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Impact of the fishing ban on fish diversity and population structure in the middle reaches of the Yangtze River, China

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The Yangtze River has experienced severe ecological degradation due to intensive human activities, including dam construction, land reclamation, and overfishing. These disturbances have disrupted the natural habitats of the Yangtze River, leading to a sharp decline in fish biodiversity and fishery resources. To address this ecological crisis, the Chinese government implemented a 10-year fishing ban in January 2021 to mitigate pressures on fish populations, restore aquatic habitats, and promote biodiversity recovery. The middle reaches of the Yangtze River are characterized by diverse fish species and a critical habitat for aquatic life, this study seeks to assess the effects of the fishing ban on fish diversity, body structure, population and community dynamics in this region. Fish monitoring data collected from 2017–2019 (pre-ban) and 2021–2023 (post-ban) were analyzed to evaluate changes in fish body size, species diversity, and community structure. The analysis results using the PSD method indicate that fish body size has increased following the fishing ban, suggesting the improvement of population structures, and a change in the complexity of food web structure. Species diversity indices showed partial recovery, but the recovery was uneven across different sampling sites. While fish populations showed signs of improvement, particularly in terms of body size and community stability, species diversity remained at relatively low levels in some areas, indicating that full recovery in biodiversity and resource levels may require extended conservation efforts. These findings suggest that while the fishing ban has had a positive initial impact on fish populations and ecological conditions, continued and long-term conservation measures are essential for fully recovering the river's biodiversity and restoring its fishery resources. The study also highlights the importance of monitoring fish species diversity, body structure, and community dynamics as part of ongoing efforts to evaluate the effectiveness of the fishing ban and refine resource management strategies for the middle reaches of the Yangtze River.

KEYWORDS

fish diversity, body length, food web, fishing ban, Yangtze River

1 Introduction

The Yangtze River, the third-largest river in the world, has undergone significant ecological changes over the last 50 years due to intensive human activities such as dam construction, land reclamation, overfishing, and bustling shipping (Chen et al., 2024; Liu et al., 2019). These activities have profoundly disrupted the river's biogeographic patterns and severely threatened its hydrobiology biodiversity (Feng et al., 2023; Höckendorff et al., 2017). The most notable consequence of this degradation was the functional extinction of the Chinese River Dolphin (*Lipotes vexillifer*) in 2017, and a significant decline in the population of the Yangtze finless porpoise (*Neophocaena asiaeorientalis)* (Wang et al., 2020; Zhang et al., 2020a). A survey from 2017 to 2021 recorded only 323 fish species in the Yangtze River basin, of which 35% are listed in the International Union for Conservation of Nature (IUCN) Red List, highlighting the critical extinction risks faced by freshwater species (IUCN, 2017; Yang et al., 2023). Compared to 1960, fishery resources in the Yangtze have decreased by 85% (Wang H. et al., 2022).

In response to this ecological crisis, the Chinese government initiated a 10-year fishing ban in January 2021, covering the mainstream, seven tributaries, and several connected lakes, including Dongting and Poyang lakes (Wang R. L. et al., 2022). Preliminary results following the implementation of the fishing ban indicate positive changes in the ecological conditions of the Yangtze River (Lei et al., 2023). Notably, the population of the Yangtze finless porpoise increased from 1,012 individuals in 2017 to 1,249 individuals in 2022 (Lei et al., 2023). This species tends to inhabit areas with high fish diversity (Wang et al., 2024), indicating the potential recovery of fish species diversity in the Yangtze River basin. In Poyang Lake, 93 fish species have been recorded after the fishing ban, with a noticeable increase in the resources of the four major Chinese carp species (Zhang et al., 2024). In the Chishui River, 11 endemic fish species have reappeared, further demonstrating the initial effectiveness of the 10-year fishing ban (Liu et al., 2023).

The Yangtze River is China's most important freshwater fishery resource area, typically divided into three regions—the upper, middle, and lower reaches—based on river characteristics and topography (Fang et al., 2023; Liu et al., 2019). The length of the middle reaches of the Yangtze River is about 955 km from Yichang (Hubei province) to Hukou (Jiangxi province), with a drainage area of 680,000 km^2 (Liu and Cao, 1992). The combination of meandering river courses, slow-flowing waters, and extensive lake-river networks in this region creates favorable hydrological conditions and abundant forage, which serve as critical feeding, wintering, and spawning grounds for a wide variety of aquatic species (Fang et al., 2023). Previous studies have recorded 215 fish species in the middle reaches, including 42 endemic (Yu, 2005). The middle reaches of the Yangtze River are spawning grounds and habitats for many economic fishes, such as the four major Chinese carps and bream (*Parabramis pekinensis*), as well as important migration routes for migratory fishes. Fish species are vital indicators of the health of freshwater ecosystems, as they occupy a crucial role in assessing the biodiversity and ecological integrity of these ecosystems (Qian et al., 2023). Studies on other regions, such as the Chishui River and Liangzi Lake, suggest that while the fishing ban has not led to dramatic changes in species diversity, it has alleviated the trend of decreasing fish body sizes and improved community structure to some extent. However, the full recovery of fish diversity, community structure, and ecosystem functionality in the Yangtze River will require substantial time and effort (Feng et al., 2023; Liu et al., 2023). Despite the fishing ban being in effect for 3 years as of 2023, there is still a lack of comprehensive and long-term studies on its impacts on fish species diversity, body size, resource recovery, population and community structure in the mainstream of the Yangtze River.

This study aims to fill this gap by analyzing fish monitoring data from 3 years before (2017–2019) and 3 years following (2021–2023) the implementation of the fishing ban. The objectives are to assess changes in fish body size, species diversity, population and community structure, and to evaluate the actual effects of the fishing ban on the recovery of fish resources in the middle reaches of the Yangtze River. By examining these trends, this study will provide a reference for fish conservation and the restoration of fishery resources in the region, as well as a baseline for future evaluations of the fishing ban's effectiveness. Furthermore, the findings will offer scientific support for refining fishing regulations and improving resource management strategies. Based on prior research, we hypothesize that while the reduction in individual fish body size will be mitigated, the recovery of species diversity, which rapidly declined during overfishing, will be low and remain at low levels (Fang et al., 2023; Feng et al., 2023; Liu et al., 2023). Fish abundance and biomass, which sharply decreased during overfishing, are expected to rise rapidly post-ban before stabilizing. Additionally, community structure in habitat utilization is expected to become more homogeneous (Petsch, 2016; Van der Sleen and Albert, 2022; Villéger et al., 2011), with an increase in the dominance of midwater fish species and a reduction in species preferring other habitats, such as benthic organisms, the three dominant species (IRI>1000) after the fishing ban, *Hypophthalmichthys molitrix*, *Hypophthalmichthys nobilis* and *Xenocypris macrolepis,* all belong to the upper middle layer of fish (Supplementary Table S1).

2 Methods

2.1 Sampling location and sampling collection

The sampling sites for this study were selected based on their accessibility and the representativeness of habitat types. The selection was further guided by consultation with prior surveys and local ecological knowledge. Three geographical sites were chosen: Jingzhou-JZ (30.3° N, 112.2° E) with broad waters and relatively stable hydrological conditions, Jianli-JL (29.8° N, 112.9° E) with relatively good water quality and minimal human disturbance, and Huangshi-HS (30.2° N,115.0° E) with diverse distribution of river channels and high fluidity of water bodies, respectively (Figure 1). Sample collections were conducted in June and October over the period from 2017 to 2019 and from 2021 to 2022. It needs to be stated that data from 2020 was excluded from the analysis due to limited monitoring during the pandemic period. Local fishermen were employed to collect the fish samples by using different types of products since the study area's water depth exceeded 1 m. At each site, fishing was done with

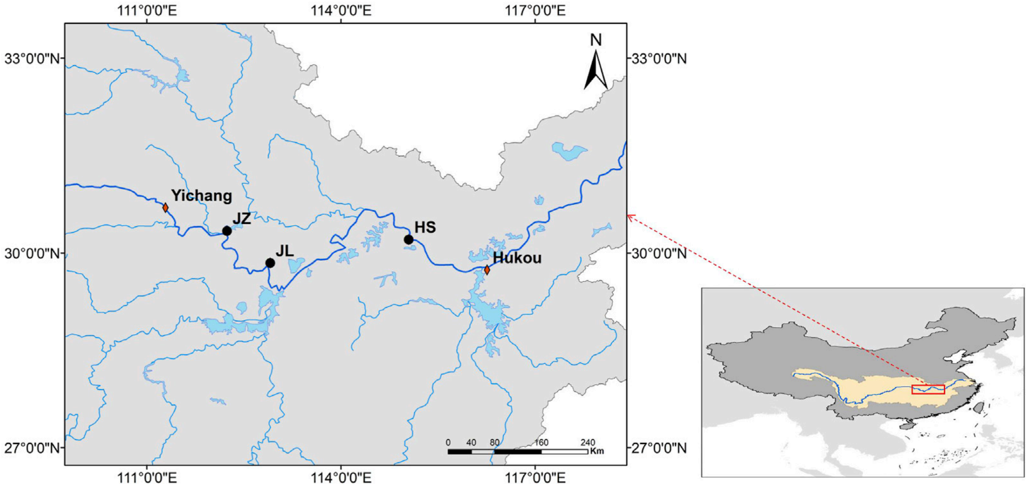

FIGURE 1
Distribution of sampling sites in the middle reaches of the Yangtze River, China.

fixed gill nets (mesh: height: length, 6 cm: 2 m: 100 m), drift nets (mesh: height: length, 2.5 cm: 2 m:230 m), ground cages (mesh: height: length, 1 cm: 0.4 m: 7 m). Ground cages were mainly placed in shallow water areas along the shore. Fishing was conducted daily for approximately 16 h from 4:00 p.m. to 8:00 a.m. Fish were identified when collected and released when practicable. Some fish samples that could not be identified were kept in formalin (5%–10%) and brought back to the laboratory for further identification. For biological measurements, fish body lengths were recorded accurately to 1 mm and body weights were measured accurately to 0.1 g.

2.2 Population body length analysis

Fish length data were statistically analyzed to determine the average length of species before the fishing ban (2017–2019) and during the post-ban period (2021–2023). A t-test was performed to analyze statistical differences, and results are presented as mean ± standard deviation (mean ± SD). Fish length categories were based on Gabelhouse's five-unit classification system, which includes Stock-Length (20% of the species' maximum recorded length), Quality Length (36%), Preferred Length (45%), Memorable Length (59%), and Trophy Length (74%). Proportional Size Distribution (PSD) was then calculated for each category, with PSD-Q representing the proportion of Quality Length, PSD-P for Preferred Length, PSD-M for Memorable Length, and PSD-T for Trophy Length (Gabelhouse, 1984). The formula follows: PSD = Proportion of individuals exceeding a specific body length/ Proportion of individuals exceeding a basic (Stock-Length) body length*100. In accordance with the regional growth conditions, standard length categories for species in the middle reaches of the Yangtze River were established using maximum recorded lengths from the Fishbase (Froese and Pauly, 2018). The maximum body length Linf was calculated by FiSAT II (version 12.2). The drawing was implemented by software of Originpro (version 2022b). The statistical significance of PSD values was determined using a t-test.

The representative 19 species of each site were selected through the index of relative importance (IRI) (Equation 1) in this study. IRI was based on the frequency of occurrence, number percentage and weight percentage, was used to determine the dominance of fish in each site (Pinkas et al., 1970).

$$IRI = (\%Ni + \%Wi) \times \%Fi \tag{1}$$

Where %Ni and %Wi are the proportion of species number and weight in the overall catch, respectively, and %Fi is the occurrence frequency. IRI values above 10% indicated that the species was dominant, while IRI values below 10% indicated that the species was common.

2.3 Species diversity and biomass analysis

Species diversity at a specific location during a defined temporal period is referred to as species diversity. In this study, fish species diversity at each sampling site was assessed based on spatial and temporal variations by using four established diversity indices: the Simpson dominance index, the Shannon-Wiener diversity index (H′), the Pielou evenness index (J′), and the Margalef richness index (D). Please refer to the relevant literature for detailed definitions and formulas about these indices (Magurran, 2013; Peet, 1974). Biomass was expressed as the catch per unit effort (CPUE), which was calculated by dividing the daily catch by the number of boats and the operating time (kg/boat*day) (Zhang et al., 2020b).

2.4 Food web inference

To investigate the structure of the fish food web, we constructed a meta-web using an adjacency matrix W, where the element $W_{ij} = 1$ indicates that species i can consume species j, and $W_{ij} = 0$ otherwise. This matrix was derived based on a niche model developed by (Gravel et al., 2013), which establishes a linear relationship between log body size and the centroid of the feeding niche. The linear model can be expressed as follows:

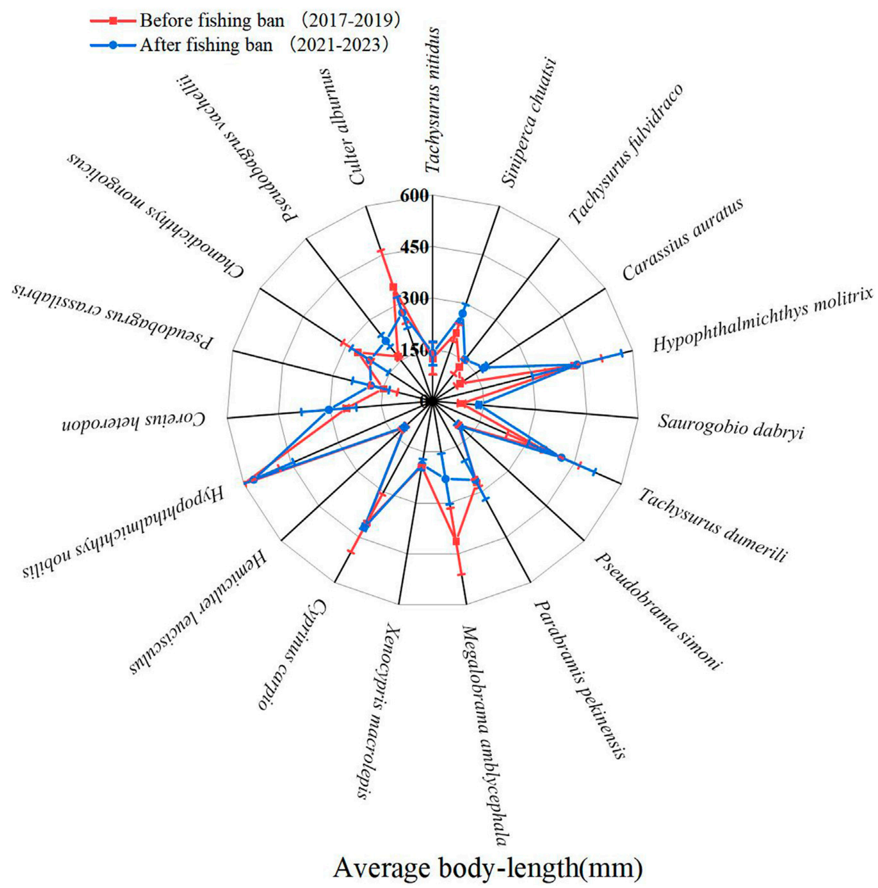

FIGURE 2
Changes in mean body length of 19 dominant fish species in the middle reaches of the Yangtze River before and after the fishing ban.

$$c = \log_{10}\left(M_{\text{prey}}\right) = \alpha_0 + \alpha_1 \times \log_{10}\left(M_{\text{pred}}\right) \quad (2)$$

Where M_{prey} and M_{pred} represent the body sizes of prey and predators, respectively. Coefficients for the model were obtained from literature values on predator-prey body size interactions (Albouy et al., 2019). Using these coefficients, niche parameters such as niche position n_i, feeding niche optimum c_i, and niche range r_i were inferred for each species. An interaction between species i and j was identified if the niche position n_j of species j falls within the interval (c_i-r_i/2, c_i + r_i/2). For each meta-web, corresponding to a particular site and year, 3 common food web metrics were computed: average clustering coefficient, average path length, and connectance.

Clustering coefficient (CC) reflects the degree of interconnectedness among nodes in the network; higher values indicate stronger local connectivity and potential network stability due to tighter relationships among neighboring nodes. Average path length (ChPath) is the mean shortest path between any two nodes in the network, with shorter values indicating higher information propagation efficiency within the network. Connectance describes the level of generalism in the network and is calculated as the ratio of actual links in the food web to the maximum possible links ($C = L/N^2$ (Equation 2), where L is the number of links and N is the number of nodes) (Danet et al., 2021). The topological network of the food web was visualized using Gephi 0.10.

2.5 Statistics

All data analyses were performed using standard statistical software (e.g., R or Origin). Differential analysis was conducted using t-tests and other appropriate statistical tests (using R package "stats" version 4.3.2). Results were considered statistically significant at a P-value of less than 0.05. The analysis also included normality tests and assumptions validation to ensure the robustness of the statistical models used. Traditional PSD calculation and its 95% confidence interval calculation were performed using R package FSA (Version 0.9.4) (Ogle, 2018).

3 Results

3.1 Changes in average body length

Before the fishing ban, the average body length of 19 dominant fish populations in the middle reaches of the Yangtze River ranged from 84.2 mm to 602.6 mm, with a median of 201.1 mm (Figure 2). After the fishing ban, the average body length of these populations ranged from 106.8 mm to 648.3 mm, with a median of 208.2 mm. Among them, the average body length of nine fish species remarkably increased by 2.4%–91.0% ($P < 0.05$). Conversely, five species

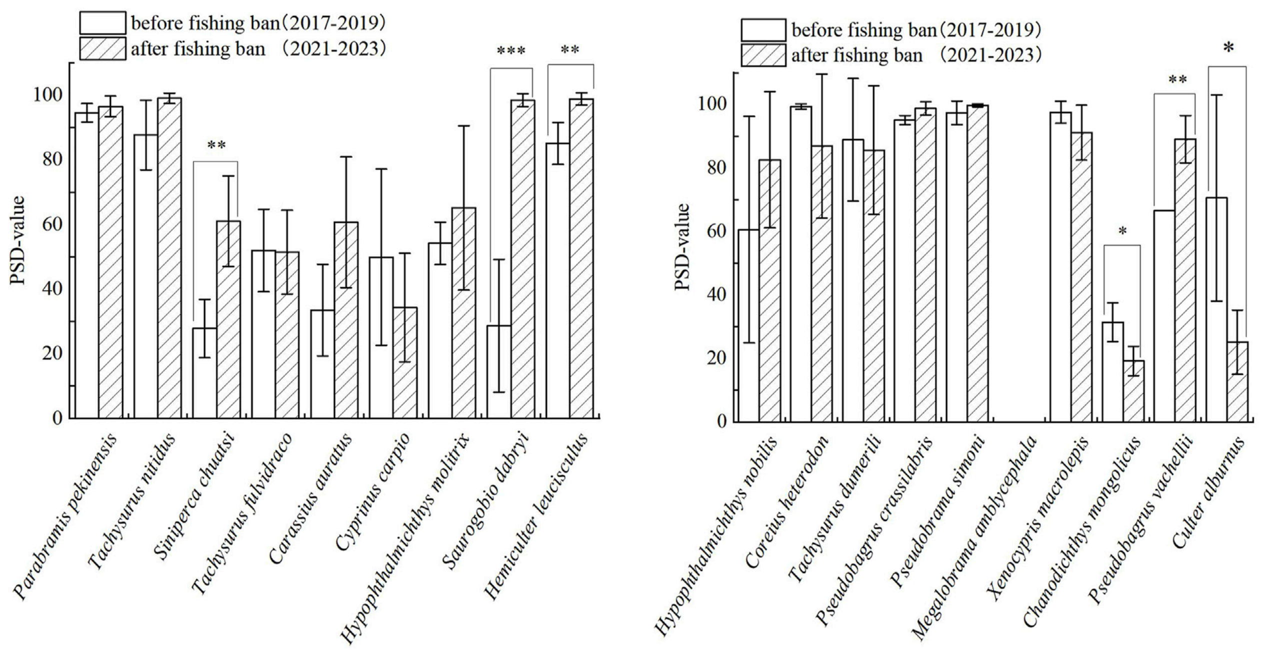

FIGURE 3
Changes in PSD of 19 dominant fish species in the middle reaches of the Yangtze River before and after the fishing ban.

exhibited no significant change in body length. In comparison, other five species—*P. pekinensis*, *Megalobrama amblycephala*, *X. macrolepis*, *Chanodichthys mongolicus*, and *Culter alburnus* showed significant decreases in body length ranging from 2.8% to 44.5% (P < 0.05).

3.2 Changes in PSD of 19 dominant fish species

The PSD values of these 19 dominant fish species exhibited marked changes before and after the fishing ban. Before the ban, PSD values ranged from 28 to 99, with a median of 73 and an average of 66. After the fishing ban, these values ranged from 34 to 100, with a median of 86 and an average of 76. Three species showed significant increases in their PSD values by 14–70 (P < 0.05). Four species exhibited an increase in PSD values, while three showed a decrease, though these changes were not statistically significant (P > 0.05). Additionally, six species did not show any significant changes in PSD values (Figure 3).

For three species with notable increases in PSD values, trends in the PSD-Q (Quality Length), PSD-P (Preferred Length), and PSD-T (Trophy Length) values were similar (Figure 4). As illustrated in Figure 4, these species exhibited increases in both PSD-Q and PSD-P values, ranging from 14 to 70 and 6 to 75, respectively. However, the PSD-M (Memorable Length) values of *Saurogobio dabryi* and *Hemiculter leucisculus* decreased by 11 and 8 respectively, while the PSD-M value of *Siniperca chuatsi* increased by 9. Futhermore, the PSD-T values of *S. dabryi* and *H. leucisculus* decreased by 1 and 7, respectively, while the PSD-T of *S. chuatsi* increased by 4.

3.3 Changes in species diversity and biomass

Regarding the diversity indices (Figure 5), the Margalef richness index of fish species at the three sampling sites ranged from 6.65 to 7.70 before the fishing ban (2017–2019), with a mean value of 7.14. After the fishing ban (2021–2023), this index ranged from 5.64 to 6.69, with a mean value of 6.25. The Pielou evenness index ranged from 0.55 to 0.74 before the ban (mean = 0.66) and from 0.58 to 0.71 after the ban (mean = 0.63). The Shannon-Wiener diversity index ranged from 2.23 to 3.14 before the ban (mean = 2.78), and from 2.00 to 3.14 after the ban (mean = 2.48). The Simpson dominance index ranged from 0.71 to 0.93 before the ban (mean = 0.85), and from 0.72 to 0.94 after the ban (mean = 0.81). Overall, the average values of these four diversity indices were higher before the fishing ban than post-ban. However, slight recoveries were observed in the Shannon-Wiener diversity index and Margalef richness index over the 3-year post-ban period. In contrast, the Pielou evenness index and Simpson dominance index showed no significant changes (P > 0.05).

Examining spatial heterogeneity across the three sampling sites, the diversity indices for Huangshi (HS) showed significant improvements after the fishing ban. Before the ban, the Margalef richness index, Pielou evenness index, Shannon-Wiener diversity index, and Simpson dominance index at HS had mean values of 4.55, 0.48, 1.74, and 0.60, respectively. After the ban, these four diversity indices increased to 4.78, 0.80, 2.69 and 0.90, respectively. For Jianli (JL) and Jingzhou (JZ), however, the mean values of the diversity indices did not show a significant increase following the fishing ban (P > 0.05, Table 1). On the other hand, catch per unit effort (CPUE) significantly increased after the fishing ban across all sampling sites, with the JZ site showing the highest increase compared to JL and HS (P < 0.05, Table 1).

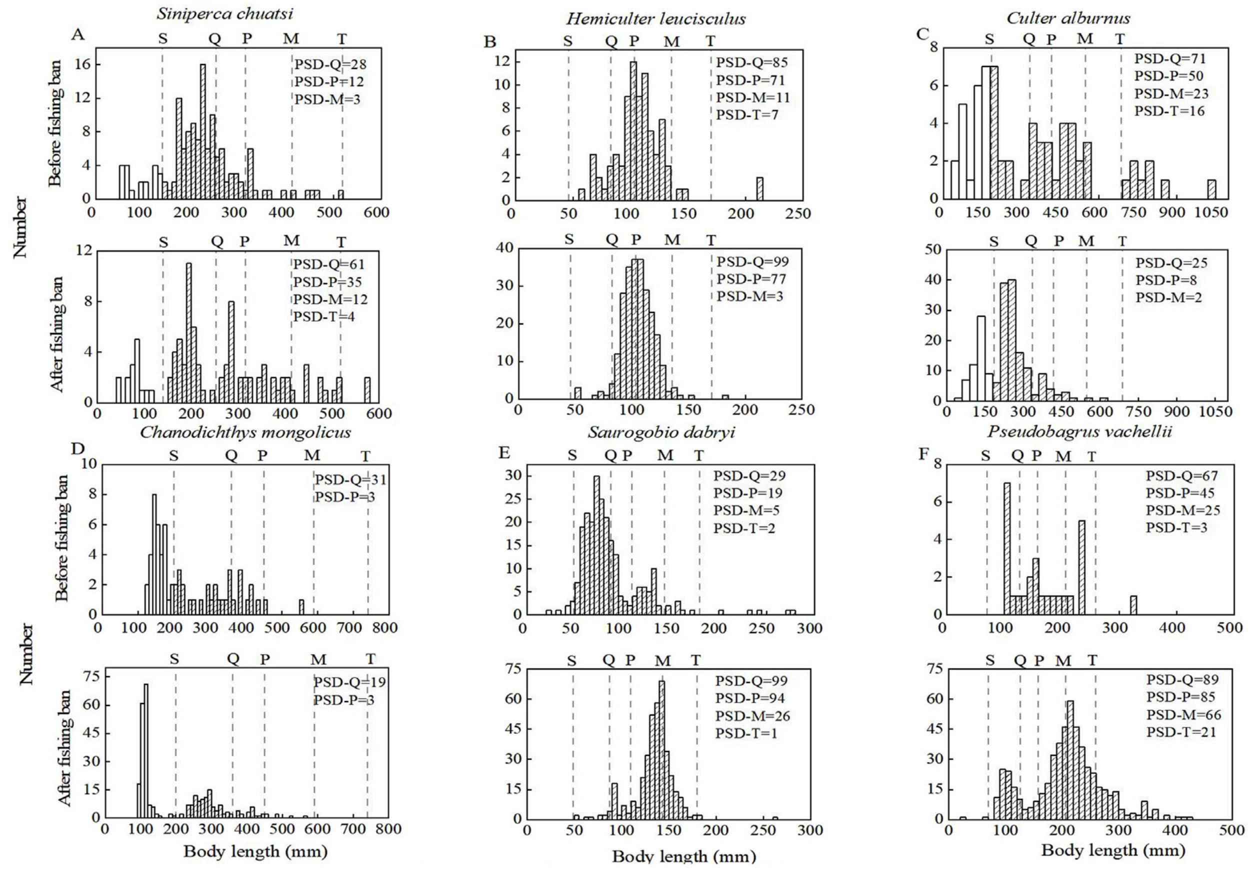

FIGURE 4
Changes in PSD of 6 dominant fish species **(A–F)** in the middle reaches of the Yangtze River before and after the fishing ban.

3.4 Changes in the food web

From Figure 6, we observed that all four indicators (nodes, connectance, CC, and ChPath) showed an increasing trend relative to the values in 2019 and 2021, which serve as key time points for assessing community recovery. Notably, the response pattern of node numbers exhibited a "delayed response" pattern (Figure 6A). In 2021, the number of nodes declined compared to 2019 before beginning a steady increase. Connectance, which represents the proportion of potential interactions within the food web, fluctuated only slightly over the study period, maintaining a consistent value of 0.12 between 2021 and 2023, consistent with the levels recorded from 2017 to 2019 (Figure 6B). However, the average clustering coefficient (CC) and average path length (ChPath) exhibited greater variability (Figures 6C, D). The topological network of 2017 has tighter local connections (high CC values) than in 2023. Notably, there was no substantial change in ChPath during the pre-ban period from 2017 to 2019, while CC steadily declined, indicating weakening connections between network nodes. In the early years of the fishing ban, CC followed an 'instant response' pattern in 2021, reflecting rapid changes in the food web structure, while ChPath showed a slight increase in 2023 compared to 2021. This suggests interactions among network nodes strengthened and the overall complexity of the network began to recover.

Across the three sampling sites, the connectance index exhibited a significant increase trend after the fishing ban (2021–2023) compared to pre-ban (2017–2019), with the JL sampling site recording the highest increase of 25% (Table 2). On the contrary, the other two indicators, ChPath and CC, showed varying degrees of decline following the fishing ban. Similarly, the JL monitoring point experienced the most significant decrease when compared to the other two locations, JL and HS sites. Regarding node indicator values, both JL and HS exhibited a downward trend post-fishing ban compared to the pre-ban period, apart from an increase at the JL station.

4 Discussion

4.1 The effect of the fishing ban on the body size and biomass

In fishery population assessments, body length structure is one of the most easily obtainable and commonly used indicators for understanding the status of fish populations (Phelps and Willis, 2013). Anderson's 5-unit body length proportional distribution (PSD) model has been widely adopted to quantitatively describe the distribution of individuals across various body length categories within a population (Anderson, 1976). By comparing PSD values at

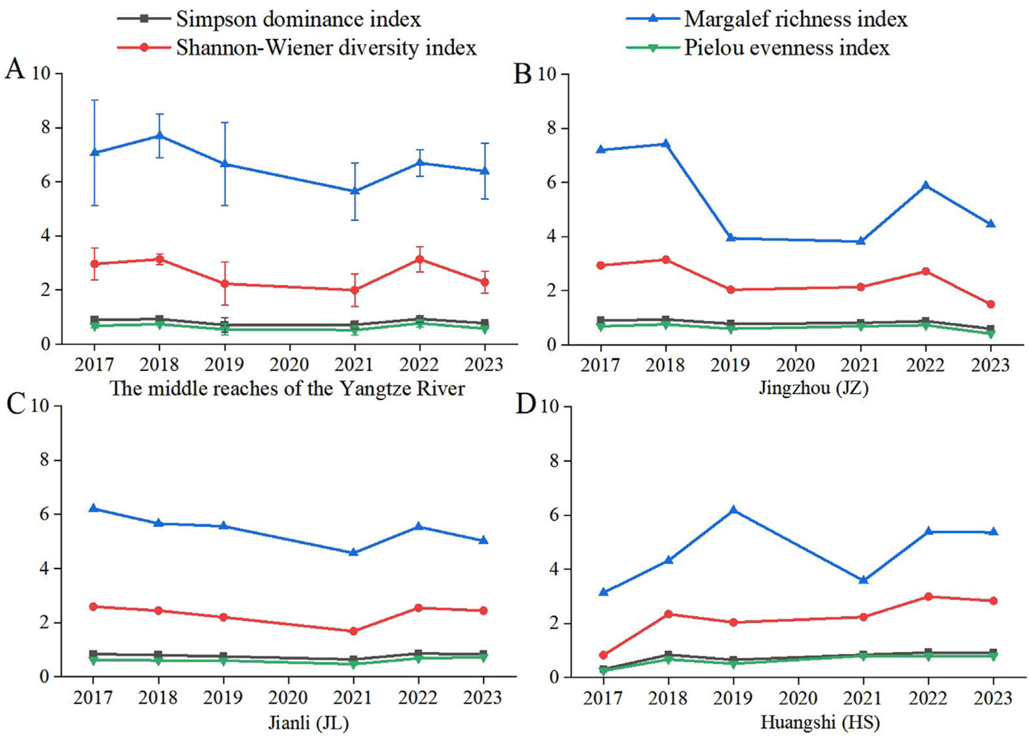

FIGURE 5
Changes in species diversity in the middle reaches of the Yangtze River **(A)** and three sampling sites [**(B–D)**, Jingzhou-JZ, Jianli-JL, Huangshi-HS] before and after the fishing ban.

TABLE 1 Spatial variation in diversity indexes and CPUE in the middle reaches of the Yangtze River.

Sites Index	Jingzhou (JZ)		Jianli (JL)		Huangshi (HS)		The middle reach of the Yangtze river (MYR)	
	Before fishing ban	After fishing ban	Before fishing ban	After fishing ban	Before fishing ban	After fishing ban	Before fishing ban	After fishing ban
Simpson	0.87 ± 0.08	0.77 ± 0.15	0.80 ± 0.05	0.78 ± 0.12	0.60 ± 0.27	0.90 ± 0.05	0.85 ± 0.12	0.81 ± 0.11
Shannon-Wiener	2.71 ± 0.59	2.12 ± 0.61	2.41 ± 0.2	2.23 ± 0.47	1.74 ± 0.80	2.69 ± 0.4	2.78 ± 0.48	2.48 ± 0.59
Margalef	6.19 ± 1.95	4.71 ± 1.05	5.81 ± 0.35	5.05 ± 0.49	4.55 ± 1.53	4.78 ± 1.04	7.14 ± 0.53	6.25 ± 0.54
Pielou	0.68 ± 0.08	0.61 ± 0.17	0.61 ± 0.01	0.63 ± 0.14	0.48 ± 0.21	0.80 ± 0.01	0.66 ± 0.10	0.63 ± 0.13
CPUE (kg/boat*day)	8.86 ± 2.39	21.04 ± 5.96	13.96 ± 1.06	27.64 ± 5.12	14.98 ± 1.86	20.22 ± 6.32	13.6 ± 3.28	21.85 ± 3.46

different time points, it is possible to access not only changes in fish population structure but also the dynamics of fish population health (Gabelhouse, 1984). Previous research has shown that fishing activities tend to favor larger individuals, thereby reducing the average body length and skewing the population structure toward smaller individuals (Allan et al., 2005; Feng et al., 2023). Prior to the comprehensive fishing ban, fish species in the Yangtze River were already showing signs of individual miniaturization, and population structure had been severely disrupted (Feng et al., 2023; Wang R. L. et al., 2022). Fishing pressure may exacerbate this trend by altering genetic factors that regulate fish size, reducing the frequency of fast-growing genotypes, and diminishing energy allocation to growth (Kokkonen et al., 2015; Morbey and Mema, 2018; van Wijk et al., 2013).

This study shows that after a 3-year fishing ban, the average body length and PSD values of 16 major fish populations in the middle reaches of the Yangtze River significantly increased. This indicates that the long-standing trend of individual miniaturization in these species has been partially alleviated. The growth of certain species PSD-P, PSD-M, and PSD-T indicates that the number of individuals in each length unit of the population has been restored orderly, and the proportion distribution of individuals in each unit

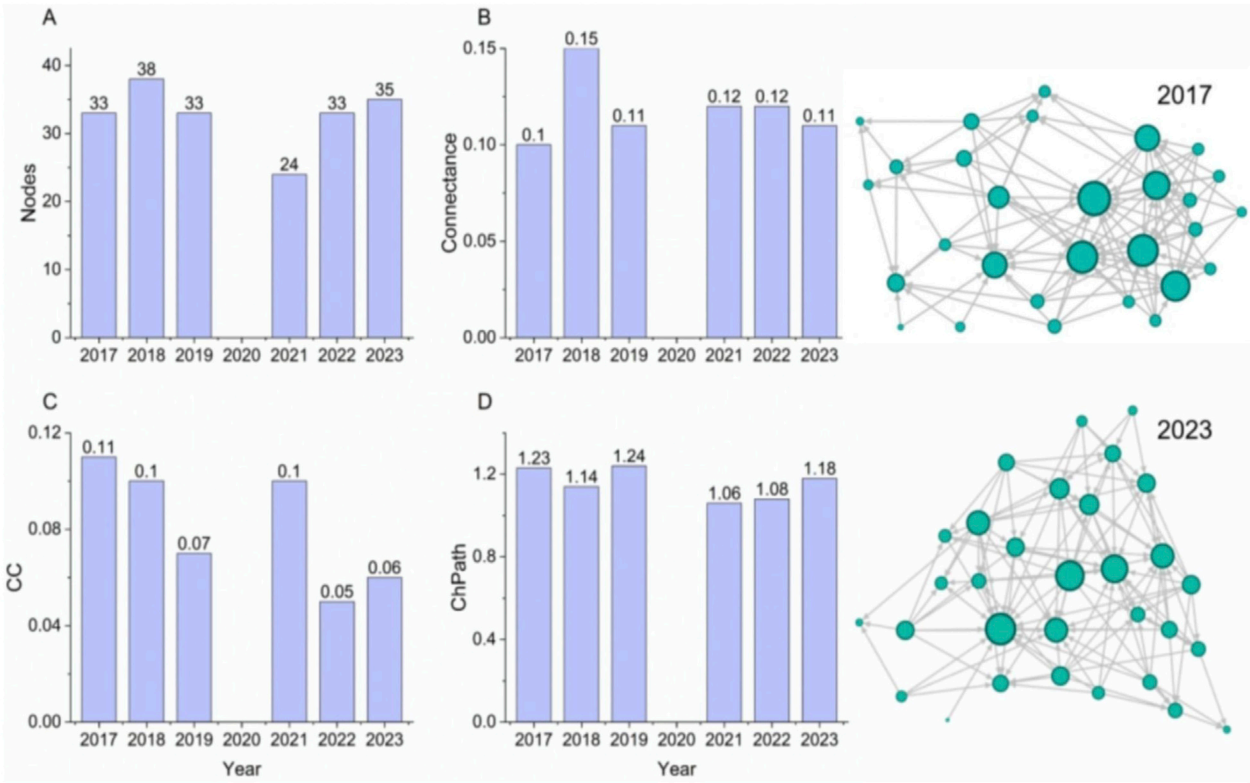

FIGURE 6
Four indexes of the food web and topological structure of fish communities between 2017 and 2023. The changes in **(A)** nodes, **(B)** Connectance, **(C)** average clustering coefficient (CC), and **(D)** average path length (ChPath) from 2017 to 2023.

TABLE 2 The average values of four indicators of the meta-network topology structure of fish communities at various sites in the middle reaches of the Yangtze River before (2017–2019) and after (2021–2023) the fishing ban.

Sites	Huangshi (HS)		Jingzhou (JZ)		Jianli (JL)	
Index	2017–2019	2021–2023	2017–2019	2021–2023	2017–2019	2021–2023
Nodes	22	20	29	16	18	23
Connectance	0.12	0.15	0.12	0.17	0.09	0.12
CC	0.08	0.06	0.09	0.05	0.13	0.06
ChPath	1.22	1.04	1.20	1.10	1.34	1.09

has gradually become complete and balanced. The population structure destroyed by overfishing has been optimized to a certain extent, and the effect of fishing bans has begun to emerge. Previous studies have also highlighted similar recovery trends, with significant increases in body size and PSD following a reduction in fishing pressure (Allen and Pine, 2000). For instance, in Lake Michigan, United States, yellow bass (*Diplophoron bifasciatum*) experienced a 2–5 cm increase in average body length after fishing pressure was reduced (Feiner et al., 2015). Similarly, the Clark salmon (*Oncorhynchus clavki*) in 19 lakes in North America showed a significant increase in both average body length and PSD after a decrease in fishing effort (Feiner et al., 2015).

Despite these positive trends, not all fish populations in the middle reaches of the Yangtze River experienced significant recovery. Some species showed either minimal improvement or even a decrease in average body length and PSD values. For example, *Culter mongolicus* and *Culter alburnus*—large, carnivorous fish that inhabit the upper and middle layers of slow-moving water bodies—experienced a decrease in body size following the fishing ban. This can be attributed to the restoration of their feed resources, such as annual bream-*P. pekinensis* (unpublished data), which increased the availability of smaller fish and led to a higher proportion of young fish being caught. Similarly, although *P. pekinensis* and *X. macrolepis* which inhabit slow-moving waters, had no noticeable changes in diet or size, the significant increase in resource availability did not translate into a noticeable shift in their body length structure. Research suggests that small fish with shorter life cycles tend to recover more rapidly after fishing pressure is removed (Cheng et al., 2020). Species such as *H. leucisculus* and *Pseudobagrus crassilabris*, which are annual fish species preferring slow-moving water bodies, did not show significant changes in body length structure, likely due to their short lifespan and relatively stable body sizes (Fang et al., 2023).

Selective fishing targeting larger individuals may truncate the body length distribution of populations, leading to structural and dynamic instability (Hixon et al., 2014). Fish populations with lower PSD values (<50) are generally characterized by a greater proportion of smaller individuals and slower growth, whereas populations with higher PSD values (<80) exhibit faster average growth rates, larger body sizes, and more stable mortality, birth rates, and overall population structure (Phelps and Willis, 2013; Shin et al., 2005; Willis et al., 2008). Therefore, PSD values serve as a reliable metric for evaluating the structural condition of fish populations. Gabelhouse and Donald's study showed that a population's PSD value exceeds a certain threshold indicating a healthy, well-balanced population (Gabelhouse, 1984). Before the fishing ban, the PSD values of 8 out of 19 major fish species in the middle reaches of the Yangtze River were below 50, with only 3 fish species having PSD values between 50 and 80, indicating significant damage to the population structure. After the ban, PSD values of 5 fish populations remained below 50, while 5 fish populations showed PSD values between 50 and 80, suggesting partial recovery. This indicates that some populations are returning to a more balanced and healthy state. Overfishing, especially the depletion of mature female fish, reduces breeding capacity and population stability, leading to the decline or depletion of fish stocks (Barneche D R et al., 2018). Overfishing is responsible for 30% of the decline in fishery resources (Wang et al., 2024). After the fishing ban, the overall fish catch has also increased, reflecting positive ecological recovery.

4.2 The effect of the fishing ban on fish species diversity

Three years after the fishing ban in the middle reaches of the Yangtze River, our study observed increases in the Margalef and Shannon-Wiener indices (Figure 5A), which indicate a recovery in species richness and ecosystem diversity. However, these indices have not yet returned to pre-ban levels (2017–2019), suggesting that recovery is still underway. Similar trends have been documented in other freshwater systems. For instance, studies in Liangzi Lake and Chishui River showed partial recovery of species in Chishui River and some restoration of ecosystem functions in Liangzi Lake following fishing restrictions (Feng et al., 2023; Liu et al., 2023; Zhang et al., 2024). Despite these improvements, the food web and community dynamics in these ecosystems still face challenges, as evidenced by the relatively low stability of the Pielou and Simpson indices. These indices reflect the uneven distribution of species, with certain species continuing to dominate the ecosystem, contributing to an imbalance in community structure (Fang et al., 2023). This imbalance suggests that ecological recovery, though ongoing, remains incomplete. The persistence of such imbalances may be attributed to a combination of long-term environmental pressures and habitat degradation (Leclerc et al., 2023; Van der Sleen and Albert, 2022). Similar findings have been reported in marine ecosystems, where fish populations can take up to 15 years to fully recover after reductions in fishing pressure (Höckendorff et al., 2017; Hutchings, 2000). Importantly, the degree of recovery has been found to be more strongly related to species-specific traits—such as age at maturity, reproductive capacity, and the extent of population depletion—rather than to the taxonomic family (Feiner et al., 2015; Hixon et al., 2014; Morbey and Mema, 2018). The uneven distribution of species, as seen in this study, can undermine the stability of the ecosystem, making it more vulnerable to external shocks and disturbances.

Overall, although some species have started to reproduce again, the overall vulnerability of the ecosystem remains a concern, especially given that the interactions between predators and prey have not fundamentally changed (Feng et al., 2023; Wang R. L. et al., 2022). This continued imbalance in species distribution is a critical issue for the stability of the ecosystem in the long term. As such, while the fishing ban has contributed to partial species recovery, the ecosystem's overall health still requires significant improvement. The ecosystem's vulnerability and imbalance in species distribution underscore the need for targeted management and restoration efforts (Wang et al., 2024; Zhang et al., 2024). By addressing habitat degradation and promoting balanced species distributions, it will be possible to enhance the long-term sustainability of the Yangtze River ecosystem (Wang H. et al., 2022; Wang R. L. et al., 2022).

From a spatial perspective, we found significant variation in species diversity across different sampling sites of the middle reaches of the Yangtze River (Figures 5B–D). The Jingzhou-JZ site exhibited the highest diversity indices, followed by the Jianli-JL site, while the Huangshi-HS site had the lowest. The JZ site, with its broad waters and relatively stable hydrological conditions, supports complex aquatic structures and abundant vegetation, creating favorable habitats for diverse fish species (Fang et al., 2023). Similarly, the JL site benefits from relatively good water quality and minimal human disturbance, contributing to its higher fish species diversity (Yang et al., 2023). In contrast, the HS site, which has been heavily impacted by urbanization and industrialization, faces declining water quality and habitat degradation, leading to lower fish diversity (Liu and Cao, 1992). These findings highlight the need for focused conservation efforts in the HS site to restore habitat conditions and improve water quality, which are essential for enhancing fish diversity in this area.

4.3 The effect of the fishing ban on the food web

Theoretical frameworks suggest that both species richness and food web structure affect community biomass and its stability (Danet et al., 2021). In particular, high food web connectivity can enhance the strength of species interactions, which may amplify population variability and potentially reduce the stabilizing effect of species richness (Thébault and Loreau, 2006). Predators can also have cascading effects on population variability and synchronicity at lower trophic levels (Shanafelt and Loreau, 2018; Teng and McCann, 2004). These theoretical insights highlight the need to consider species richness and food web structure simultaneously, as their effects may conflict or interact in complex ways (Danet et al., 2021). In this study, we employed food-web structure metrics to examine how the fish community in the middle reaches of the Yangtze River under a fishing ban policy. We measured food web complexity using four key metrics: nodes, connectance, CC, and ChPath. The number of nodes and connectance are positively correlated with food-web complexity (Montoya and Solé, 2003), providing insights into the overall structure and functioning of the ecosystem.

Our results suggest a slight increase in food web complexity following the fishing ban, although the current structure has not yet returned to pre-ban levels observed from 2017 to 2019. Notably, the connectance values in our study were lower than those reported in other aquatic ecosystems, where connectance is typically around 0.2 (Danet et al., 2021; Leclerc et al., 2023). This suggests that the food web in the middle Yangtze River is characterized by relatively weak interspecies connections (Brose, 2010; Marina et al., 2018), which may partly explain the food web's lower stability during the early recovery period (2021–2023). Weak interspecies interactions can impede the natural flow of energy through the system, potentially limiting the overall resilience of the ecosystem during recovery. Across the three sampling sites, the JL site is the most complex in the food web structure compared to JZ and HS, which may be attributed to its proximity to Dongting Lake and the advantages of slow water flow, abundant aquatic plants, and sufficient bait (Fang et al., 2023). Meanwhile, it is far from the Three Gorges Dam compared to JZ, avoiding severe erosion and having better sediment (Li et al., 2021). All of these are beneficial for the reproduction and recovery of fish, promoting the complexity of the food web structure.

Furthermore, although the taxonomic richness showed considerable variation, we observed relatively low changes in the average path length (ChPath) and a slight increase in the average clustering coefficient (CC) and the number of links during the initial recovery period (2021–2023). However, these values have not yet returned to the pre-ban levels observed in 2017–2019. This indicates that, although recovery is underway, the food web structure remains unstable compared to the period before the fishing ban. It is important to recognize that the stability and complexity of the food web are influenced by various factors, including habitat quality and ecosystem productivity (Leclerc et al., 2023). While fish communities in the Yangtze River are beginning to recover, habitat restoration is a slower process that will likely take longer (Wang H. et al., 2022; Zhang et al., 2024). This ongoing dynamic suggests that the fish populations and community structures have not yet reached a stable equilibrium. These findings indicate that the food web in the middle reaches of the Yangtze River remained relatively unstable in the early years following the fishing ban. The interspecies connections within the food web are weak, and the overall complexity of the food web has not increased significantly. Given that food web complexity typically increases with species richness and interaction strength (Marina et al., 2018), future research should focus on long-term monitoring to better understand the dynamic changes in the food web. Such research will provide crucial insights into the conservation and management of the Yangtze River ecosystem, particularly during the ongoing fishing ban.

4.4 Suggestions for fish conservation

Our research underscores the complexity of fishery resource management and highlights the necessity of a more comprehensive, multi-faceted conservation approach. Although beneficial in reducing immediate threats from overfishing, the current fishing ban policy does not sufficiently address the degradation of key aquatic habitats and the disruption of riverine connectivity (Zhang et al., 2020b; Zhang, 2022). Habitat destruction, pollution, and infrastructure development continue to fragment habitats, hindering the migration and reproduction of fish species (Höckendorff et al., 2017). Therefore, relying exclusively on the fishing ban policy is unlikely to provide the long-term ecological resilience needed for sustainable fish populations in the Yangtze River (Wang H. et al., 2022). Considering these considerations, we recommend the continued enforcement of the fishing ban, with a focus on its long-term implementation and continuous monitoring. However, this should be complemented by measures aimed at improving the connectivity between rivers and lakes, as well as enhancing the quality of aquatic habitats (Cheng et al., 2020; Wang R. L. et al., 2022). Restoring ecological corridors and mitigating habitat fragmentation would provide aquatic organisms with more extensive and more suitable living spaces (Chen et al., 2024), thereby increasing the overall effectiveness of the fishing ban and supporting the recovery of biodiversity.

Additionally, the experiences from regions such as Liangzi Lake and Chishui River, where fishing bans have been implemented, underscore the necessity of adopting a holistic approach to aquatic conservation (Feng et al., 2023; Liu et al., 2023). These case studies reveal that while fishing bans have led to some positive outcomes, they alone are insufficient to fully restore aquatic biodiversity. Future conservation strategies must involve integrated resource management, which includes habitat restoration, pollution control, and sustainable fisheries management (Barneche D R et al., 2018; Brose, 2010; Chen et al., 2024). Only through such comprehensive measures can we ensure the long-term sustainability of the Yangtze River ecosystem and the conservation of its biodiversity. In conclusion, while the fishing ban represents a crucial first step in reversing the decline of fish populations, it must be seen as part of a broader, integrated conservation strategy that includes habitat restoration, improved connectivity, and ecosystem management. The successful recovery of aquatic biodiversity in the Yangtze River requires a long-term commitment to both ecological restoration and sustainable resource management.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Author contributions

JD: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Visualization, Writing–original draft, Writing–review and editing. HT: Data curation, Writing–review and editing. ZX: Writing–review and editing, Data curation. KZ: Writing–review and editing, Funding acquisition. LY: Supervision, Writing–review and editing. XD: Supervision, Writing–review and editing. DC: Supervision, Writing–review and editing. JX: Supervision, Writing–review and editing. ML: Supervision, Writing–review and editing.

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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.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2024.1530716/full#supplementary-material

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