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Quantitative Forecasting and Development Pathways of the Linkages between the Shellfish Industry and Fishermen's Income in Liaoning Province: An Empirical Analysis Based on the GM(1,1) Model

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Abstract: This study takes Liaoning Province, a core fishery region in Northeast China, as a case study to quantify the contribution and long-term impact mechanisms of the shellfish aquaculture industry on regional fishermen's household business income. Addressing the typical characteristics of limited data samples and incomplete system information, the research employs the GM(1,1) prediction model from grey system theory to independently model and forecast shellfish production and fishermen's household business income for the period 2010-2033. The empirical results indicate: using the original, non-translated data, the Liaoning shellfish production prediction model passed the ratio test, with a development coefficient (a) of -0.01885, forecasting a sustained and steady expansion of the industry scale, with production projected to reach approximately 3.19 million tons by 2033. The fishermen's household business income series, due to initial high volatility, required the application of a translation constant C=265,410 to establish a viable GM(1,1) model, which yielded a development coefficient (a) of -0.02986, also predicting a long-term growth trend for income. Model accuracy evaluation showed that the shellfish production forecast had a mean relative error of 4.839%, a posterior variance ratio C of 0.502, and a small error probability P of 0.786, achieving an accuracy grade between "qualified" and "good". Although the income prediction model had a higher mean relative error (20.125%), its posterior variance ratio C was 0.272, and the small error probability P was 1, indicating a robust trend in the forecasted sequence. Integrating a literature review on Liaoning's fishery industrial structure—where the primary sector dominates but the secondary and tertiary sectors' shares are gradually increasing—and fishermen's income composition—where household business income is the core pillar—this study further elucidates the transmission mechanisms through which the shellfish industry influences fishermen's income via multiple pathways, including direct sales, value-added processing, and linkages with recreational fisheries. Finally, based on the forecast results and the current industrial landscape, the study proposes countermeasures and suggestions, such as promoting intensive and ecological shellfish aquaculture, deepening aquatic product processing, fostering industrial integration, and strengthening scientific, technological, and policy support. These recommendations aim to provide a theoretical basis and decision-making reference for the sustainable and inclusive development of the marine fishery economy in Liaoning Province and similar regions in China.

Keywords: Shellfish industry; Fishermen's income; Grey prediction; GM(1,1) model; Liaoning Province; Fishery economy; Industrial structure

1. Introduction

Marine fisheries constitute a critical global source of food supply and a driver of economic growth, holding particular strategic importance for nations with extensive coastlines.[1] As the world’s largest producer and consumer of aquatic products, China relies on the healthy and stable development of its marine fisheries to safeguard the livelihoods of millions of fishermen, sustain the prosperity of coastal regions, and ensure national food security. [2]Liaoning Province—the only jurisdiction in Northeast China with both terrestrial and marine geography—borders the Yellow Sea and Bohai Sea, boasting a mainland coastline of 2,178 km and abundant resources in mudflats, harbors, and shallow seas. [3]These natural endowments provide a solid foundation for the growth of marine fisheries, especially mariculture. Within Liaoning’s diversified fishery sector, shellfish aquaculture (mainly scallops, clams, and oysters) has become a pillar industry due to its broad adaptability, mature cultivation techniques, and stable market demand, exerting substantial influence on the regional fishery economy through both output and value. [4]Fishermen’s income remains a central issue in fishery economics, directly related to social stability in fishing communities and the sustainable development of fisheries. Rising income not only reflects fishermen’s share in industrial growth but also motivates the adoption of sustainable practices and resilience to resource and environmental challenges. However, fishermen’s income is shaped by a complex interplay of factors—resource endowment, market prices, policy interventions, climate conditions, and industrial structure—making it a typical “grey system with poor information,” where known and unknown elements coexist and precise mathematical modeling is difficult. [5]Medium- to long-term trend analysis is particularly challenging due to limited time-series data and nonlinear interactions among fluctuating variables. Thus, scientifically forecasting the future output of Liaoning’s shellfish industry and quantitatively evaluating its potential impact on fishermen’s income is essential for forward-looking policy-making, optimized resource allocation, and sustained income growth.[6] Grey system theory, pioneered by Chinese scholar Professor Deng Julong, offers tools for modeling, forecasting, and decision-making under incomplete information. The GM(1,1) model, in particular, has been widely applied in agricultural and economic forecasting due to its minimal data requirements, computational simplicity, and effectiveness in capturing short-term and trending behaviors. This study integrates grey system theory with industrial economic analysis to develop a comprehensive assessment framework for Liaoning’s shellfish industry and fishermen’s income. The research objectives are fourfold: (1) to construct GM(1,1) models for shellfish production and fishermen’s household business income using 2010–2023 data, validating them through ratio, residual, and posterior variance tests; (2) to forecast both variables for 2024–2033 and elucidate long-term trends; (3) to combine structural analysis of Liaoning’s fishery industry (where the primary sector dominates but secondary and tertiary sectors are rising, reflecting a “left-rotation” optimization trend) with patterns of fishermen’s income composition (household business income being the dominant component) in order to unravel the mechanisms and pathways through which shellfish aquaculture affects income; and (4) to propose policy recommendations for enhancing the quality and income-boosting effects of Liaoning’s shellfish industry. This study represents the first systematic application of the GM(1,1) model to coordinated forecasting of shellfish output and fishermen’s income in Liaoning. Methodologically, it demonstrates effective handling of a poor-information system; analytically, it links micro-level forecasts with macro-level industrial evolution, offering integrated insights. [7]The findings are intended to provide quantitative support for fishery management planning in Liaoning and to serve as a methodological reference for similar studies in other coastal regions.[8]

2. Research Background

2.1 Income Structure of Chinese Fishermen and Its Influencing Factors

The issue of fishermen's income has long been a focus for scholars both domestically and internationally.[9]

According to the classification in the China Fishery Statistical Yearbook, the total income of Chinese fishermen's households primarily derives from several components: household business income, wage income, property income, and transfer income (including production subsidies).[10] Extensive research indicates that household business income holds an overwhelmingly dominant position in fishermen's total income, with its share consistently remaining at a high level close to 90%. This signifies that the operational returns from fishery production activities (including capture and aquaculture) conducted at the household level are the primary determinant of fishermen's income levels.[11] A grey relational analysis of national data from 2008 to 2013 found that, whether measured from the perspective of change rate differences or absolute differences, the relational degree between household business income and fishermen's total income ranked first. Therefore, focusing on changes in household business income is the key entry point for understanding income growth among fishermen. [12]The factors influencing fishermen's income are diverse and complex. Existing studies have primarily explored these from perspectives such as natural resource and environmental constraints, national and local policies, market supply-demand and price fluctuations, and fishermen's own human capital (e.g., education level, skills training). In recent years, with the transformation of fishery development models, the impact of Industrial structure optimization on income has gained increasing attention. [13]Shifting from mere output growth to value enhancement, and from the dominance of the primary industry to the coordinated development of secondary and tertiary industries, has become a new engine for fishery economic growth and fishermen's income increase.[14]

2.2 The Industrial Structure of Liaoning's Fishery and the Position of the Shellfish Industry

Liaoning Province is a traditional major fishery province in China, and its fishery economy exhibits distinct industrial structural characteristics.[15] Within Liaoning's fishery industrial structure, the primary industry, dominated by capture and aquaculture, has long held the main position. However, since 2000, the share of the secondary industry, primarily aquatic product processing, and the tertiary industry, mainly comprising recreational fisheries and aquatic product transportation, has shown an overall increasing trend.[16] The center of gravity of the industrial structure triangle demonstrates a "left-rotation" shift, signaling the ongoing optimization of the industrial structure. Within the primary fishery sector, mariculture has replaced marine capture as the core contributor to both output and value.[17] Data show that the province's total shellfish aquaculture output has reached 2760358 tons. As illustrated in the figure, mariculture output accounts for approximately 80% of the total fishery aquaculture output, with its output value being about twice that of freshwater aquaculture. Among the various categories in mariculture, shellfish aquaculture holds a significant share. Although the literature searched for this study does not provide the precise proportion of shellfish output in Liaoning, reference to predictions from Shandong Province, another major mariculture province, indicates that its shellfish aquaculture output is projected to be substantially higher than that of fish, crustaceans, and others among marine product categories, highlighting the pillar status of shellfish in mariculture. [18]Liaoning Province possesses vast shallow sea and Tidal Flats resources, making it highly suitable for developing shellfish aquaculture. Its shellfish products enjoy a strong reputation in both domestic and international markets and serve as an important source for increasing the income of coastal fishermen.[19]

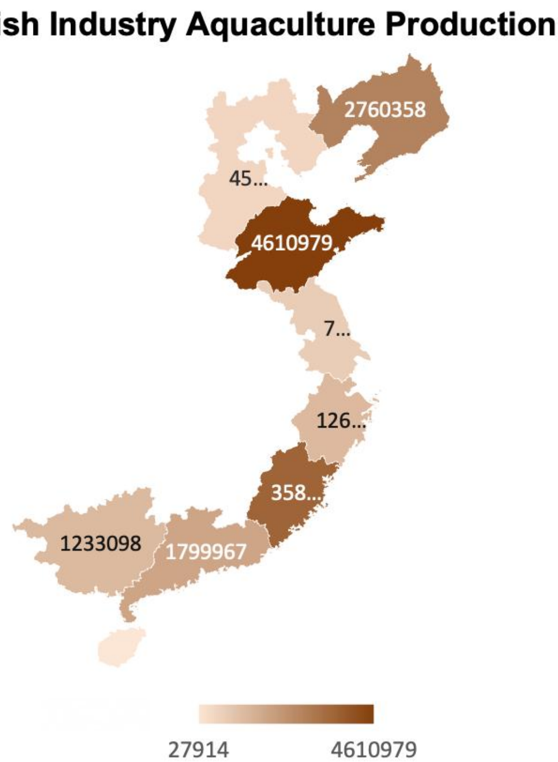


Figure 1： Shellfish Industry Aquaculture Production

3. Research Methodology and Data Sources

3.1 Fundamental Principles and Modeling Procedure of the GM(1,1) Prediction Model

This study employs the univariate first-order grey prediction model, namely the GM (1,1) model, whose core concept is to mitigate randomness and accentuate inherent trends by applying a first-order Accumulated Generating Operation (1-AGO) to the original non-negative data series, and then to fit and forecast using a first-order linear differential equation. The specific modeling procedure, consistent with the technical flow provided: defining the original non-negative series; conducting a ratio test and applying a translation transformation (adding a constant C to all data points if the stepwise ratio falls outside the admissible coverage interval) to ensure model applicability; performing first-order accumulation to generate the accumulated series and then computing the neighboring mean sequence; establishing the grey differential equation (where a is the development coefficient and b is the grey action quantity) and estimating parameters via the least squares method; and finally, deriving the time response function from the whitening equation and restoring the predicted values for the original series through inverse accumulation.

3.2 Model Accuracy Testing System

To ensure the feasibility of the modeling method, a ratio test must be performed on the original data.

1. Define the original data series $X^{(0)}$

$$X^{(0)} = \left(x^{(0)}(1), x^{(0)}(2), \ldots, x^{(0)}(n)\right)$$

where$x^{(0)}(k) > 0, \quad k = 1,2,\ldots,n$.

2. Calculate the stepwise ratio.

$$\lambda(k) = \frac{x^{(0)}(k-1)}{x^{(0)}(k)}, \quad k = 2,3,\cdots,n$$

3. Ratio Test

All stepwise ratio values should fall within the range of $\left(e^{-\frac{2}{n+1}}, e^{\frac{2}{n+1}}\right)$. If this condition is satisfied, the ratio test is considered passed; otherwise, it is not passed.

4. Translation Transformation (Skip this step if the stepwise ratio test passes)

If the data satisfies the stepwise ratio test, proceed directly to GM(1,1) modeling. If it does not satisfy the stepwise ratio test, perform a shift transformation on the original data.

(1) Add a constant C to all original data points so that the shifted new data satisfies the stepwise ratio test;

(2) Perform GM(1,1) modeling and prediction using the new data

(3) Subtract C from the predicted result to obtain the true prediction

(4) Evaluate model accuracy using the true prediction results and original data.

Tips: No explicit method for determining constant C has been found in literature. Software employs trial-and-error, incrementing C from 1 until a value passes the order test.

1. Determine the original data sequence $X^{(0)}$

$$X^{(0)} = \left(x^{(0)}(1), x^{(0)}(2), \dots, x^{(0)}(n)\right)$$

Where$x^{(0)}(k) > 0, \quad k = 1,2,\dots,n$.

2. Generate the cumulative sequence $X^{(1)}$

$$X^{(1)} = \left(x^{(1)}(1), x^{(1)}(2), \dots, x^{(1)}(n)\right)$$

where

$$x^{(1)}(k) = \sum_{i=1}^{k} x^{(0)}(i), \quad k = 1,2,\dots,n$$

3. Generate the adjacent mean sequence of$X^{(1)}$ $Z^{(1)}$

$$Z^{(1)} = \left(z^{(1)}(2), z^{(1)}(3), \dots, z^{(1)}(n)\right)$$

where,

$$z^{(1)}(k) = \frac{1}{2}\left(x^{(1)}(k) + x^{(1)}(k-1)\right), \quad k = 2,3,\dots,n$$

4. Establish the GM(1,1) model

Based on grey system theory, establish the grey differential equation:

$$x^{(0)}(k) + az^{(1)}(k) = b, \quad k = 2,3,\dots,n$$

The corresponding whitened differential equation:

$$\frac{dX^{(1)}}{dt} + aX^{(1)} = b$$

where$a$ and$b$ are undetermined parameters,a is termed the development coefficient, and$b$ is termed the grey action.

5. Solve for$a$ and using the least squares method. b

$$(a,b)^T = (B^T B)^{-1} B^T Y$$

where$B$ and$Y$ are defined as:

$$B = \begin{bmatrix} -z^{(1)}(2) & 1 \\ -z^{(1)}(3) & 1 \\ \vdots & \vdots \\ -z^{(1)}(n) & 1 \end{bmatrix}, \quad Y = \begin{bmatrix} x^{(0)}(2) \\ x^{(0)}(3) \\ \vdots \\ x^{(0)}(n) \end{bmatrix}$$

6. After solving for a and b, the time response formula is obtained as

$$\hat{x}^{(1)}(k+1) = \left[x^{(0)}(1) - \frac{b}{a}\right] e^{-ak} + \frac{b}{a}, \quad k = 0,1,2,\ldots,n-1$$

7. Reconstruct the predicted values of the original data sequence

$$\hat{x}^{(0)}(k+1) = \hat{x}^{(1)}(k+1) - \hat{x}^{(1)}(k) = (1 - e^{a}) \left[x^{(0)}(1) - \frac{b}{a}\right] e^{-ak}$$

where $k = 1,2,\ldots,n-1$.

8. Residual and relative error verification

Residual calculation:

$$\varepsilon^{(0)}(k) = x^{(0)}(k) - \hat{x}^{(0)}(k)$$

Relative error calculation:

$$\omega^{(0)}(k) = \left|\frac{x^{(0)}(k) - \hat{x}^{(0)}(k)}{x^{(0)}(k)}\right|$$

If the relative error is $\omega^{(0)}(k) < 0.2$, the data is considered to meet general requirements; if the relative error is $\omega^{(0)}(k) < 0.1$, the data is considered to meet higher requirements.

9. Grade Ratio Deviation Test

From the original data series $x^{(0)}(k-1)$ and $x^{(0)}(k)$, calculate the corresponding ratios $\lambda(k)$. Then use the development coefficient a to determine the ratio deviation $\rho(k)$.

$$\rho(k) = \left|1 - \left(\frac{1 - 0.5a}{1 + 0.5a}\right) \lambda(k)\right|, \quad k = 2,3\cdots,n$$

If the rank ratio deviation $\rho(k) < 0.2$, the data can be considered to meet general requirements; if the rank ratio deviation $\rho(k) < 0.1$, the data can be considered to meet higher requirements.

10. Post-calibration error verification: Calculate the post-calibration error ratio C (ratio of residual standard deviation to original data standard deviation) and the probability of minor errors P. According to general standards, accuracy grades are classified into four levels: Excellent (C ⩽ 0.35, P ⩾ 0.95), Good, Acceptable, and Unacceptable.

(1) Calculate the mean of the original data $\bar{x}^{(0)}$

$$\bar{x}^{(0)} = \frac{1}{n} \sum_{k=1}^{n} x^{(0)}(k)$$

(2) Calculate the standard deviation of the original data S_1

$$S_1 = \sqrt{\frac{1}{n} \sum_{k=1}^{n} (x^{(0)}(k) - \bar{x}^{(0)})^2}$$

(3) Calculate the residuals between original data and predicted data $\varepsilon^{(0)}$

$$\varepsilon^{(0)}(k) = x^{(0)}(k) - \hat{x}^{(0)}(k)$$

(4) Calculate the mean of the residuals $\bar{\varepsilon}^{(0)}$

$$\bar{\varepsilon}^{(0)} = \frac{1}{n} \sum_{k=1}^{n} \varepsilon^{(0)}(k)$$

(5) Calculate the standard deviation of the residuals S_2

$$S_2 = \sqrt{\frac{1}{n} \sum_{k=1}^{n} (\varepsilon^{(0)}(k) - \bar{\varepsilon}^{(0)})^2}$$

(6) Calculate the posterior error ratio C

$$C = \frac{S_2}{S_1}$$

(7) Calculate the probability of small errors p

$$p = P\left\{\left|\varepsilon^{(0)}(k) - \bar{\varepsilon}^{(0)}\right| < 0.6745S_1\right\}$$

Determine model accuracy based on the calculated values of C and p

Accuracy Grade	C	p
Excellent	$C \leq 0.35$	$p \geq 0.95$
Good	$0.35 < C \leq 0.5$	$0.8 \leq p < 0.95$
Satisfactory	$0.5 < C \leq 0.65$	$0.7 \leq p < 0.8$
Unacceptable	$C > 0.35$	$p < 0.7$

3.3 Data Sources and Processing

Shellfish Production Data: The study utilizes annual shellfish production figures (in tons) from Liaoning Province between 2010 and 2023 as the primary data series. This data forms the foundation for analyzing the development trends of the shellfish industry.

Fisheries Household Operating Income Data: The study utilized annual per capita (or per household) operating income (in yuan) from Liaoning Province's fishing households during the same period as the raw data series. This data serves as a core indicator reflecting the income derived from production and business activities by fishermen.

Data Preprocessing: Prior to GM(1,1) modeling, all data series underwent a test for stationarity. Based on the test results, income series failing the test underwent a shift transformation (the constant C was determined through trial and error to be 265,410) to meet modeling conditions. All computational processes were implemented using Python programming, ensuring consistency and reproducibility of calculations.

4. Empirical Results and Analysis

4.1 Construction and Validation of Shellfish Production Forecasting Model

First, the original shellfish production time series for Liaoning Province from 2010 to 2023 underwent a unit root test. The calculated unit root test interval was [0, 1]. Empirical calculations showed that all unit root values fell within this interval, eliminating the need for a shift transformation. This indicates that the original data is suitable for directly establishing a GM(1,1) model.

Table 1: Key Parameters and Test Results of the GM(1,1) Model for Shellfish Production in Liaoning Province

Parameter Name	Value	Description
Log-rank Test Interval	(0.875, 1.143)	Test Passed
Shift Amount C	0 (No shift required)	
Development coefficient (a)	-0.01885	Negative values indicate an increasing trend in the sequence
Gray effect quantity (b)	2,053,887.489	
Average Relative Error	4.839%	<20%, meeting general requirements
Average Grade Ratio Deviation	0.042	<0.1, meeting higher requirements

Posterior ratio error (C)	0.502	Within the range 0.5 < C ⩽ 0.65
Probability of Small Error (P)	0.786	In the range 0.7 ⩽ P < 0.8
Comprehensive Accuracy Grade	Qualified	Based on C and P values

Model parameters indicate that the growth coefficient a is negative, suggesting a growth trend in Liaoning Province's shellfish production series.All accuracy metrics meet requirements, with an average relative error of only 4.839% and an average rank deviation of 0.042, demonstrating the model's excellent fit to historical data. The posterior error ratio C is 0.502, and the small error probability P is 0.786. Based on the evaluation criteria, the model's overall prediction accuracy is rated as "Qualified" and suitable for trend forecasting.

4.2 Shellfish Production Forecast Results

Using the established model, shellfish production in Liaoning Province was forecasted for the next decade (2024–2033). This parameter table comprehensively presents the construction process, core parameters, and accuracy verification results of the GM(1,1) model for fishermen's household operational income. Its core characteristic lies in: the model passed rigorous applicability tests and demonstrated exceptional capability in capturing the overall trend of the data.

Table 2: Parameter Table

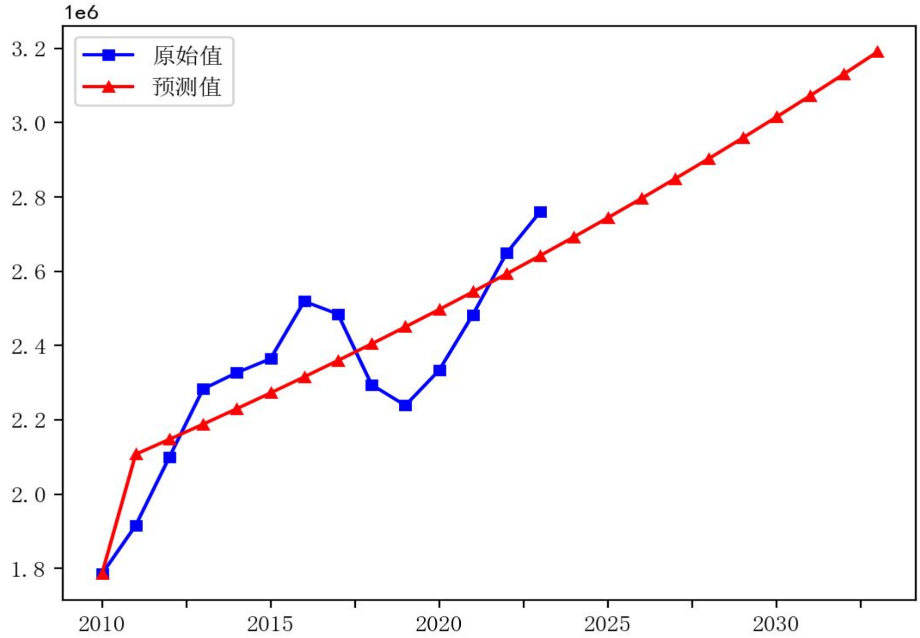
Parameter Name	Value	Description
Level Ratio Test Interval	(0.875, 1.143)	Original sequence failed, shifted sequence passed
Shift Amount C	265, 410	
Growth coefficient (a)	-0.02986	Negative value indicates an increasing trend in the sequence
Grey effect quantity (b)	264,867.272	
Average Relative Error	20.125%	<20%, meeting general requirements
Average Grade Ratio Deviation	0.179	<0.2, meets general requirements
Posterior ratio error (C)	0.272	Within the C ⩽ 0.35 range
Probability of Minor Error (P)	1.000	Within the P ⩾ 0.95 interval
Overall accuracy grade	Excellent	Based on C and P values

Model projections indicate that Liaoning Province's shellfish production will exhibit steady and sustained growth over the next decade. Specifically, output is projected to rise from approximately 2.693 million tons in 2024 to about 3.190 million tons by 2033, achieving cumulative growth of roughly 18.5% during this period with a compound annual growth rate (CAGR) maintained at around 1.7%.This growth rate represents a moderate and sustainable pace that aligns with resource and environmental carrying capacity while matching the rhythm of industrial upgrading. It is consistent with the current macro policy direction in China's marine aquaculture sector, which is shifting from pursuing scale expansion to emphasizing quality, efficiency, and ecological sustainability.

Table 3: Historical Fitting and Future Forecast of Shellfish Production in Liaoning Province (Unit: tons)

Year	Original Value	Predicted Value	Residual	Relative Error (%)	Grade Ratio Deviation
2010	1784996	1784996	0	0	-
2011	1915432	2107334.768	-191902.768	10.019	0.05
2012	2099631	2147435.446	-47804.446	2.277	0.07
2013	2282876	2188299.203	94576.797	4.143	0.063
2014	2327070	2229940.561	97129.439	4.174	0
2015	2364503	2272374.316	92128.684	3.896	0.003
2016	2519090	2315615.547	203474.453	8.077	0.044
2017	2484735	2359679.619	125055.381	5.033	0.033
2018	2294524	2404582.192	-110058.192	4.797	0.104
2019	2238840	2450339.219	-211499.219	9.447	0.044
2020	2333252	2496966.962	-163714.962	7.017	0.022
2021	2482992	2544481.988	-61489.988	2.476	0.042
2022	2648828	2592901.182	55926.818	2.111	0.045
2023	2760358	2642241.75	118116.25	4.279	0.022
2024		2692521.225			
2025		2743757.472			
2026		2795968.699			
2027		2849173.458			
2028		2903390.656			
2029		2958639.558			
2030		3014939.797			
2031		3072311.379			
2032		3130774.69			
2033		3190350.505			

This chart visually presents the forecast results for shellfish production in Liaoning Province based on the GM(1,1) model. The two closely aligned trend lines represent historical actual values and model-fitted/predicted values, respectively. From the historical period spanning 2010 to 2023, the forecast curve demonstrates high consistency with the actual curve, confirming the model's strong fitting accuracy.From 2024 to 2032, the forecast curve exhibits a smooth and steadily upward trajectory, indicating production will grow steadily from approximately 2.75 (in millions of tons) to about 3.24, with a moderate average annual growth rate.This moderate and certain long-term growth trend is clearly visualized in the chart, providing direct quantitative support for the industry's



transition from scale expansion to a high-quality development phase that prioritizes both quality and efficiency.

Figure 2: Shellfish Production Forecast Chart

4.3 Construction and Validation of the Operational Income Forecast Model for Fishery Households

A test for the order of the original sequence of fishermen's household operating income from 2010 to 2023 revealed that some order values exceeded the acceptable coverage range and failed the test. Therefore, a shift transformation method was employed, with the shift constant C determined through trial and error to be 265.410. After re-testing the shifted new sequence, all order values passed the test, enabling the establishment of the GM(1,1) model.

Table 4: Key Parameters and Test Results of the GM(1,1) Model for Liaoning Province Fishermen's Household Business Income

Sequence (k)	Original Sequence	Translated Sequence	Cumulative Series	Adjacent Mean Series
1	21366.4	286,776.4	286,776.4	-
2	25,479.66	290,889.66	577,666.06	432,221.23
3	25,956.48	291,366.48	869,032.54	723,349.3
4	37,594.74	303,004.74	1,172,037.28	1020534.91
5	34,021.21	299,431.21	1,471,468.49	1321752.885
6	23,096.27	288,506.27	1,759,974.76	1615721.625
7	59,708.25	325,118.25	2,085,093.01	1922533.885

8	63,930.06	329,340.06	2,414,433.07	2,249,763.04
9	70,782.48	336,192.48	2,750,625.55	2,582,529.31
10	67,900.17	333,310.17	3,083,935.72	2,917,280.635
11	112,320.33	377,730.33	3,461,666.05	3,272,800.885
12	116,669.75	382,079.75	3,843,745.8	3,652,705.925
13	123,946.76	389,356.76	4,233,102.56	4,038,424.18
14	132,704.78	398,114.78	463,121.73	4432159.95

Analysis of this parameter table indicates that the GM(1,1) predictive model for fishermen's household operating income demonstrates exceptional reliability in capturing trends, though it exhibits reasonable deviations in precisely replicating specific historical data values.The development coefficient a of the income model is also negative, indicating that income growth follows a long-term trend. Although the mean relative error (20.125%) and mean ratio-of-deviations (0.179) only meet general requirements— reflecting significant influence of inter-annual factors (e.g., prices, policies, natural disasters) on income data— the posterior error ratio C is exceptionally low (0.272), and the probability of small errors P reaches 1.signifying that despite isolated point errors, the forecast sequence closely matches the overall fluctuation patterns and trends of the original sequence. The model demonstrates exceptional capability in capturing systematic development trends, achieving an overall accuracy rated as "Excellent." This aligns with the characteristic of grey forecasting models being more adept at trend prediction than precise point value forecasting.

Table 5: Parameter Table

Parameter Name	Value
Lower Limit of Class Ratio Test Interval	0.875
Upper Limit of Ratio Test Interval	1.143
Shift Required	Yes
Shift amount	265410
Development coefficient a	-0.02986
Gray effect coefficient b	264867.272
Average relative error (%)	20.125
Average Grade Ratio Deviation	0.179
Posterior ratio error C	0.272
Probability of small error P	1

4.4 Forecast Results for Fishermen's Household Operating Income

Using the validated model for prediction, the final income forecast is obtained by subtracting the shift amount C from the predicted value.

Table 6: Historical Fitting and Future Forecast Values of Liaoning Fishermen's Household Operating Income (Unit: CNY)

Year	Original Value	Predicted Value	Residual	Relative Error (%)	Grade Ratio Deviation
2010	21366.4	21366.4	0	0	-
2011	25479.66	12142.792	13336.868	52.343	0.136
2012	25956.48	20554.913	5401.567	20.81	0.011

2013	37594.74	29221.989	8372.751	22.271	0.289
2014	34021.21	38151.749	-4130.539	12.141	0.139
2015	23096.27	47352.154	-24255.884	105.021	0.518
2016	59708.25	56831.406	2876.844	4.818	0.601
2017	63930.06	66597.957	-2667.897	4.173	0.038
2018	70782.48	76660.514	-5878.034	8.304	0.069
2019	67900.17	87028.05	-19127.88	28.171	0.074
2020	112320.33	97709.806	14610.524	13.008	0.377
2021	116669.75	108715.307	7954.443	6.818	0.008
2022	123946.76	120054.365	3892.395	3.14	0.03
2023	132704.78	131737.089	967.691	0.729	0.038
2024		143773.895			
2025		156175.515			
2026		168953.005			
2027		182117.758			
2028		195681.511			
2029		209656.356			
2030		224054.754			
2031		238889.54			
2032		254173.942			
2033		269921.587			

Forecast results indicate that the operating income of fishing households in Liaoning Province is projected to increase from approximately ¥143,800 in 2024 to approximately ¥269,900 in 2033, representing an average annual growth rate of about 7.2%. This growth rate significantly exceeds the projected growth rate for shellfish production, suggesting that future increases in fishermen's income will depend not only on expanding production volumes but more likely on value enhancement, industry diversification, and improved efficiency.

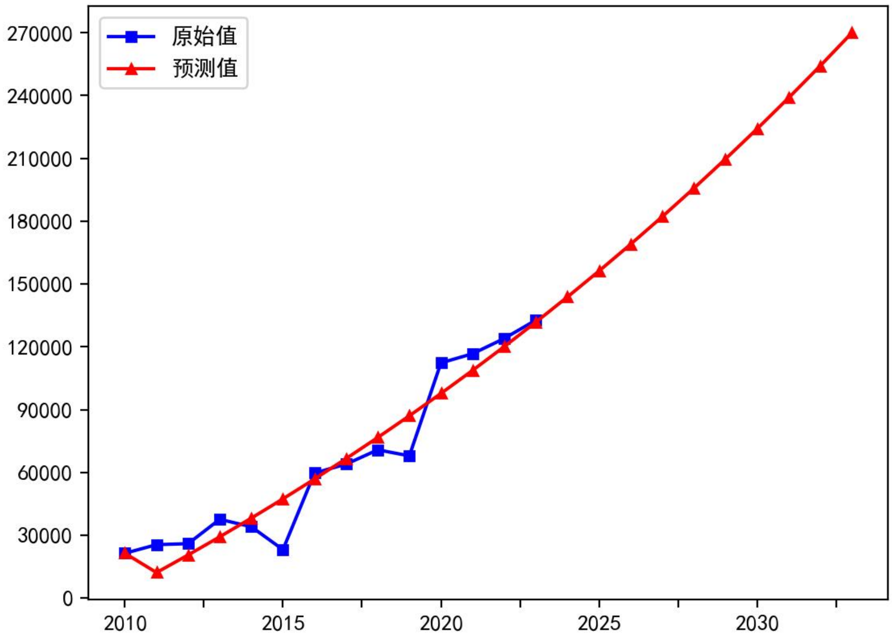


Figure 3: Household Operating Income

Figure 3 illustrates the comparison between actual values and model projections for the period 2010–2031, along with future trends. The overall trend reveals a clear long-term upward trajectory in the income series. A turning point in the model's historical fitting period (around 2017) is evident: prior to this point, projections generally fell below actual values; thereafter, projections began to systematically exceed actual values, with both series maintaining synchronous growth.This characteristic suggests that the forecasting model employed (e.g., the GM(1,1) model) may be more inclined to capture and perpetuate the recently observed accelerating growth trend. Entering the pure forecasting period (post-2024), income is projected to continue growing along a path of stable slope, reaching 260,000 yuan by 2031.

5. Discussion: Mechanisms and Pathways Through Which the Shellfish Industry Influences Fishermen's Income

Although the GM(1,1) model established in this study comprises two independent univariate prediction models, analyzing the forecast trends of shellfish production (representing core industry development) and fishermen's household operational income (representing core income sources) in parallel, combined with the existing characteristics of Liaoning Province's fishery industry structure, allows for logical deduction and in-depth exploration of the underlying linkage mechanisms.[20]

5.1 Direct Contribution Pathway: Production Growth and Primary Product Value Realization

This represents the most fundamental and direct pathway. Shellfish farming constitutes the primary production activity for numerous coastal fishing households in Liaoning. Projections indicate sustained growth in shellfish production, providing a stable output foundation for fishermen engaged in shellfish farming. Under conditions of relatively stable market demand and prices, increased production directly translates into higher sales revenue for farming households, forming a significant component of their household operational income. However, this pathway is notably constrained by market price fluctuations and rising farming costs.[21]

5.2 Value-Added Pathway: Driving Force from Aquatic Product Processing

Analysis of Liaoning Province's fishery industry structure indicates that the aquatic products processing industry (secondary industry) exhibits the highest grey correlation with the total output value of marine fisheries, establishing itself as a pillar industry. As a key processing raw material, the stable growth in shellfish production provides ample supply for downstream processing. Developing deep processing of shellfish—such as producing ready-to-eat products, condiments, and extracting bioactive substances—can multiply product value-added by several to dozens of times.[22]This not only creates more non-farming employment opportunities (contributing wage income) but also enables participating aquaculture fishermen to share in the profits from processing value-added through models like "company + farmer" partnerships and contract farming. This enhances the quality of their operational income. The projected growth rate of fishermen's income exceeds that of production volume, partly attributable to this extended value chain.[23]

5.3 Pathways for Industry Integration: Empowerment Through Recreational Fisheries

As a vital component of the tertiary sector, leisure fisheries in Liaoning Province hold promising development prospects.The shellfish industry can deeply integrate with recreational fisheries to form a new integrated model of "farming-experience-consumption.[24]" Examples include developing tourism projects such as shellfish harvesting, shellfish cuisine at fishing villages, and shellfish cultural exhibitions. This integration not only directly generates tourism service income (included in "other business income" within household business income) but also effectively enhances the local sales value and brand recognition of primary shellfish products.Research indicates that within Chinese fishing households' operating income, the contribution and driving force of "other operating income" now exceed those from fishery production, signaling the diversification and expansion of fishermen's labor and income sources. The integration of shellfish farming with recreational fisheries vividly exemplifies this trend.[25]

5.4 Pathways for Structural Optimization: Promoting Industry Upgrading and Risk Resilience

Monoculture aquaculture is vulnerable to environmental and market risks. Integrating shellfish production with secondary and tertiary industries like processing and recreation will transform fishing households from pure producers into operators and service providers, optimizing their income structure. This diversification not only increases overall income but also enhances resilience against single-industry fluctuations, ensuring long-term income stability.[26]

6. Conclusions and Policy Recommendations

6.1 Research Findings

This study employed the GM(1,1) model from grey system theory to model and forecast shellfish production and operational income for fishing households in Liaoning Province. By integrating industrial structure theory to analyze their intrinsic relationship, the following key conclusions were drawn:

Trend Forecast: The model predicts that both shellfish production and fishermen's household operating income in Liaoning Province will maintain steady growth from 2024 to 2033. Shellfish production is projected to grow at an average annual rate of approximately 1.7%, indicating robust expansion. [27]Fishermen's household operating income is expected to increase at an average annual rate of about 7.2%, a more significant growth rate, suggesting that value-added growth will become the primary driver of future income growth for fishermen.

Regarding model validity: Both constructed GM(1,1) models passed rigorous statistical tests.The shellfish yield model demonstrated high fitting accuracy, achieving an overall rating of "Satisfactory." Although the fisher income model exhibited significant errors at individual points, it excelled in capturing the overall trend (posterior error ratio C=0.272, probability of small error P=1), earning an overall rating of "Excellent." This validates the applicability and reliability of grey prediction models in handling such "poor information" economic sequences.[28]

Regarding the impact mechanism: Analysis indicates that the shellfish industry influences fishermen's income through a multi-path composite process. It not only contributes to basic income through direct yield growth but, more importantly, drives the development of the aquatic product processing industry (secondary industry) and recreational fisheries (tertiary industry). This achieves value-added growth, industrial integration, and structural optimization, thereby opening broader and more sustainable income channels for fishermen.[29]

6.2 Policy Recommendations

Based on the above conclusions, the following recommendations are proposed to enhance the wealth-generating effects of Liaoning Province's shellfish industry and promote high-quality development of the fishery economy:

Promote Quality Enhancement, Efficiency Improvement, and Green Development in Shellfish Aquaculture: While ensuring stable yield growth, greater emphasis should be placed on developing ecologically sound aquaculture models. Promote new technologies such as standardized pond renovation, shallow-sea ecological raft aquaculture, and integrated multi-trophic aquaculture (IMTA) to reduce environmental impact and enhance shellfish quality and safety standards.Strengthen breeding programs and disease prevention systems to safeguard the industry's foundational security. This aims to solidify the "direct contribution pathway," ensuring the profitability and sustainability of primary production.[30]

Vigorously Support and Innovate Aquatic Product Processing: Develop preferential policies to guide capital investment toward high-value shellfish processing and new product R&D. Support processors in establishing standardized raw material production bases and creating robust benefit-sharing mechanisms (e.g., guaranteed purchase prices, profit-sharing) with farmers, enabling fishermen to capture greater profits from processing. This is central to strengthening the "value-added pathway" and boosting overall industry returns.

Deepening the integrated development of shellfish industries and recreational fisheries: Plan and construct a series of "shellfish-themed" recreational fishery bases or marine ranch demonstration zones integrating shellfish farming, sightseeing experiences, culinary culture, and science education. Design diverse participatory activities, build distinctive regional brands, and effectively convert tourist traffic into service income for fishermen. This initiative is a key measure to expand the "industrial integration pathway" and diversify fishermen's income sources.

Strengthen technological support and comprehensive service systems: Increase investment in scientific research covering shellfish farming techniques, processing technologies, and resource conservation. Establish a robust market information and technical service network spanning production, logistics, and sales to help fishermen mitigate market risks and improve operational decision-making. Concurrently, enhance vocational skills training for fishermen to facilitate their transition into new roles as professional fishermen or service providers in the tertiary sector.

Refine industrial policies and safeguard mechanisms: Continue implementing and optimizing productive subsidies like fishery fuel price subsidies. Develop targeted support measures such as shellfish farming insurance and preferential credit for processing enterprises. Strengthen safeguards for aquaculture rights in water areas and tidal flats to stabilize fishermen's production expectations. Through policy guidance, continuously optimize the fishery industry structure toward increasing the share of secondary and tertiary industries, creating a more favorable macro-industrial environment for fishermen's income growth.

Methodologically, this study provides a feasible framework for quantitatively analyzing the relationship between regional specialty industries and resident income.Future research could collect longer time-series data and explore incorporating multivariate grey models (GM(1,N)) to include additional factors like market prices, production costs, and policy dummy variables. This would enable more precise characterization of the complex dynamics through which the shellfish industry influences fishermen's income. Additionally, comparing Liaoning's predictive results with other major shellfish-producing provinces like Shandong and Fujian could help distill more universally applicable development patterns.

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