductions in mariculture output.

Table 2. Model correction variables and consideration factors for predicting marine aquaculture production.

1,459 km² (Fig. 5; Appendix C). Mariculture activities in 2022 were predominantly concentrated in nearshore zones (<10 m water depth), exhibiting significant spatial overlap with MPAs. Other marine uses in the area include port construction, maritime transportation, and ocean dumping, covering a total sea area of 420 km² (Fig. 5).

The resulting spatial interpolation maps for all environmental indicators are provided in supplementary material (Appendix C, Figures C3–C7). The environmental suitability assessment indicated DIP concentration ranging from 0.001 to 0.016 mg/L (mean 0.006 mg/L), DIN concentration between 0.01 and 0.58 mg/L (mean 0.28 mg/L), DO concentration of 5.0–8.8.0.8 mg/L (mean 7.2 mg/L), chlorophyll-a concentration of 13.1–19.2 µg/L (mean 14.6 µg/L), and zooplankton density varying from 1 to 84 ind/m³ (mean 9 ind/m³). Through spatial interpolation analysis and hierarchical grid-based evaluation, we extracted grids classified as Grade 1 and 2 to generate a composite layer. Subsequent overlay analysis with offshore distance data identified the marine area beyond 15 km from the coastline as environmentally suitable space (Fig. 6), encompassing a total area of 3,678 km².

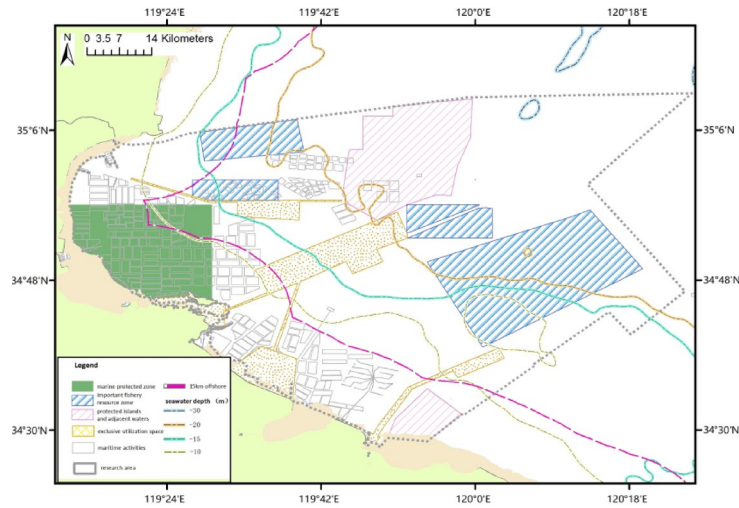


Fig. 5. Distribution of protected areas, fishery habitats and sea use space (Generated by ArcGIS 10.2, <http://www.esri.com/software/arcgis/arcgis-for-desktop>).

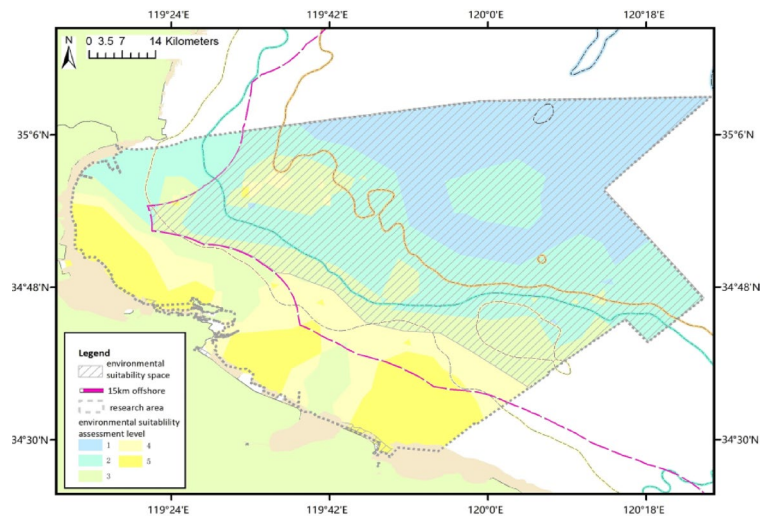


Fig. 6. Spatial distribution of environmental suitability for marine aquaculture (Generated by ArcGIS 10.2, <http://www.esri.com/software/arcgis/arcgis-for-desktop>).

Based on the mariculture suitability assessment (Fig. 6) and spatial conflict analysis^{29–31} (Appendix A), fishery habitats (891.7 km²) were designated as fishery conservation zones. After excluding marine protected areas (MPAs), conservation island zones, and exclusive-use maritime spaces (e.g., shipping lanes), the environmentally suitable zones were stratified by water depth (10 m, 15 m, and 20 m). Following the principle of contiguous spatial allocation, we identified 1,853.8 km² as suitable for mariculture, comprising: (1) 1,205.4 km² for deep-water aquaculture (20–30 m depth), and (2) 648.4 km² for shallow-water aquaculture (10–20 m depth), of which 188.3 km² represents multifunctional three-dimensional space suitable for co-utilization with offshore wind farm development (Fig. 7b).

Comparing the spatial patterns before (Fig. 7a) and after (Fig. 7b) optimization reveals the following changes: (1) all aquaculture activities are relocated outside MPAs and other exclusive zones, thereby eliminating spatial conflicts (Appendix A); (2) deep-water cage culture and hanging-basket shellfish aquaculture are shifted to offshore areas beyond 15 km from the coast—specifically into the deep-water aquaculture zone—where water depth (> 15 m), current velocity (30–50 cm/s), and zooplankton density (> 10 ind/m³) meet the optimal requirements; and (3) raft-based macroalgae cultivation is concentrated in the shallow-water aquaculture zone with suitable DIN concentrations (0.4–0.6 mg/L), while incompatible activities are avoided.

Layout of mariculture spaces in different scenarios

Four distinct scenarios were constructed by pairing two projected mariculture outputs for Jiangsu Province in 2030 (1.1375 and 1.0658 million tonnes) with two alternative yield-per-unit-area estimates derived from: (1) the

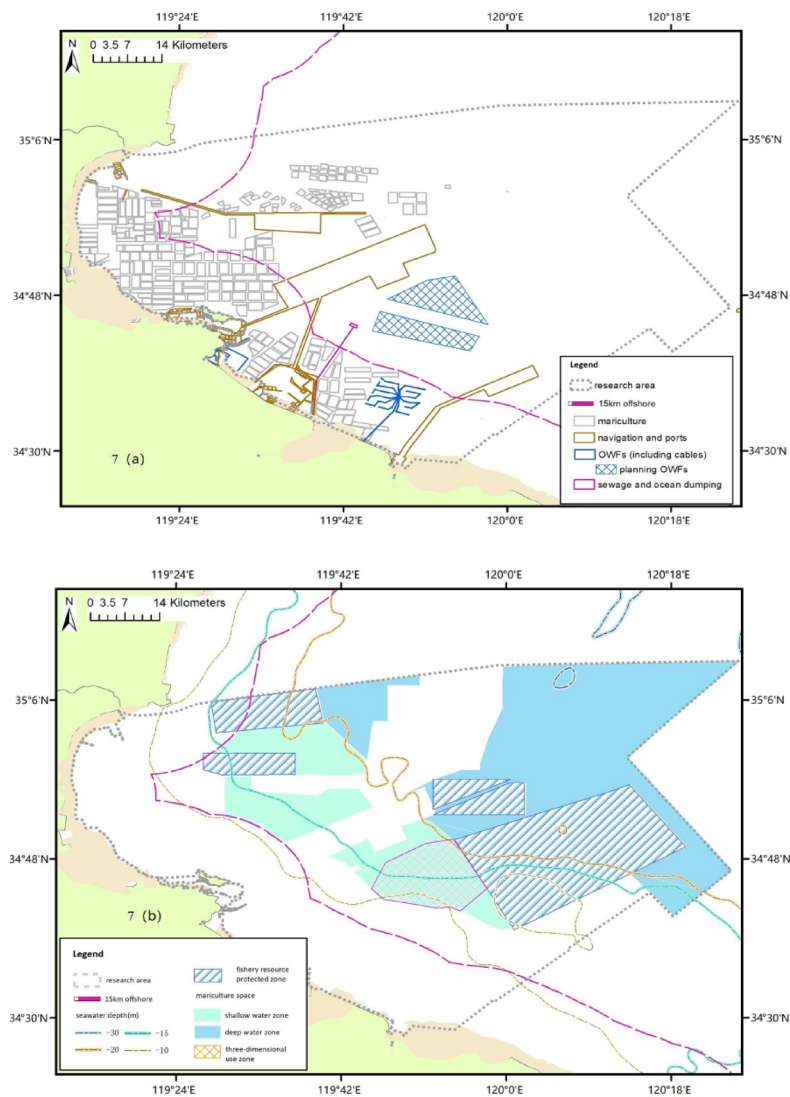


Fig. 7. Comparison of spatial distribution of mariculture before (2022) and after optimization. (a) Current spatial pattern showing overlapping uses and nearshore concentration; (b) Optimized pattern with resolved conflicts and offshore expansion. (Generated by ArcGIS 10.2, <http://www.esri.com/software/arcgis/arcgis-for-desktop>).

Scenarios	Jiangsu’s predicted production /10 ⁴ t	Unit area mariculture production in Jiangsu /t·ha ⁻¹	The study area’s predicted production /10 ⁴ t	Predicted mariculture area /ha
Scenario A	113.75	5.6	17.3179	30924.78
Scenario B	106.58	5.6	15.8839	28364.07
Scenario C	113.75	5.7	17.3154	30377.98
Scenario D	106.58	5.7	15.8816	27862.54

Table 3. Predicted Mariculture Production (in 10000 tonnes) and Aquaculture Space Area (in hectares) in Four Scenarios by 2030.

2022 baseline productivity (5.6 t/ha) and (2) its adjusted value at 1.018 times this baseline. Applying the study area’s proportional coverage (approximately 0.15) of Jiangsu’s offshore waters (seaward of the 0 m isobath), we calculated both the projected mariculture production (excluding pond and industrial systems) and the required spatial footprint for each scenario (Table 3). The results show:

- Scenario A: 173,179 tonnes production requiring 30,924.78 ha.
- Scenario B: 158,839 tonnes production requiring 28,364.07 ha.
- Scenario C: 173,154 tonnes production requiring 30,377.98 ha.

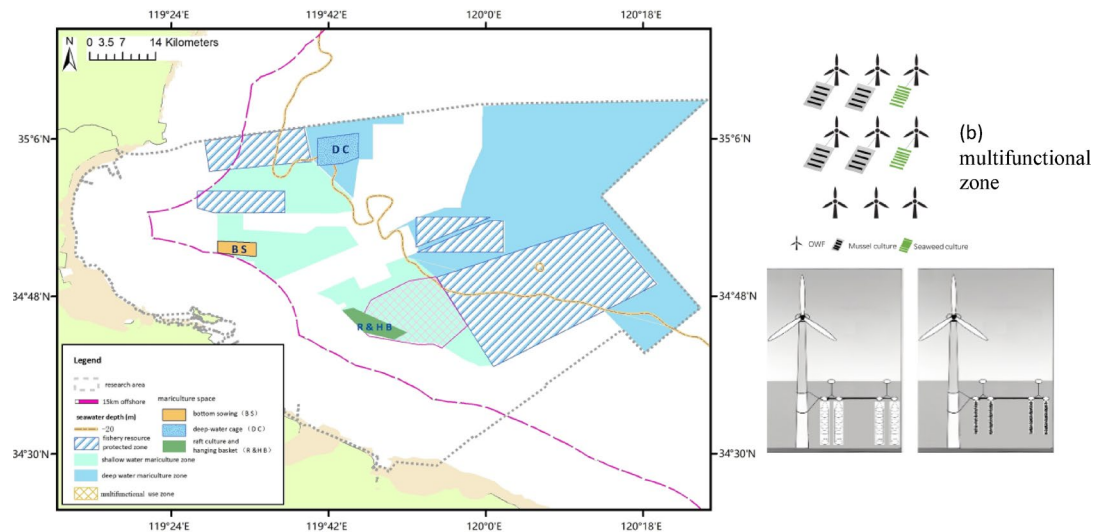


Fig. 8. Distribution prediction of aquaculture areas using different methods, (b) illustrates the spatial configuration of multifunctional three-dimensional marine utilization in the study area. The schematic diagram shows how offshore wind farm infrastructure can be integrated with multi-trophic aquaculture practices within the same spatial footprint. (Generated by ArcGIS 10.2, <http://www.esri.com/software/arcgis/arcgis-for-desktop>).

- Scenario D: 158,816 tonnes production requiring 27,862.54 ha.

The spatial requirements for different aquaculture methods across four scenarios were calculated by applying matched spatial parameters (Table 1) and the production Formula (4), resulting in optimized mariculture spatial configurations (Fig. 8). Deep-water cage culture was exclusively allocated to northern deep-water zones (22–25 m depth) characterized by DIN concentrations of 0.1–0.2 mg/L, zooplankton density of 14.5 ind/m³, and maximum current velocity of 87 cm/s, with required culture volumes of 4,035 m³ (Scenarios A/C), 3,715 m³ (Scenario B), and 3,725 m³ (Scenario D). Raft culture occupied southern shallow-water areas (10 m depth) with 0.2 mg/L DIN, 14.8 ind/m³ zooplankton density, and 45 cm/s currents velocities, where low nutrient conditions favored shellfish production over macroalgae, resulting in combined raft/hanging basket culture areas of 2,165 ha (including 295 ha hanging baskets), 1,765 ha (320 ha), 1,955 ha (725 ha), and 1,755 ha (690 ha) for Scenarios A–D respectively. Bottom-sowing culture was situated in western zones (12 m depth) with conditions similar to raft areas, requiring 1,855 ha, 1,845 ha, 1,520 ha, and 1,280 ha across the four scenarios.

Discussion

Drivers of mariculture demand and production volatility

Recent studies have extensively investigated aquatic product supply and demand from perspectives of seafood consumption behavior^{32–34}, supply-demand relationships^{35–37}, and influencing factors^{38,39}. Analytical findings indicate a growing global demand for marine aquatic products. An examination of China's import and export trends reveals that the import value of marine aquatic products has consistently increased since 2014, reaching parity with export value by 2022. Over this eight-year period, the import growth rate exceeded 150%. If this 2014–2022 trend persists, China's imports of marine aquatic products are projected to far surpass exports by 2030, reflecting a substantial increase in domestic demand.

In contrast to this robust demand growth, regression analysis reveals fluctuating mariculture production in Jiangsu Province ($R^2 < 0.8$), with notable declines observed in 2015 and 2021. These fluctuations likely result from multiple interacting factors: (1) methodological shifts in production practices, (2) spatial reallocation of aquaculture operations, and (3) policy-driven reductions in coastal reclamation. The production declines in 2015 and 2021 coincide temporally with two events: regulatory restrictions on nearshore aquaculture expansion and extreme environmental conditions (e.g., green tides in 2021). This juxtaposition of rising demand and volatile supply highlights the need for strategic planning to reconcile production stability with conservation imperatives.

Methodological rationale for the CAGR

Given the observed volatility in production data and the well-established long-term demand trends, selecting an appropriate forecasting model becomes critical. The existence of a robust long-term increasing trend in global and domestic aquatic product demand is well established in the literature. For instance, the Food and Agriculture Organization (FAO) projects a global annual growth rate of 1.0–2.9% in fish consumption over the next three decades, and Chinese scholars^{3,4} have consistently predicted rising demand for aquatic products through 2030 and beyond. These external projections provide a strong theoretical basis for assuming a sustained upward trajectory in mariculture output.

Such interannual volatility, if modeled directly with time series or regression techniques, could lead to overfitting of short-term shocks and produce unstable or misleading projections, especially when the underlying long-term trend is masked by episodic disturbances. Mariculture yield is inherently an economic variable, and the compound annual growth rate (CAGR) model is widely applied in economic forecasting (e.g., GDP growth, market size) due to its simplicity, interpretability, and capacity to incorporate expert-informed adjustments.

Given the overall long-term growth trend of mariculture and differentiation of independent years, we selected the CAGR model due to its ability to capture inherent growth patterns through geometric progression rather than arithmetic averaging^{40,41}. In this study, this approach provides three key advantages: (1) it accounts for compounding effects, yielding greater accuracy in multi-period analyses; (2) it generates a smoothed annualized growth rate that eliminates short-term fluctuations while preserving long-term trends; and (3) it maintains dependence on initial and terminal values while allowing flexible adjustment of correction variables to accommodate forecast period variations, thereby enhancing both model adaptability and operational feasibility.

Correction factors influencing production projections

In the CAGR model, factors influencing mariculture yield were identified as correction factors, with adjustment values constrained within $\pm 5\%$. Three categories of correction factors were quantified based on empirical data and back-testing.

The technological correction factor demonstrated a positive impact on production output. Notably, between 2018 and 2022, despite a reduction in mariculture spatial extent, the yield per unit area increased from 4.92 t/ha to 5.6 t/ha. This trend suggests that technological advancements will continue to drive industry upgrading and yield enhancement over the long term⁴². To quantify this effect, through comprehensive analysis, the technological variable was determined to have a correction rate of 2%. The 2% technological correction factor represents a regionally calibrated estimate that integrates the universal influence of technological progress with localized constraints of production scale and structural characteristics (Appendix B).

The impact of macro-policy factors on mariculture production demonstrates dual-directional effects, manifesting both positive and negative influences. The primary negative impact has been the substantial reduction in available aquaculture space. Jiangsu's coastal waters, characterized by shallow depths and extensive tidal flats, have historically relied on pond aquaculture and raft-culture methods, leading to accumulated conflicts between ecological conservation and resource utilization. Following China's 2018 implementation of ecological protection redlines, coastal wetland conservation policies, and reclamation controls⁴³, Jiangsu's mariculture area decreased by 17,600 hectares compared to 2014 levels. Conversely, macro-policies have also generated positive production incentives. The China's "Marine Power" and "Blue Granary" strategies have actively promoted deep-sea aquaculture expansion and three-dimensional spatial utilization as key drivers for quality development in mariculture^{44,45}. This policy-driven transformation is evidenced by the 3,000 m³ increase in deep-water cage farming and 1,400 ha expansion of hanging baskets mariculture observed in Jiangsu between 2018 and 2022. Through model back-testing across two policy phases (2014–2018 and 2018–2022) with policy variables as the sole adjustment factor, we quantified the net policy effect as demonstrating a correction rate range of -0.5% to 0.65% .

The risk factor represents another critical correction variable, with environmental hazards such as extreme heat, storm surges, and green tides consistently demonstrating negative impacts on mariculture productivity^{46,47}. As documented in the Jiangsu Marine Disaster Bulletin (2019–2022), the study area experienced frequent occurrences of severe gales, giant waves, extreme weather events, and ecological disasters. Particularly notable were the 2021 outbreaks of green tides and sea ice events, which caused measurable reductions in mariculture output. Through model back-testing focused on the 2021–2022 period with risk variables as the sole adjustment factor, our analysis quantified the risk correction rate at -1% . This value reflects the significant but temporally concentrated nature of environmental risks in the Jiangsu region, where episodic extreme events rather than chronic stressors dominate production volatility.

To assess the robustness of the CAGR-based projections incorporating these correction factors, we conducted a back-testing exercise using independent production data from Jiangsu Province for selected years (2015, 2017, and 2022). The predicted value deviated from the actual value by approximately -2.4% to 7% , indicating reasonable model performance. The correction factors within $\pm 1\%$ leads to a $\pm 3.5\%$ change in projections. Future applications should consider scenario-based uncertainty analysis to improve decision-making under variability.

Spatial optimization implications and study limitations

Beyond production forecasting, the spatial dimension of mariculture expansion warrants careful consideration. Analysis of current marine spatial patterns in China reveals significant concentration of human activities in nearshore waters, with mariculture accounting for approximately 75% of coastal zone utilization in many regions⁴⁸. Marine fishery development is predominantly concentrated within the 10 m isobath, while the spatial utilization rate for aquaculture between the 20 m and 30 m isobaths remains below 10%⁴⁹. Our study area reflects this broader trend, where nearshore waters are heavily occupied by traditional pond aquaculture, raft culture, and other human activities, leaving deeper offshore areas relatively underutilized.

Building on this context, our study explores the potential of a 15-km offshore boundary as a spatially explicit planning parameter for aquaculture expansion. This boundary was determined by synthesizing multiple factors specific to the Lianyungang sea area, including water depth gradients, dissolved inorganic nitrogen (DIN) distribution, and the spatial requirements of traditional aquaculture species and methods. For instance, beyond 15 km from shore, DIN concentrations drop below the optimal range for macroalgae cultivation ($0.4\text{--}0.6\text{ mg/L}$), making raft-based algae farming unsuitable in these waters. Thus, the 15-km boundary serves as a region-specific spatial parameter tailored to local environmental and operational contexts, rather than a

universally applicable standard. This approach aligns with broader discussions about balancing marine food production with environmental sustainability^{45,50}. Comparisons with other sea areas (e.g., the North Sea, Yellow Sea, and offshore Fujian) suggest that the optimal offshore distance for aquaculture expansion varies considerably depending on local environmental gradients, existing use patterns, and regulatory frameworks—underscoring the necessity of region-specific assessments when applying spatial planning tools. The framework intentionally prioritizes offshore systems over traditional pond mariculture, reflecting emerging policy trends aimed at gradually reducing coastal aquaculture footprints. However, the actual implementation timeline for such transitions remains uncertain and would require further policy development, stakeholder engagement, and site-specific feasibility assessments.

The spatial distribution of mariculture activities is fundamentally constrained by environmental conditions. In this study, we classified spatial parameters into two categories: generic and specific factors. The generic parameters, including chlorophyll-a concentration and DO, exhibited relatively stable spatial distributions across the study area, maintaining consistent suitability thresholds for all four aquaculture modes. Specifically, the optimal ranges were determined as 10–30 µg/L for chlorophyll-a and >3.5 mg/L for DO^{51–53}. In contrast, specific parameters demonstrated distinct spatial heterogeneity that critically influenced aquaculture suitability. Water depth and current velocity emerged as crucial determinants for deep-sea cage culture, where enhanced flow promotes nutrient cycling and primary productivity, thereby increasing zooplankton density—a vital food source for farmed fish⁵⁴. Similarly, DIN concentration proved essential for raft culture, with algal growth showing positive correlation within optimal thresholds⁵⁵. DIN concentration in the study area showed a significant decreasing trend from nearshore to offshore, with concentrations at locations beyond 15 km from shore (0.2 mg/L) falling below the suitable range for algal cultivation (0.4–0.6 mg/L), precluding raft-based algae farming in these waters. Furthermore, bathymetric features were incorporated into our mariculture spatial planning. The strategic placement of deep-sea cages in northern areas adjacent to islands leverages topographic upwelling effects. The interaction between water masses and reef formations promotes vertical transport of nutrient-rich, cooler deep waters to mid-upper layers, creating favorable conditions for fish aggregation and growth⁵⁶.

This study proposes a methodological framework for marine fisheries planning and spatial optimization, with several limitations to consider: (1) The CAGR model was selected based on observed historical growth trends projected to 2030, but does not incorporate potential disruptions from extreme events (e.g., disease outbreaks, geopolitical conflicts, or other unforeseen circumstances); (2) The analysis assumes consistent production methods and equivalent per-unit-area yields between the study area and Jiangsu Province—while this standardization may be reasonable within Jiangsu's context, applications to other regions would require adjustment to local productivity patterns and operational characteristics; (3) Scenario outputs represent theoretical optima requiring practical adaptation during implementation; and (4) While providing spatial allocation solutions, the proposed offshore mariculture layouts may require additional economic feasibility assessments regarding implementation costs, operational expenses, and investment returns before practical application.

Conclusion

i) Based on the CAGR model with 2018 and 2022 as baseline years, we project Jiangsu Province's total mariculture output to reach 1.1375 million tonnes and 1.0658 million tonnes respectively by 2030. Correspondingly, the study area is estimated to contribute approximately 173,200 tonnes (2018 baseline) and 158,800 tonnes (2022 baseline). The predictive model incorporates correction factors for macroeconomic policies, technological advancements, and natural disasters. By analyzing historical production trends in the study area, the direction and magnitude of each correction factor were determined, with adjustment rates constrained to ±5% to ensure robustness.

ii) The spatial optimization of the study area, assessed through identification of conservation spaces, environmental suitability and functional compatibility, identifies distinct marine fishery resources zones comprising fishery conservation spaces (891.7 km²) that incorporate vital spawning grounds and *Penaeus* germplasm reserves, alongside strategically allocated mariculture areas including deep-water aquaculture zones (>20 m depth; 1,205.4 km²) and shallow-water aquaculture zones (10–20 m depth; 648.4 km²), all deliberately situated beyond 15 km offshore to effectively alleviate ecological pressures and minimize interference from human activities, thereby establishing an integrated spatial framework that harmonizes fishery production with marine ecosystem conservation.

iii) Four scenarios were developed through pairwise combinations of: (1) two production projections and (2) yield per unit area (with corresponding multiples). An optimal matching matrix was developed to correlate aquaculture methods with spatial parameters including nutrient concentrations, current velocity, water depth, and zooplankton density. Targeting optimal production output, we matched these spatial parameters to refine the spatial distribution of four primary aquaculture methods (deep-water cages, raft culture, bottom sowing, and hanging baskets) across all scenarios. The spatial allocation analysis for the four scenarios (A–D) yielded the following results: For deep-water cage culture, the volumes were 4,035 m³ (Scenario A), 3,715 m³ (Scenario B), 4,035 m³ (Scenario C), and 3,725 m³ (Scenario D). The combined raft and hanging basket culture areas measured 2,165 ha (Scenario A, including 295 ha hanging baskets), 1,765 ha (Scenario B, 320 ha hanging baskets), 1,955 ha (Scenario C, 725 ha hanging baskets), and 1,755 ha (Scenario D, 690 ha hanging baskets). Bottom-sowing culture areas were 1,855 ha (Scenario A), 1,845 ha (Scenario B), 1,520 ha (Scenario C), and 1,280 ha (Scenario D).

Data availability

The authors declare that the data supporting the findings of this study are available within the paper. Should any raw data files be needed in another format they are available from the corresponding author upon reasonable request.

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Author contributions

Qiulu Wang wrote the main text of the manuscript, performed the data analysis and summaries, and drew all the figures. Changjuan Li and Yaning Li collected relevant information and helped to organize the structure of the paper. All authors have read and agreed to the manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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