frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 08 January 2025
DOI 10.3389/fmars.2024.1518235

OPEN ACCESS

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RECEIVED 28 October 2024
ACCEPTED 16 December 2024
PUBLISHED 08 January 2025

CITATION
Liu Z, Lu W, Wang T, Zhang Y, He L, Yang L and Deng L (2025) The assessment of carrying capacity of marine fishery resources in China.
Front. Mar. Sci. 11:1518235.
doi: 10.3389/fmars.2024.1518235

The assessment of carrying capacity of marine fishery resources in China

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Introduction: The sustainable development of marine fisheries has been a major concern, with the carrying capacity of marine fishery resources becoming a focal point of research.

Methods: This study, utilizing remote sensing data, marine capture fisheries catch data, and fishing effort data from 2013 to 2020, aims to determine the maximum sustainable yield using a surplus production model and provide a comprehensive assessment of the status and potential of China's marine fishery resources.

Results: The results indicate that China's marine fishery resources exhibit significant regional variability, with the East China Sea contributing the largest share of catch and maintaining sustainability, while regions such as the South China Sea, Yellow Sea, and Bohai Sea have exceeded their ecological carrying capacities. Correlation analysis highlights that nutrient levels and water quality (e.g., chemical oxygen demand) are critical for resource stability, while the distribution and management of protected areas further influence carrying capacity.

Discussion: This study contributes to the development of more effective fishery policies, aiming to balance economic benefits with ecological health. By understanding these dynamics, policymakers can better address the challenges facing sustainable marine fisheries.

KEYWORDS

marine fishery resources, fishing effort, surplus production models, carrying capacity, correlation analysis, sustainable marine fisheries

1 Introduction

Sustainable management of marine fisheries is essential for maintaining ecological balance and supporting human livelihoods, particularly in regions where fishing plays a significant economic role (Pauly et al., 1998; FAO, 2020; Kemp et al., 2023). China's coastal and offshore waters are among the most productive globally, supporting a rapidly expanding fishing industry that has developed significantly over the past few decades (Shen and Heino, 2014). However, increasing demand for fish products and the growing capacity of fishing fleets have placed unprecedented pressure on Chinese marine fisheries, raising concerns about resource depletion, ecosystem degradation, and the sustainability of fishery resources (Han, 2018; Tang et al., 2016; Szuwalski et al., 2017; Chen et al., 2018; Yin et al., 2024). In response, marine resource management practices in China have made some advances, including improved regulations and monitoring systems (Shen and Heino, 2014; Chen et al., 2023; Yue et al., 2023), but the challenges of sustainable fishery resource management, particularly in terms of accurately assessing and managing the carrying capacity of marine ecosystems, remain substantial.

Carrying capacity, in the context of marine ecosystems, refers to the maximum population of fish that an ecosystem can support without undergoing degradation (Odum, 1997; Wang et al., 2022). Estimating this capacity is essential for preventing overexploitation and ensuring the sustainability of fishery resources. A common approach to assess carrying capacity is through the use of surplus production models (SPMs), which estimate the maximum sustainable yield (MSY) —the highest catch that can be maintained over time without depleting the fishery (Hilborn and Walters, 1992). The MSY serves as a critical benchmark in fishery management, offering insights into the capacity of marine resources to support fishing activities. By providing a quantitative estimate of the MSY, SPMs allow researchers and policymakers to evaluate the sustainability of current fishing practices and help develop management strategies to maintain fish stocks within sustainable limits (Jacobson et al., 2002; Kokkalis et al., 2024). However, most studies using SPMs and MSY focus on single species or specific regions, often neglecting the broader, more complex interactions within entire marine ecosystems (Wang and Liu, 2013; Stäbler et al., 2016; Derhy et al., 2024; Sultana et al., 2023).

Recent studies have called for a more integrated approach that applies MSY not only at the species level but also across larger geographic scales, incorporating ecosystem dynamics to better understand the carrying capacity of marine fisheries on a broader level (Fulton et al., 2022; Sun et al., 2020; Demirel et al., 2020; Griffiths et al., 2024). Comprehensive assessments of fishery resource carrying capacity across entire marine regions remain scarce, particularly for large, productive areas such as China's waters, where systematic evaluations are needed to inform sustainable management strategies.

This study applies the surplus production model as a key tool to estimate the MSY for marine fishery resources in Chinese waters. Using extensive data collected from statistical yearbooks, we analyze marine fishery catch trends over the past eight years. The estimated MSY is then employed to construct a carrying capacity evaluation model that assesses the current status of China's marine fisheries, followed by an analysis of the factors influencing this status. The goal of this research is to provide a scientific basis for managing marine fishery resources in China, as well as to offer insights that may benefit global fisheries management.

2 Materials and methods

2.1 Data resource

The data used in this study primarily includes marine fishery catch data, fishing effort, environmental factors, aquaculture distribution data and protected area information from 2013 to 2020. The main sources of data are the China Fishery Statistical Yearbook, Global Fishing Watch (GFW), China Marine Ecological Early Warning Monitoring Surveys, and official reports from provincial government websites (Table 1).

2.1.1 Catch data

Catch data used in this study were sourced from the China Fishery Statistical Yearbooks (Bureau of Fisheries of Ministry of Agriculture and Rural Affairs of China, 2014– 2021). The data are collected through standardized government surveys and compiled by provincial and national fishery bureaus. Although the accuracy of catch statistics available from these Yearbooks has been questioned in the past, with suggestions of over-reporting domestic fisheries production, it is also acknowledged that "a more effective statistical system for domestic fisheries has been developed" (Pauly et al., 2014). Indeed, there have been three major adjustments in the China Fishery Statistical Yearbooks throughout

TABLE 1 Summary of data sources used in the study.

Data Type	Data source	Data Summary
Catch data	the China Fishery Statistical Yearbooks	Includes annual catch data for marine species
the daily fishing vessel operation time	Global Fishing Watch	Provides global fishing activity data, updated daily, with a 10° resolution
SST, pH, DIN, PO_4^{3-}, DO,COD, and chl-a	China Marine Ecological Early Warning Monitoring Surveys	Includes seawater quality, meteorological, hydrological, and ecological data from 2041 monitoring sites
Aquaculture Distribution Data	National sea area ownership records	Includes spatial distribution of aquaculture zones, licensing status, and certification dates
Protected area data	official provincial reports	Includes information on protected area location, size, species protection, etc.

this period of years to reduce past inaccuracy and uncertainty in reported catches, accompanied by timely updating of China's fisheries data based on these adjustments in the Food and Agriculture Organization of the United Nation's (FAO) global capture production database. Detailed revision information about China's fisheries data has been described by its Fisheries Bureau of the Ministry of Agriculture and Rural Affairs (1999).

2.2.2 The fishing effort data

The fishing effort data is represented by the total annual fishing hours of Chinese vessels. This data was derived by filtering the daily fishing vessel operation time provided by GFW to include only vessels registered in China (Global Fishing Watch, 2021). The Global Fishing Watch dataset is a globally recognized platform that utilizes Automatic Identification System (AIS) signals from fishing vessels, combined with advanced algorithms, to monitor fishing activities worldwide. This dataset provides detailed spatial resolution (10th-degree grids) and temporal resolution (daily) of fishing effort, including vessel locations, activity intensity, and fishing types. GFW collaborates with international organizations such as the Food and Agriculture Organization (FAO) and regional fishery management bodies, ensuring alignment with global fisheries management standards. Its data have been widely cited in peer-reviewed publications and used for policy-making in fisheries management.

2.2.3 Environmental monitoring data

Environmental monitoring data was collected from the 2013–2020 China Marine Ecological Early Warning Monitoring Surveys. China Marine Ecological Early Warning Monitoring Surveys provide comprehensive data on marine ecological changes, focusing on three aspects: trend monitoring of large-scale, long-term changes; thematic monitoring of specific regions or ecological issues; and research-oriented monitoring supporting restoration and disaster management. Key indicators include seawater quality (e.g., nutrients, pH), hydro-meteorological factors (e.g., temperature, salinity), and biological metrics (e.g., biodiversity, habitat conditions). This study used the data of sea surface temperature (SST), pH, dissolved inorganic nitrogen (DIN), phosphate (PO_4^{3-}), dissolved oxygen (DO), chemical oxygen demand (COD), and chlorophyll-a (chl a) concentrations from 2,041 stations. The monitoring framework is guided by annual work plans and coordinated by the Ministry of Natural Resources, with coastal provinces and marine research institutions responsible for conducting the surveys. To ensure data consistency and reliability, all monitoring activities adhere to national protocols, such as the Specifications for Oceanographic Survey—Part 4: Survey of Chemical Parameters in Seawater (GB/T 12763.4-2007) and the Specification for Marine Monitoring—Part 4: Seawater Analysis (GB 17378.4-2007). A rigorous quality control system is in place, including regular training and multi-level review processes. After completing three levels of review—local, regional, and national—the data are submitted to the national data management agency for final validation and approval before being authorized for use.

2.2.4 Aquaculture distribution data

Aquaculture distribution data used in this study were obtained from sea area ownership records. These records include detailed information on the spatial distribution of aquaculture activities, licensing, and usage rights for designated marine areas. The data collection process adheres to national standards and guidelines to ensure consistency and reliability, forming a robust basis for assessing aquaculture's role in marine resource management.

2.2.5 Protected area data

Data on marine protected areas (MPAs) were obtained from official provincial reports, which document MPA designations, sizes, and management measures. Provincial natural resource authorities organize the designation and delineation of protected areas based on unified rules set by the National Forestry and Grassland Administration. Following expert evaluation and approval, the finalized information is submitted to the National Forestry and Grassland Administration for record-keeping. These records were used to assess spatial coverage and protection impacts.

2.2 Model calculate

The surplus production model of Schaefer (1954) was applied in this study to the per annum total catch in tons and standardized number of fishing units. This model considered the stock as one big unit of biomass.

The Schaefer model expresses the relationship between catch yield (Y) and fishing effort (E) using a quadratic function:

$$Y = a \times E - b \times E^2$$

Where:

Y: the catch yield.

E: the fishing effort.

a and b are model parameters that are determined by fitting the data.

Using the Least Squares Method to estimate the optimal values for a and b, which minimizes the sum of squared errors between the predicted and actual values. Once the parameters a and b are determined, MSY and the corresponding fishing effort (E_{msy}) can be calculated.

The fishing effort at E_{msy} occurs when the yield is maximized. This can be found by taking the derivative of the Schaefer model with respect to E and setting it to zero:

$$\frac{dY}{dE} = a - 2bE = 0$$

$$E_{msy} = \frac{a}{2b}$$

MSY is then obtained by substituting E_{msy} back into the original equation:

$$MSY = a \times E_{msy} - b \times E_{msy}^2 = \frac{a^2}{4b}$$

The catch per unit effort (CPUE) was used to analyze fishery productivity, and together with MSY and E_{msy}, it provides a comprehensive understanding of the relationship between fishing effort, catch, and stock biomass.

The carrying capacity of marine fishery resources is represented by the ratio of the annual CPUE to the catch per unit effort corresponding to MSY. The formula is as follows:

$$B = \frac{CPUE}{MSY/E_{msy}}$$

Where:

B: carrying capacity of marine fishery resources.

According to the evaluation results of marine fishery carrying capacity B, a classification assessment is conducted based on Table 2, following the principle of maintaining stability by reasonably controlling offshore fishing intensity.

2.3 Correlation coefficients

Since temperature and nutrients are influenced by both human activities and natural processes, "environmental" and "anthropogenic" factors were distinguished in this study to distinguish between direct and indirect anthropogenic stressors. For environmental factors, SST, pH, cholorophyII a, DIN, PO_4^{3-}, DO and COD were included, which covered a range of physical and chemical indicators, as well as the pollution indicators that are important in a marine environment. For human activities aspect, mariculture and establishment of marine protected areas were selected.

To assess the relationship between fishery resource status and environmental factors, we employed the grey correlation analysis (Tosun, 2006). The fishery resource status was represented by CPUE, which provides a standardized measure of fishery resources accounting for fishing effort. Environmental factors, including sea surface temperature, salinity, dissolved oxygen, and nutrient levels, were used as independent variables. Data were log-transformed where necessary to ensure normality. The steps is :

First, the original data were normalized by the mean method.

$$x_i(k) = \frac{x_i(k)}{\frac{1}{n}\sum_{k=1}^{n} x_i(k)}$$

where $x_i(k)$ and $xj(k)$ are normalized, and $x_i(k)$ and $Xj\ (k)$ are original.

Secondly, the correlation coefficient ε0i (k) was calculated as follows:

$$\varepsilon_{0i}(k) = \frac{\Delta_{min} + \rho\Delta_{max}}{\Delta_{0i}(k) + \rho\Delta_{max}}$$

where $\Delta_{0i}(k) = |x_0(k) - x_i(k)|$, $x_0(k)$ denotes the reference sesequence, and $x_i(k)$ denotes the comparability sequence. ρ is distinguishing or identification coefficient which is between 0 and 1 (taking 0.5). Δ_{min} is the minimum values of $\Delta_{0i}(k)$.

Finally, the grey correlation degree was calculated as the average value of the grey correlation coefficient, which was defined as follows:

$$r_i = \frac{1}{n}\sum_{k=1}^{n}\varepsilon_{0i}(k)$$

where r_i is the grey relational grade which represents the level of correlation between the reference sequence and the comparability sequence. If a particular comparability sequence is more important than the other comparability sequences to the reference sequence, then the grey correlation degree for that comparability sequence and reference sequence will be higher than others.

3 Results

3.1 Marine fishery catch yield

China's marine fishery catch exhibited a clear trend from 2013 to 2020, first increasing and then gradually decreasing (Figure 1). From 2013 to 2015, the catch yield grew steadily, reaching a peak of 13.14 million tons in 2015. And between 2015 and 2020, the catch volume declined steadily.

The marine fishery catch yield also exhibited considerable variability across different sea regions. Among the four major sea areas—namely the East China Sea, the South China Sea, the Bohai Sea, and the Yellow Sea—the East China Sea consistently contributed the largest share to the overall national catch. This region's relatively higher productivity can be attributed to a combination of favorable environmental factors, such as nutrient-rich waters, and its geographic proximity to key fishing grounds. The South China Sea, while also significant, contributed slightly less, followed by the Bohai Sea and Yellow Sea, which produced comparatively smaller portions of the total catch volume. These differences reflect not only regional ecological conditions but also varying levels of fishing effort and resource management strategies across these zones. The annual variation in catch volume within these regions generally aligned with the national trends. For instance, the peak in 2015 and subsequent decline between 2015

TABLE 2 The evaluation method of carrying capacity of marine fishing resources.

Evaluation Basis	Evaluation Results	Definitions
B≥1.2	sustainable capacity	resource use is sustainable and does not impose significant pressure on the ecosystem.
0.9≤B<1.2	overloaded	resource use leads to resource depletion risks and potential ecosystem imbalance
B<0.9	critically overloaded	resource use causes substantial resource depletion and long-term damage to the ecosystem.

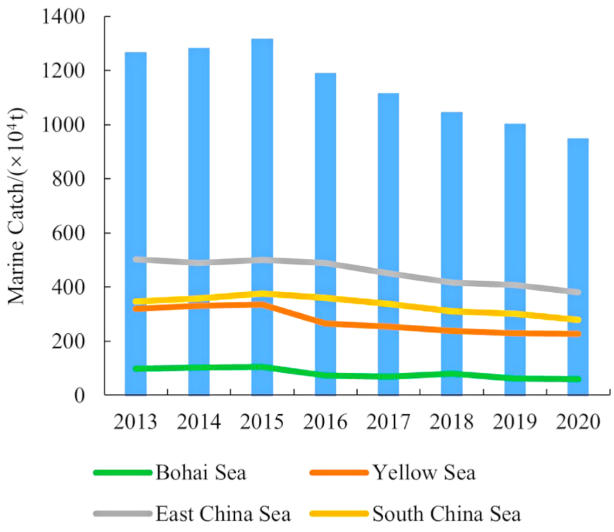

FIGURE 1
The annual variation trend chart of marine catch.

and 2020 were observed across all four sea areas. This consistency suggests that the factors influencing marine fishery catch volume—such as overfishing, environmental changes, and possible resource depletion—were not isolated to one region but were instead part of broader, nationwide trends affecting China's marine fisheries.

In terms of species composition, fish constituted the majority of the catch, representing approximately 68.48%, followed by crustaceans at 19.11% (Figure 2). The dominant fish species between 2013 and 2020 included *Trichiurus*, *Engraulis*, *Caranx*, *Scomberomorus*, *Pampus*, *Nemipterus*, *Muraenesox*, *Larimichthys*, *Collichthys*, *Sparus*, *Thamnaconus* and *Sphyraenus*, with *Trichiurus* and *Engraulis* being the most prevalent. Crustacean catches primarily consisted of *Portunus*, *Scylla*, *Paramamosain*, *Acetes*, *Penaeus*, *Trachypenaeus*, with *Portunus* and *Acetes* comprising the majority. Thus, *Trichiurus*, *Engraulis*, *Portunus* and *Acetes* emerged as the key species in China's marine fishery, with *Trichiurus* being the most dominant. The remaining catch was comprised of mollusks, algae, and cephalopods, all of which, though less dominant, still played an important role in the overall marine ecosystem and fisheries economy.

3.2 Marine fishing effort

The fishing effort in China's offshore waters was assessed based on the duration of fishing operations by vessels registered in China. The results indicated a fluctuating trend in fishing effort between 2013 and 2020, with an initial increase followed by a decline (Figure 3). From 2013 to 2018, the fishing effort showed a gradual upward trend, peaking at 9,650 hours in 2018. A slight decrease was observed between 2019 and 2020, though the overall effort remained higher than pre-2018 levels. Comparing these results with catch data from 2015 to 2020 revealed that, despite no significant reduction in fishing effort, the total catch gradually declined. This may indicate that overfishing has led to a depletion of fishery resources.

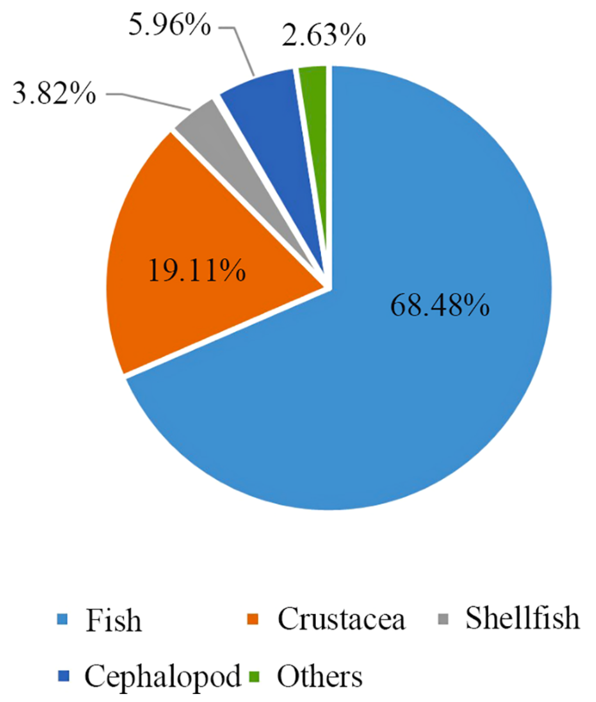

FIGURE 2
The species composition of fisheries catch in 2020.

Spatial analysis of fishing effort across the four major sea regions—Bohai Sea, Yellow Sea, East China Sea, and South China Sea—revealed significant regional variation. The Bohai Sea exhibited the lowest fishing effort, likely due to its smaller geographic area and possibly lower fishery productivity. The East China Sea, known for its historically high levels of fishing activity, showed a fluctuating downward trend in effort. The Yellow Sea and South China Sea exhibited a pattern of rising fishing effort followed by a decrease, mirroring the national trend. These regions may have benefited from the initial expansion in fishing capacity but are now experiencing the consequences of sustained pressure on fishery resources. The synchronization of these trends with the national

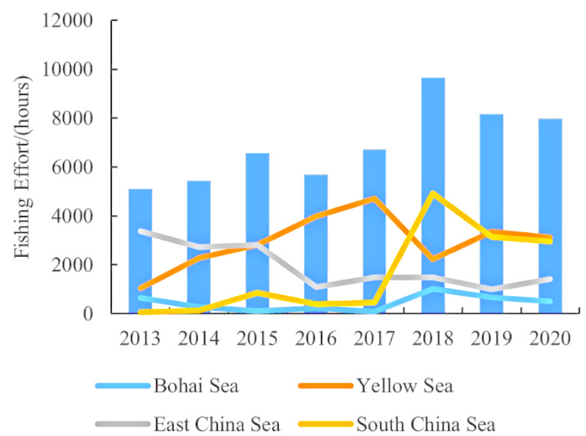

FIGURE 3
The annual variation trend of fishing effort.

pattern suggests that broader economic and regulatory factors, such as fishing subsidies, technological advancements, or nationwide policy interventions, may be influencing fishing behavior across regions.

3.3 The MSY for marine fishery resources

MSY and $E_{ms\gamma}$ values were computed for each study region using the Schaefer surplus production model. Table 3 presents a detailed summary of the computed values for each region, showcasing the potential yield of marine fishery resources under optimal fishing efforts.

The results indicate that the overall MSY for Chinese marine fishery resources was 12,165,299.60 tons, achieved at an effort of 6,328.88 hours. Upon further analysis, it was observed that the MSY and $E_{ms\gamma}$ values differed significantly across the four major seas of China, reflecting the variability in marine productivity and fishing pressure in each region. In the Bohai Sea, the MSY was calculated at 1,017,054.40 tons, with a corresponding $E_{ms\gamma}$ of 603.89 hours. This relatively smaller effort suggests that the Bohai Sea has a lower productivity compared to other regions, likely due to its limited water exchange and greater influence of anthropogenic activities. For the Yellow Sea, the MSY was 3,038,229.16 tons, with an $E_{ms\gamma}$ of 2,968.01 hours. This sea, with a larger surface area and significant water exchange compared to the Bohai Sea, can sustain higher fishing efforts, reflecting a relatively higher productivity. In the East China Sea, the MSY reached 5,389,914.82 tons, at an $E_{ms\gamma}$ of 2,422.17 hours. The East China Sea, benefiting from both the Kuroshio current and continental runoff, presents high biological productivity, contributing to its high MSY. However, the increasing fishing intensity in this region requires careful management to avoid overexploitation. Lastly, the MSY in the South China Sea was 4,407,318.90 tons, with a corresponding $E_{ms\gamma}$ of 2,841.84 hours. This region, characterized by its deep waters and diverse marine ecosystems, holds considerable fishery potential, yet its relatively large fishing effort indicates a need for stricter controls to maintain sustainability.

TABLE 3 MSY calculation results for each region.

	Items	Result
Bohai Sea	Schaefer Model	a = 3368.36 b = 2.79
	MSY	1017054.40
	$E_{ms\gamma}$	603.89
Yellow Sea	Schaefer Model	a = 2047.32 b = 0.345
	MSY	3038229.16
	$E_{ms\gamma}$	2968.01
East China Sea	Schaefer Model	a = 4450.49 b = 0.92
	MSY	5389914.82
	$E_{ms\gamma}$	2422.17
South China Sea	Schaefer Model	a = 3101.73 b = 0.55
	MSY	4407318.90
	$E_{ms\gamma}$	2841.84
China Sea	Schaefer Model	a = 3844.38 b = 0.304
	MSY	12165299.60
	$E_{ms\gamma}$	6328.88

3.4 Carrying capacity of marine fishery resources

Between 2013 and 2016, the overall fishery resources in China's seas remained within sustainable limits, as indicated by CPUE/(MSY/$E_{ms\gamma}$) ratios consistently above 1, which suggest that despite total catch volumes approaching or slightly exceeding MSY, the ecosystems' carrying capacities were largely intact. However, beginning in 2017, a marked decline in the CPUE/(MSY/$E_{ms\gamma}$) ratio was observed, dropping below 1, indicating a shift toward overexploitation. By 2018, the ratio had fallen to unsustainable levels, further corroborating the negative impact of increased fishing pressure on the ecosystems' ability to regenerate (Table 4).

In the Bohai Sea, the CPUE/(MSY/$E_{ms\gamma}$) ratio was 0.90 in 2013, reflecting a state of critical overexploitation, where the fishing effort slightly exceeded the ecosystem's sustainable limits. However, significant improvements were observed in 2014 and 2015, with CPUE/(MSY/$E_{ms\gamma}$) ratios rising sharply to 2.29 and 5.66, respectively, while fishing time reduced significantly. These changes suggest that resource use was highly efficient during these years. Nevertheless, by 2018, the CPUE/(MSY/$E_{ms\gamma}$) ratio had dramatically declined to 0.46, coupled with a fishing effort that surpassed sustainable thresholds. This indicates a return to overexploitation and significant stress on the Bohai Sea's fishery resources (Table 5).

From 2013 to 2015, the Yellow Sea's fishery remained within sustainable limits, with CPUE/(MSY/$E_{ms\gamma}$) ratios consistently above 1. However, starting in 2016, the carrying capacity declined significantly, with the CPUE/(MSY/$E_{ms\gamma}$) ratio dropping from 1.34 to 0.66 by 2017. This rapid decline suggests that increased fishing pressure during this period outpaced the region's resource replenishment capacity. Despite a reduction in fishing effort in 2018, the CPUE saw only a modest recovery, indicating that the region's fishery resources had not yet fully returned to sustainable levels (Table 6).

The East China Sea showed signs of overexploitation between 2013 and 2015, with CPUE/(MSY/$E_{ms\gamma}$) ratios below 1. However, a notable recovery occurred in 2016, when the ratio surged to over 2.0, and fishing effort significantly decreased. This marked a transition toward more sustainable resource management, with the CPUE/(MSY/$E_{ms\gamma}$) ratio remaining above 1 in the following years. By 2020, the ratio stood at 1.21, indicating that the East China Sea had largely recovered from its previous overexploitation and was operating within sustainable limits (Table 7).

From 2013 to 2017, the South China Sea maintained relatively high CPUE/(MSY/$E_{ms\gamma}$) ratios, indicating that fishing activities

TABLE 4 The assessment results of carrying capacity of marine fishing resources in China.

Year	Catch yield (tone)	Fishing effort (h)	CPUE	B	Assessment results
2013	12643822	5107	2475.782651	1.28800209	Sustainable Capacity
2014	12808371	5425	2360.990046	1.228282342	Sustainable Capacity
2015	13147811	6576	1999.362987	1.040149346	Critically Overloaded
2016	11872029	5688	2087.206224	1.085848944	Critically Overloaded
2017	11124203	6719	1655.633725	0.861327507	Overloaded
2018	10444647	9650	1082.346839	0.563080523	Overloaded
2019	10001515	8157	1226.12664	0.63788058	Overloaded
2020	9474104	7977	1187.677573	0.617877823	Overloaded

TABLE 5 The assessment results of carrying capacity of marine fishing resources in the Bohai Sea.

Year	Catch yield (tone)	Fishing effort (h)	CPUE	B	Assessment results
2013	975257	643	1516.729393	0.900578881	Critically Overloaded
2014	1023741	265	3863.173585	2.293812304	Sustainable Capacity
2015	1039627	109	9537.862385	5.663236613	Sustainable Capacity
2016	735124	219	3356.730594	1.993104831	Sustainable Capacity
2017	698002	84	8309.547619	4.933907873	Sustainable Capacity
2018	790300	1010	782.4752475	0.464605411	Overloaded
2019	629572	675	932.6992593	0.553802978	Overloaded
2020	602415	494	1219.463563	0.724073217	Overloaded

TABLE 6 The assessment results of carrying capacity of marine fishing resources in the Yellow Sea.

Year	Catch yield (tone)	Fishing effort (h)	CPUE	B	Assessment results
2013	3185005	1033	3083.257502	3.011997653	Sustainable Capacity
2014	3315958	2285	1451.18512	1.417645517	Sustainable Capacity
2015	3350841	2805	1194.595722	1.16698638	Sustainable Capacity
2016	2656281	3989	665.9014791	0.65051125	Overloaded
2017	2529459	4698	538.4118774	0.525968172	Overloaded
2018	2385959	2243	1063.735622	1.039150702	Critically Overloaded
2019	2292305	3347	684.8834777	0.669054539	Overloaded
2020	2268382	3111	729.1488267	0.712296833	Overloaded

remained sustainable. However, 2018 marked a drastic shift, with the CPUE/(MSY/E_{msy}) ratio plummeting to 0.40, and fishing effort exceeding 173% of the E_{msy}. This sharp decline reflects severe overexploitation, with fish stocks being depleted at unsustainable rates. Although fishing effort was slightly reduced in 2019 and 2020, the CPUE remained low, around 0.60, indicating that the South China Sea's resources had not yet recovered from the prior overexploitation (Table 8).

3.5 Factors influencing the sustainability of marine fishery resources

The grey relational analysis results (Figure 4) reveal the degree of association between environmental factors and CPUE across the Bohai Sea, Yellow Sea, East China Sea, and South China Sea. The following findings illustrate the key factors influencing the fishery resource carrying capacity in each sea area.

TABLE 7 The assessment results of carrying capacity of marine fishing resources in the East China Sea.

Year	Catch yield (tone)	Fishing effort (h)	CPUE	B	Assessment results
2013	5022719	3376	1487.772216	0.668588901	Overloaded
2014	4898709	2733	1792.429199	0.805498487	Overloaded
2015	4999644	2812	1777.967283	0.798999457	Overloaded
2016	4883270	1086	4496.565378	2.020708327	Sustainable Capacity
2017	4513623	1474	3062.15943	1.376101656	Sustainable Capacity
2018	4172797	1475	2829.014915	1.271329007	Sustainable Capacity
2019	4075847	998	4084.01503	1.835312619	Sustainable Capacity
2020	3808428	1410	2701.012766	1.213806212	Sustainable Capacity

TABLE 8 The assessment results of carrying capacity of marine fishing resources in the South China Sea.

Year	Catch yield (tone)	Fishing effort (h)	CPUE	B	Assessment results
2013	3460841	55	62924.38182	40.57365244	Sustainable Capacity
2014	3569963	142	25140.58451	16.2106533	Sustainable Capacity
2015	3757699	850	4420.822353	2.850547029	Sustainable Capacity
2016	3597354	394	9130.340102	5.887244899	Sustainable Capacity
2017	3383119	463	7306.952484	4.711524244	Sustainable Capacity
2018	3095591	4922	628.9295002	0.405533852	Overloaded
2019	3003791	3137	957.5361811	0.617419498	Overloaded
2020	2794879	2962	943.5783255	0.60841947	Overloaded

In the Bohai Sea, most environmental factors exhibit moderate to high correlations with the CPUE, with values generally exceeding 0.6. The highest correlations are observed with PO_4^{3-} (0.64), COD (0.64), and area of protected areas (0.63), suggesting that nutrient levels (PO_4^{3-}) and COD, a proxy for water pollution, significantly impact fishery resource sustainability. Additionally, the influence of protected areas highlights the importance of marine spatial management in maintaining fishery resources in this region.

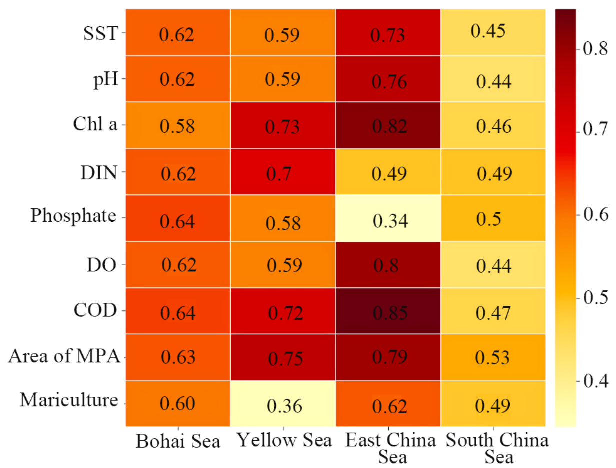

FIGURE 4
The correlation analysis between environmental, anthropogenic factors, and CPUE.

In the Yellow Sea, Chl a (0.73), COD (0.72), DIN (0.70), and area of protected areas (0.75) exhibit the strongest correlations with CPUE. This indicates that nutrient availability (Chl a, DIN) and water quality (COD) are key drivers of the fishery resource carrying capacity. The high correlation with protected areas suggests that expanding and optimizing marine protected zones could contribute positively to the sustainable management of fishery resources in this sea.

The East China Sea shows notably high correlation values for DO (0.80), COD (0.85), and area of protected areas (0.79), indicating that DO and COD are critical factors affecting the fishery resource carrying capacity. These factors suggest that water quality, particularly regarding oxygen levels and organic pollution, plays a significant role in sustaining the fishery resources in this region. Additionally, protected areas are shown to have a substantial influence on resource maintenance.

The correlations between environmental factors and CPUE in the South China Sea are generally lower compared to other regions, with the highest correlations seen for PO_4^{3-} (0.50), DIN (0.49), and area of protected areas (0.53). While these factors have moderate correlations, it is evident that nutrient levels (PO_4^{3-}, DIN) and protected areas still play an essential role in influencing the fishery resource carrying capacity, although the effects are less pronounced compared to other sea regions.

4 Discussion

4.1 The status and trends of fishery resource capacity

During the study period (2013–2020), China's marine fishery resources were predominantly within sustainable limits prior to 2017. However, after 2017, a clear shift toward overexploitation was observed, with declining CPUE/(MSY/E_{msy}) ratios across all sea regions. The transition to overexploitation after 2017 aligns with studies highlighting the escalating fishing pressures and environmental degradation in China's seas (Liu, 2019; Sun et al., 2023). This overall pattern is consistent with global fisheries, where overfishing and poor management policies often result in a rapid decline in resource availability (Andersen et al., 2024; Kang, 2006; Ritchie and Roser, 2023). While the overall trend is clear, the conditions in each sea area differ considerably.

The fisheries carrying capacity in the Bohai Sea is relatively low, primarily due to its semi-enclosed geography and limited water exchange capacity, which result in the accumulation of nutrients and pollutants within the water column (Zou et al., 2024). Key factors affecting the resource status in this region include PO_4^{3-} and COD, with correlation coefficients of 0.64. Phosphate serves as a limiting nutrient in the Bohai Sea, where increased concentrations enhance phytoplankton productivity, thereby improving fishery resource conditions. Previous studies have shown that phosphate levels in the confined environment of the Bohai Sea directly impact marine primary productivity (Xu et al., 2010; Zhang et al., 2023). Additionally, rising COD levels, associated with organic pollutant accumulation, exacerbate hypoxia, further stressing fishery resources (Zhao et al., 2011).

In contrast, the Yellow Sea exhibits a relatively high resource carrying capacity. Although coastal development in the Yellow Sea is intensive, its open connection with larger bodies of water facilitates strong water exchange, which provides stable nutrient input to support fishery productivity (Yang et al., 2022). Despite this higher carrying capacity, the Yellow Sea's fishery resources remain overexploited. Chl a, COD, DIN, and protected area coverage show high correlations with CPUE, with protected area size being the most critical factor. This finding underscores the role of protected areas in mitigating fishing pressure and promoting resource recovery. Furthermore, fluctuations in DIN directly affect phytoplankton growth, with both excess and deficiency disrupting ecological balance, destabilizing food supply chains for fish populations, and impacting the sustainable productivity of fishery resources (Zhang et al., 2019; Jin et al., 2021).

The East China Sea has a high resource carrying capacity, largely due to favorable water exchange conditions and abundant nutrient inputs. The interaction between the Kuroshio Current and river runoff provides substantial nutrients and oxygen, supporting high fishery productivity (Wang et al., 2020; Luo et al., 2023). The resource status in the East China Sea is generally sustainable, with DO, Chl-a, and COD identified as key influencing factors. However, eutrophication and hypoxia have been found to limit the recovery of fishery resources in certain areas (Chang et al., 2012; Xu et al., 2024).

The South China Sea also demonstrates a relatively high carrying capacity for fishery resources, aided by its deep-water environment and diverse ecosystems that offer favorable habitats. Sufficient nutrient supply and effective water circulation naturally support fishery productivity. Despite this, fishery resources in the South China Sea face overexploitation, with PO_4^{3-} levels and protected area coverage being pivotal factors (Zhang, 2024). Given the relatively low nutrient concentrations in the South China Sea, increased phosphate can directly stimulate phytoplankton productivity, supporting the recovery of fishery resources (Yi et al., 2014; Song et al., 2019). While existing protected areas have shown some effectiveness in alleviating fishing pressure, incomplete management and enforcement limit their ability to control overfishing in certain areas (Teh et al., 2017).

4.2 Implications for future fisheries management

4.2.1 Diversify fisheries management measures

Given the diversity of marine environments in China, a more diversified set of management measures is necessary. Different regions face distinct challenges: the Bohai Sea suffers from severe pollution and habitat degradation, while the South China Sea is subject to intense fishing pressure. Research recommends implementing Total Allowable Catch systems tailored to the specific conditions of each region. Pilot projects in areas like Maoming have shown that the introduction of catch quotas and Total Allowable Catch systems has successfully improved sustainability by reducing overfishing and optimizing resource allocation (Lyu et al., 2022). Expanding these programs to include economically significant species in China's marine fisheries can strengthen population management and reduce resource depletion (Zhu et al., 2021). Furthermore, refining Total Allowable Catch programs can balance ecological sustainability with social equity, especially in regions with severe overfishing (Ding et al., 2022).

4.2.2 Strengthen and tailor fishing bans

Tailoring the duration and timing of fishing bans to the biological characteristics of local species and the carrying capacity of fishery resources is essential for maximizing the effectiveness of these bans. For instance, Yan and Lu (2020) argue that implementing an earlier fishing ban in the South Yellow Sea would significantly enhance the protection of spawning cycles, based on their analysis of local fish population dynamics and the critical timing of spawning events. Studies have shown that region-specific management strategies have successfully reduced overfishing in other contexts as well (Zhao and Jia, 2020). This approach can further promote the recovery of fish populations across various marine regions (Chen et al., 2020).

4.2.3 Expand Marine Protected Areas (MPAs) and restore habitats

Expanding Marine Protected Areas (MPAs) is crucial for the recovery and sustainability of fishery resources, particularly in overfished regions (McDonald et al., 2024). MPAs allow fish populations to regenerate by restricting fishing activities, and studies have shown that this leads to increased abundance, size, and diversity of species within the protected zones. Additionally, spillover effects from MPAs, where fish migrate to adjacent areas, help boost catches in nearby fisheries, benefiting both conservation and economic goals (Kerwath et al., 2013). MPAs also protect breeding grounds and promote biodiversity, leading to higher resilience and growth rates in fish populations (Marshall et al., 2019; Franceschini et al., 2024). Combining MPA expansion with habitat restoration efforts, such as the creation of artificial reefs, further enhances fishery recovery, as seen in Daya Bay where artificial reefs increased species diversity and biomass (Yu et al., 2015). This integrated approach ensures both ecological and economic benefits, promoting long-term sustainability of fishery resources.

4.3 Limitations and future research directions

One limitation of this study is the reliance on relatively coarse estimates of marine fishery resources from the "China Fisheries Statistical Yearbook", which may not fully capture the spatial and temporal variations in fishery dynamics. To address this, we utilized data from Global Fishing Watch to represent fishing effort more accurately. This dataset provides more granular and comprehensive information on fishing activity, allowing for a better understanding of regional and global patterns in fishing pressure. However, integrating such global datasets with local data sources could further improve the accuracy of fishery resource assessments.

Another limitation of this study is the absence of data from 2021 to 2023. The COVID-19 pandemic disrupted global fishing operations, data collection, and reporting, leading to gaps and inconsistencies in the available records. Additionally, the fishing effort data used in this study is sourced from Global Fishing Watch, which requires substantial time for processing, integration, and validation to ensure high reliability. As a result, the most recent validated dataset extends only to 2020. While the data from 2013 to 2020 provide a robust baseline for analysis, future studies incorporating post-2020 data would further validate and refine the findings presented here.

Additionally, this study uses CPUE as the primary indicator of fishery health. While CPUE is widely used to reflect the abundance and availability of fish stocks, it does have limitations, such as being influenced by changes in fishing technology or effort rather than actual stock health. Future studies could incorporate more direct biological indicators, such as spawning biomass and recruitment rates, to provide a more holistic view of fishery sustainability and resource dynamics.

5 Conclusion

Based on the findings of this study, several key conclusions can be drawn. Between 2013 and 2020, China's marine fishery resources underwent notable changes, with catch yields showing an initial increase followed by a gradual decline. There were clear regional differences in fishery yields across major sea areas, with the East China Sea consistently contributing the largest share to total catch. Additionally, the composition of species in the catch highlights the biodiversity of China's coastal fisheries, with species such as *Trichiurus* and *Engraulis* playing a significant role.

Fishing effort trends varied across regions, with the East China Sea showing fluctuating and slightly decreasing fishing intensity, while the South China Sea and Yellow Sea initially increased, followed by a gradual decline. The Bohai Sea, however, maintained consistently low fishing effort. These differences illustrate diverse fishing strategies and resource pressures across regions.

Regarding resource carrying capacity, there were significant differences in MSY among the sea regions. The East China Sea had the highest MSY, supported by the nutrient influx from the Kuroshio Current and land runoff, resulting in higher biological productivity. The South China Sea followed, benefiting from a rich marine ecosystem. The Yellow Sea's MSY was also substantial due to frequent water exchange, while the Bohai Sea's MSY was relatively low due to geographical constraints and anthropogenic impacts. These variations underscore the need for tailored management strategies that align with each region's ecological conditions and resource management requirements. Notably, only the East China Sea remains within sustainable limits, whereas the South China Sea, Yellow Sea, and Bohai Sea have surpassed their ecological carrying capacities, indicating evident overexploitation. Enhanced management in these regions is essential to mitigate the ecological pressures of overfishing.

The results of the grey relational analysis further indicate that factors influencing resource sustainability vary across regions. Nutrient levels and water quality (e.g., chemical oxygen demand) are critical determinants of fishery sustainability, while the distribution and management of protected areas significantly contribute to resource stability.

Data availability statement

The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding author.

Author contributions

ZL: Conceptualization, Methodology, Project administration, Writing – review & editing. WL: Methodology, Supervision, Validation, Writing – review & editing. TW: Data curation, Formal analysis, Funding acquisition, Methodology, Writing – original draft. YZ: Methodology, Writing – original draft. LH: Methodology, Writing – original draft. LY: Conceptualization, Methodology, Software, Writing – original draft. LD: Methodology, Resources, Writing – original draft.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This work was supported by 2024 National Statistical Science Fund of China (2024LZ024).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

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