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EDITED BY
Yang Jin,
Carnegie Institution for Science,
United States

REVIEWED BY
Carlos Freitas,
Federal University of Amazonas, Brazil
Hadayet Ullah,
WorldFish, Malaysia

*CORRESPONDENCE
Jilong Wang
wangjilong@hrfri.ac.cn

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Assessment of fishery management parameters for major prey fish species in the lower reaches of the Songhua River

Wanqiao Lu[1,2], Peilun Li[1,2], Bo Ma[1,2,3], Tangbin Huo[1,2], Zengqiang Yin[4], Fujiang Tang[1,2] and Jilong Wang[1,2]*

[1]Heilongjiang River Fisheries Research Institute, Chinese Academy of Fisheries Sciences, Harbin, China, [2]Scientific Observing and Experimental Station of Fishery Resources and Environment in Heilongjiang River Basin, Ministry of Agriculture and Rural Affairs, Harbin, China, [3]Yingkou Enrichment Experiment Station, China Academy of Fisheries Science, Yingkou, China, [4]College of Marine Science, Technology and Environment, Dalian Ocean University, Dalian, China

The stability of the ecosystem directly affects the water quality and safety, fishery production, and people's quality of life along the route. In this study, extensive biological information on five dominant species of prey fish, including *Hemiculter leucisculus* (Basilewsky, 1855), *Acheilognathus macropterus* (Bleeker), *Rhodeus sericeus* (Pallas,1776), *Pseudorasbora parva* (Temminck & Schlegel, 1846), and *Squalidus argentatus* (Sauvage & Dabry de Thiersant, 1874), was collected in the lower reaches of the Songhua River, and the population parameters and variation rules of these fish were evaluated. The results showed that at present, the fish resources in the lower reaches of the Songhua River were in an overexploited state. Although the growth rate of prey fish was accelerating, their growth potential was decreasing. In addition to the homogeneous structure of the fish community, it was increasingly evident that a high proportion of small-sized fish were present in the fish community. In addition, the growth length coefficients of the five prey fish species were all greater than 0.2, indicating that the prey fish were growing at a faster rate, and the range of the growth performance indicators were 3.49 ~ 4.37. Our data also demonstrated that the exploitation rates of *Hemiculter leucisculus* and *Squalidus argentatus* were both greater than 0.5, and the exploitation rates of all species were higher than E_{max} except for *Pseudorasbora parva*. Finally, based on the above results, the mesh size of all nets should be controlled above 45 mm to ensure the size of the main prey fish populations in the lower reaches of the Songhua River. In summary, these results provided variation rules and growth of prey fish resources in the lower reaches of the Songhua River. At the same time, the distribution of major commercial or endangered baiting grounds in the lower reaches of the Songhua River was determined, which was beneficial to the balance and integrity of the ecosystem.

KEYWORDS

prey fish, ecosystem, FISAT II, population dynamics, fishery management, Songhua River

1 Introduction

The Songhua River, located in the northeastern part of China, is one of the seven major river basins in China. The northern source of the Songhua River originates from the Nengjiang River in the Yilehuli Mountains, a branch of the Daxinganling Mountains, and the southern source originates from the west-flowing Songhua River in the Changbai Mountains, which converges into the main channel of the Songhua River in Zhaoyuan County, Daqing (Yu et al., 2018). The river basin covers an area of about 55.7×10^4 square kilometers (Lu et al., 2022). As the mother river of Heilongjiang and Jilin provinces, the extensive basin and special geographical environment of the Songhua River have created their own rich fish resources. Since the 1930s, fish surveys have been conducted successively on the Songhua River (Yang et al., 2015). However, with the development of agriculture and industry and the increase of population, the fish resources of the Songhua River are greatly challenged by illegal anthropogenic fishing practices such as electrofishing and over-small nets. In addition, the construction of hydroelectric power stations and dams along the Songhua River has resulted in changes to the river and watershed (Han et al., 2017; Ma et al., 2022), seriously damaging the "three grounds and one channel" (overwintering ground, baiting ground, spawning ground, and migration channel) for local fish, and threatening the water quality and safety, environmental carrying capacity, and fishery resources of the Songhua River.

At present, studies on the Songhua River are focused on fish toxicology (Liu et al., 2009; Wang and Wang, 2019), community structure analysis (Li et al., 2018), early fish resource research (Yang et al., 2019), economic fish biology (Wang et al., 2020; Wang et al., 2021), resource variability (Lu et al., 2021), and behavioral observations (Li et al., 2021); whereas little research has been conducted on prey fish in the Songhua River. In addition, a significant portion of prey fish such as *Hemiculter leucisculus* and *Acheilognathus macropterus* in the Songhua River are omnivorous. Therefore, as the main food source for medium and large commercial and endangered fish, prey fish is a key element of primary productivity in the ecosystem, and their population size and variation affect the community structure of commercial fish as well as fish in the entire ecosystem. However, compared with other large and medium-sized fish, prey fish have limitations such as low economic value and low social impact, which directly lead to little research on prey fish and incomplete understanding the current status of exploitation of prey fish resources. In addition, under the current high-intensity commercial fishing operations, an urgent issue to be addressed is how to ensure the sustainable development of prey fish population resources and the stability of fish community structure in the Songhua River.

Therefore, the prey fish in the lower reaches of the Songhua River was taken as the research object in this study. The dynamic of population were studied, and fish community structure in the lower reaches of the Songhua River was determined. Meanwhile, based on the research results, reasonable fishing management policies are proposed to provide a reasonable reference for the development of relevant fisheries management measures and provide a scientific basis for the sustainable development of the Songhua River and the stability of the ecosystem.

2 Materials and methods

2.1 Sample collection and identification

Samples were collected from the river sections of the Songhua River in Tangyuan County, Huachuan County, Fujin City and Tongjiang City. The sampling sites are shown in Figure 1, which was drawn using ArcGis 10.5 software. Samples for each site were collected in the summer (June–July), autumn (October–November), and winter (December) in 2020 as well as in the spring (May) and summer (July–August) in 2021. Gill nets and ground cages were used for sample collection. Each gill net was 20,000 cm long and 250 cm high with dimensions of 1 cm, 2 cm, 4 cm, 6 cm, 8 cm, and 10 cm, respectively. The ground cages were 1500 cm long, 40 cm wide and 40 cm high with dimensions of 0.5 cm. The size of the net was measured by straightening the opposite knot. Sampling was conducted in accordance with the related reference (Zhang, 1995; Xie, 2007; Zhao, 2018). The sampling specifications such as measurement records and anatomy of samples were in accordance with the relevant manuals and specifications of the Inland Fisheries Natural Resources Survey (Zhang, 1991).

2.2 Data analysis and processing

2.2.1 Sample analysis and dominant species identification

Based on the results of catch collection during the survey, the dominant species were identified using the relative importance index (IRI) method. The IRI is calculated as follows:

$$IRI = (N + w) \times f \times 10^4$$

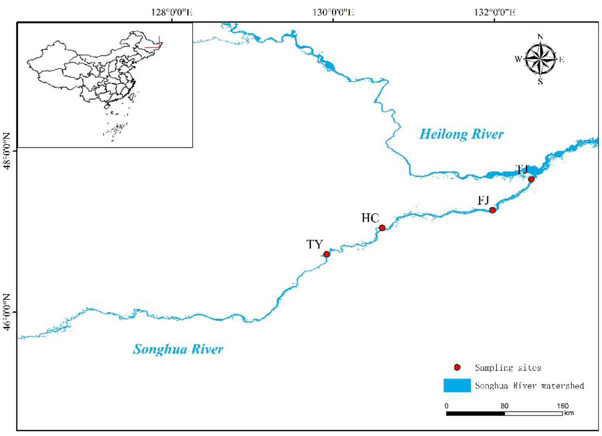

FIGURE 1
Sampling area. TY, Tangyuan county; HC, Huachuan county; FJ, Fujin city; TJ, Tongjiang city.

where N is the proportion of the number of a certain species to the total catch, w is the proportion of the mass of a species to the total catch, and f is the frequency of a certain species. The IRI of each catch species was in the range of [0, 1), [1, 10), [10, 100), [100, 1000), and [1000, +∞), representing rare, ordinary, common, important, and dominant species, respectively (Pauly and Munro, 1984; Thangaraj et al., 2022). Considering the actual situation of the Songhua River, five prey fish with IRI index greater than 200 were selected as the objects of this study.

2.2.2 Basic growth characteristics and parameters

The relationship between the body length-weight coefficients of target fish in the lower reaches of the Songhua River conforms to the power function curve (Fei, 1990). To establish the length-weight relationship, the existent equations were applied (Ricker, 1975; Quinn and Deriso, 1999), and the body length-weight relationship is calculated as follows:

$$W = a \bullet L^b$$

where W is body weight *(g)*, L is body length *(mm)*, a is a condition factor for growth, and b is a power exponent coefficient. Based on the principle of least squares, the values of parameters a and b can be estimated by using the linear regression of the logarithm of body weight on the logarithm of body length.

The von Bertalanffy growth formula (VBGF) was fitted to estimates of the length-at-age curve using non-linear least-squares estimation procedures (Pauly et al., 1992). The VBGF is defined by the equation:

$$L_t = L_\infty[1 - e^{-k(t-t_0}]$$

where L_t is the theoretical length at age t, L_∞ is the asymptotic length of the sample, k is the average curvature of the sample growth curve (relative rate of convergence to the asymptotic value), t is the age of the sample, and t_0 is the theoretical initial age at which the length is zero (Pauly and David, 1981; Newman, 2002). $L_\infty$and k of the VBGF were estimated by means of ELEFAN I in the FISAT II computer program (Pauly, 1981; Pauly, 1982). t_0 of target fish in the lower reaches of the Songhua River was calculated ac cording to an empirical formula by Pauly and David (1981).

The estimates of L_∞ and k were used to estimate the growth performance indices (φ') and growth inflection point age (t_{tp}) (Pauly and Munro, 1984) using the following equations:

$$\varphi' = \mathrm{lg}k + 2\mathrm{lg}L_\infty$$

$$t_{tp} = \frac{\mathrm{lnb}}{k} + t_0$$

2.2.3 Death, development and survival parameters

The total instantaneous mortality (Z) was estimated using the body length converted catch curve method in the FiSAT II computer program (Pauly, 1983; Pauly, 1984; Pauly, 1990), which is expressed as follows:

$$ln\left(\frac{N}{\triangle t}\right) = -Zt + b$$

where $ln(\frac{N}{\triangle t})$ is the number of mortalities in this population N at instant t and b is a parameter.

The instantaneous rate of natural mortality (M) was obtained using the empirical relationship of Pauly (Pauly, 1980), which is expressed as follows:

$$\ln M = -0.0066 - 0.279 lnL_\infty + 0.6543 \ln k + 0.4634 \ln T$$

where T is the annual habitat temperature (°C) of the water in which the stocks live.

Once Z and M had been obtained, the instantaneous rate of fishing mortality (F), exploitation rate (E) (Guo et al., 2016), and survival rate (S) were represented by the relationship between the three transient mortality rates according to a previous study by the authors (Yin et al., 2016):

$$F = Z - M$$

$$E = \frac{F}{Z}$$

$$S = e^{-Z}$$

The critical age of the population (t_{cr}) is the age at which the instantaneous rate of natural mortality of an individual is the same as the relative growth rate of its body weight, or when the biomass of a generational population of fishery organisms reaches its maximum. This could be expressed as follows:

$$\frac{dWt}{(Wt \times dt)} \approx \frac{dB}{(B \times dt)} = M$$

2.2.4 Survival probability estimation

The length-based Bayesian biomass (LBB) method in the FISAT II computer program was chosen for survival probability estimation of target fish in the lower reaches of the Songhua River. Some numerical values were taken from the Markov chain Monte Carlo equation (MCMC) (Froese et al., 2018), which is expressed as follows:

$$N_L = N_{L_{start}} \left(\frac{L_\infty - L}{L_\infty - L_{start}}\right)^{\frac{Z}{k}}$$

where L_{start} is the minimum body length of the target fish stock to be caught, which is considered as the opening trap body length, and N_L is the number of surviving individuals of length L caught in the target fish population.

Under the premise of no commercial fishing operations, there is no information about the magnitude of the variables in the formula. Therefore, mathematical statistics can be directly used to calculate the survival rate of individuals with body length L for the target fish population in the lower reaches of the Songhua River when $F = 0$ (Wang et al., 2020), as follows:

$$P_{L \to L_\infty} = \left(1 - \frac{L}{L_\infty}\right)^{\frac{M}{k}}$$

2.2.5 Catch per unit of replenishment

The relative yield per recruit (*Y'/R*) was analyzed through the improved Beverton-Holt (B-H) dynamic equation (Pauly and Soriano, 1986; Gayanilo et al., 2005), which is expressed as follows:

$$Y'/R = EU^{M/k}[1 - \frac{3U}{1+m} + \frac{3U^2}{1+2m} - \frac{U^3}{1+3m}]$$

$$(\mathrm{U} = 1 - \frac{L_c}{L_\infty},\ \mathrm{m} = \frac{k}{Z})$$

where L_c is the opening catch length of target fish, and E is the exploitation rate.

3 Results

3.1 Catch statistics

A total of 21,520 fish, with a total weight of 2,833,900.85 g, belonging to 60 species of fish in 7 orders and 14 families were collected in this study (Table 1). Among them, the dominant prey fish were *Hemiculter leucisculus*, *Acheilognathus macropterus*, and *Pseudorasbora parva*, and the common prey fish were *Squalidus argentatus*, *Rhodeus sericeus*, *Gobio cymocephalus* (Dybowsky,1869), and seven other species. To investigate the population status of major prey fish in the lower reaches of the

TABLE 1 Composition of the catches.

Species	*f*	*N*	*w*	*IRI*	*IRI%*
Hemiculter leuciscулus	100	31.44	14.82	4626.20	0.2612
Carassius auratus gibelio	100	9.50	11.65	2115.55	0.1194
Xenocypris argentea	75	4.78	15.80	1543.20	0.0871
Acheilognathus macropterus	100	11.51	3.67	1518.19	0.0857
Pseudorasbora parva	100	9.90	0.93	1082.65	0.0611
Gyprinus carpio	100	0.72	9.20	991.95	0.0560
Pelteobagrus nitidus	100	4.87	2.80	767.49	0.0433
Squalidus argentatus	100	5.01	0.63	563.23	0.0318
Hypophthalmichthys molitrix	100	0.36	5.14	550.02	0.0311
Silurus asotus	75	1.55	5.77	548.61	0.0310
Hemibarbus maculatus	100	0.92	2.77	369.28	0.0208
Leuciscus waleckii	100	0.91	2.11	302.05	0.0171
Silurus soldatovi	50	0.00	5.64	282.40	0.0159
Rhodeus sericeus	100	2.00	0.23	223.20	0.0126
Gobio cymocephalus	75	1.68	0.65	175.02	0.0099
Saurogobio dabryi	100	1.28	0.39	167.85	0.0095
Culter alburnus	100	0.22	1.43	165.18	0.0093
Rhodeus ocellatus	75	1.96	0.23	163.90	0.0093
Opsariichthys bidens	100	0.71	0.93	163.33	0.0092
Parabramis pekinensis	75	0.31	1.67	148.76	0.0084
Aristichthys nobilis	25	0.01	4.93	123.52	0.0070
Pseudobagras ussuriensis	100	0.41	0.79	120.80	0.0068
Leiocassis argentivittatus	75	1.34	0.08	106.95	0.0060
Ctenopharyngodon idella	50	0.02	2.06	103.99	0.0059
orther	–	8.56	5.68	790.37	0.0446

f, instantaneous fishing mortality.
N, the proportion of the number of a certain species to the total catch.
w, the proportion of the mass of a species to the total catch mass.
IRI, the index of relative importance.
IRI%, the percentage of total species IRI index for each species.

Songhua River, the top five categories in the IRI index were selected for this study.

3.2 Basic growth characteristics of prey fish

According to the basic growth characteristics of the captured 3259 target samples, including 1258 *Hemiculter leucisculus*, 772 *Acheilognathus macropterus*, 347 *Rhodeus sericeus*, 483 *Pseudorasbora parva, and* 399 *Squalidus argentatus*, the frequency distribution of length frequency distribution, length-weight relationship (Supplementary Figures 1, 2), and the growth characteristics of prey fish were obtained. As shown in Table 2, the *b*-values of *Hemiculter leucisculus, Acheilognathus macropterus, Rhodeus sericeus, Pseudorasbora parva, and Squalidus argentatus* were 3.0083, 3.2031, 2.8775, 2.9773, and 2.9603, respectively. In terms of φ', all five prey fish were between 3.4 and 4.4. *Hemiculter leucisculus* (φ' = 4.37) had the highest growth performance index, while *Rhodeus sericeus* (φ' = 3.49) was the lowest. The growth equation could be fully expressed based on the length frequency distribution using the VBGF. The asymptotic length of *Hemiculter leucisculus* was 198.2 mm, which was different from other fish. The asymptotic lengths of other fish were all around 100 mm. Among them, *Squalidus argentatus* had the smallest asymptotic length of 89.25 mm. In terms of growth rate, the *k*-value of *Rhodeus sericeus* was lower than that of the other fish, although all the fish belonged to the same fast-growing species.

3.3 Prey fish population parameters

The population parameters of major prey fish in the lower reaches of the Songhua River were obtained from length frequency relationship. As presented in Figure 2, the Z of *Hemiculter leucisculus, Acheilognathus macropterus, Rhodeus sericeus, Pseudorasbora parva, and Squalidus argentatus* was 1.98, 2.17, 1.16, 2.33, and 3.13, respectively. The water temperature *T* was 12°C based on our year-round monitoring in the target waters. The *M*, *F*, *S*, *E*, and t_{cr} of the target fish could be further obtained in Table 3.

3.4 Status of prey fish resources in the lower Songhua River and management strategies

As shown in Table 1, the proportions of medium- and large-sized fish were small at this stage. On the contrary, the dominant and common species were mostly small- and medium-sized prey fish. Therefore, it was reasonable to conclude that the current fishing pressure in the lower reaches of the Songhua River and the small mesh sizes used had resulted in a continuous increase in the fishing yield of prey fish that were originally caught as bycatch. In addition, the opening length (L_c) of the target prey fish, including *Hemiculter leucisculus* (40 mm), *Acheilognathus macropterus* (30 mm), *Rhodeus sericeus* (20 mm), *Pseudorasbora parva* (20 mm), and *Squalidus argentatus* (25 mm) could be inferred based on the results of fishing gear in the target waters. Currently, the opening catch length is known, so samples with body lengths smaller than the opening catch length are identified as a supplemental population. Taking *Hemiculter leucisculus* as an example, with the increase in fishing intensity, biomass (B'/R) loss gradually increases and yield (Y'/R) first increases and then decreases, with the inflection point being E_{max} (Figure 3). The exploitation rates, including $E_{0.1}$, $E_{50\%}$, and E_{max} of the target prey fish were obtained by the knife-edge selection hypothesis in the (B-H) dynamic equation (Table 3). The dynamic change trend between the yield per unit replenishment, L_c and *E* was estimated as shown in Figure 4. When the fishing intensity is constant, L_c decreases, Y'/R increases and then decreases, and the point of inflection is E_{Lopt}.In the current fishing mode, the values of L_C/L_∞ and *E* were 0.20 and 0.51, respectively. Similarly, the values of L_C/L_∞ and *E* values for other fish species are detailed in Table 3.

4 Discussion

4.1 Changes in major commercial fish species in the lower reaches of the Songhua River

The Songhua River in the Three Rivers Plain has an irreplaceable ecological status due to its unique geographical location and extensive watershed. Therefore, fish resource surveys

TABLE 2 Basic growth characteristics of major prey fish in the lower reaches of the Songhua River.

Species	Body length-weight relationship	t_0	φ'	t_{tp}	Growth equation
Hemiculter leucisculus	$W = 1*10^{-5} \cdot L^{3.0083}$	-0.27	4.37	1.57	$L_t = 198.20[1-e^{-0.6(t+0.27)}]$
Acheilognathus macropterus	$W = 1*10^{-5} \cdot L^{3.2031}$	-0.31	3.93	1.63	$L_t = 119.00[1-e^{-0.6(t+0.31)}]$
Rhodeus sericeus	$W = 3*10^{-5} \cdot L^{2.8775}$	-0.75	3.49	3.31	$L_t = 109.20[1-e^{-0.26(t+0.75)}]$
Pseudorasbora parva	$W = 2*10^{-5} \cdot L^{2.9773}$	-0.27	3.85	1.27	$L_t = 99.75[1-e^{-0.71(t+0.27)}]$
Squalidus argentatus	$W = 2*10^{-5} \cdot L^{2.9603}$	-0.27	3.77	1.20	$L_t = 89.25[1-e^{-0.74(t+0.27)}]$

t_0, theoretical initial age of the population.
φ', the growth performance indice.
t_{tp}, growth inflection point age.

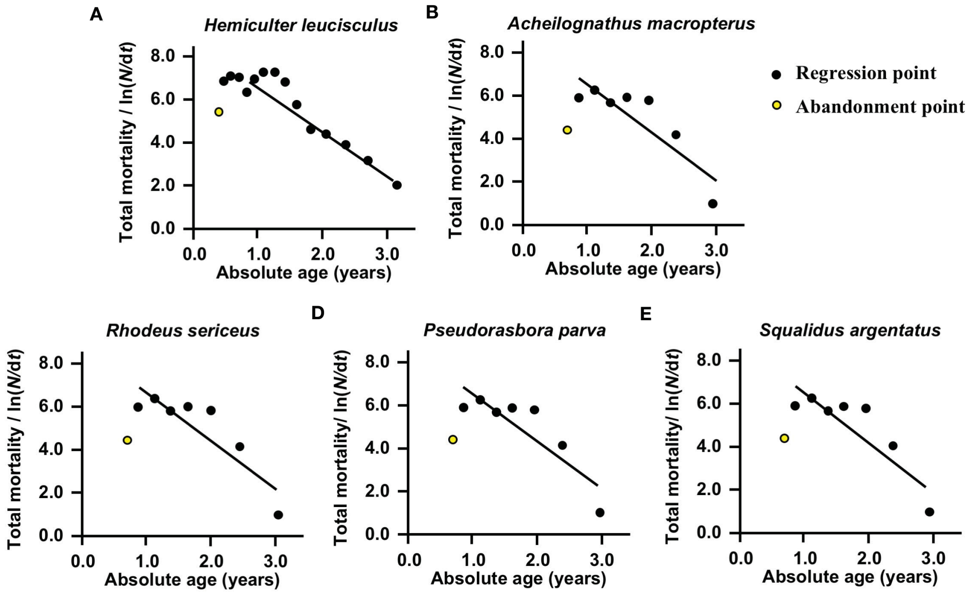

FIGURE 2
Length-converted catch curves of **(A)** *Hemiculter leucisculus*, **(B)** *Acheilognathus macropterus*, **(C)** *Rhodeus sericeus*, **(D)** *Pseudorasbora parva, and* **(E)** *Squalidus argentatus* in the lower reaches of the Songhua River. The slope of each straight line is the total instantaneous mortality rate (*Z*) of the target fish population.

on the lower reaches of the Songhua River have been conducted since 1950. First, in terms of fish community structure in the lower Songhua River, previous studies had recorded a total of 98 species of fish in the Songhua River basin, including 10 orders, 20 families, and 68 genera, of which a total of 80 species (including subspecies), including 9 orders and 19 families and 60 genera, were collected in the lower reaches (Yang et al., 2015). In the latest study, 60 species of fishes were collected from the lower reaches of the Songhua River, including 7 orders and 14 families, with 20 fewer species than in the previous study. Second, according to the fishery resources survey report of the Songhua River system, the catches of *Gyprinus carpio* (Linnaeus, 1758) and *Parabramis pekinensis* (Basilewsky, 1855) tended to accounted for about 60% of the total annual catches, followed by the *Culter ilishaeformis* (Basilewsky, 1855) (10% on average), *Hypophthalmichthys molitrix* (Valenciennes, 1844) (10% on average) and *Ctenopharyngodon idella* (Valenciennes, 1844) (5% on average) around the 1960s. In addition, *Oncorhynchus keta* (Walbaum, 1792), *Amur sturgeon* (Brandt, 1869), *Kaluga sturgeon* (Georgi, 1775), *Hucho taimen* (Pallas, 1773), and *Brachymystax lenok* (Pallas, 1773) also occupied a certain proportion of the total annual catches. After the 1980s, the commercial fish that caught in production amounts were changed to *Gyprinus carpio*, *Carassius auratus* (Linnaeus, 1758), *Silurus asotus* (Linnaeus, 1758), *Hypophthalmichthys molitrix*, *Aristichthys nobilis* (Richardson, 1845), *Ctenopharyngodon idella*, and *Hemibarbus maculatus* (Bleeker, 1871) (Wei, 2018). In addition, the proportion of fish began to change, with *Culter ilishaeformis* becoming the most productive fish, accounting for about 60% of the total production. *Gyprinus carpio* production dropped from about 60% to about 10%, followed by *Parabramis pekinensis* (Basilewsky, 1855) (about 12.5%) and *Hypophthalmichthys molitrix* (about 7.6%). According to our survey results in 2015, the dominant and common species in the lower reaches of the Songhua River were *Gyprinus carpio*, *Hypophthalmichthys molitrix*, *Silurus asotus*, *Carassius auratus*, *Hemiculter leucisculus*, *Xenocypris argentea* (*Günther*, 1868), *Pelteobagrus nitidus* (*Sauvage et Dabry*, 1874), *Parabramis pekinensis*, and *Hemibarbus maculatus*. Compared to the present results, most of these fish were of relatively high economic value. In

TABLE 3 Parameters of major prey fish populations in the lower reaches of the Songhua River.

Species	Z	S	E	t_{cr}	$E_{0.1}$	$E_{50\%}$	E_{max}
Hemiculter leucisculus	1.98	0.14	0.51	1.48	0.37	0.28	0.45
Acheilognathus macropterus	2.17	0.11	0.48	1.44	0.41	0.29	0.49
Rhodeus sericeus	1.16	0.31	0.43	2.25	0.36	0.26	0.44
Pseudorasbora parva	2.33	0.10	0.40	1.04	0.37	0.28	0.45
Squalidus argentatus	3.13	0.04	0.56	1.02	0.42	0.30	0.51

$E_{0.1}$, Reduction in marginal growth for Y′/R 10% development rate.
$E_{50\%}$, Exploitation rate when biomass is reduced to 50% of original level.
E_{max}, Development rate at maximum production.

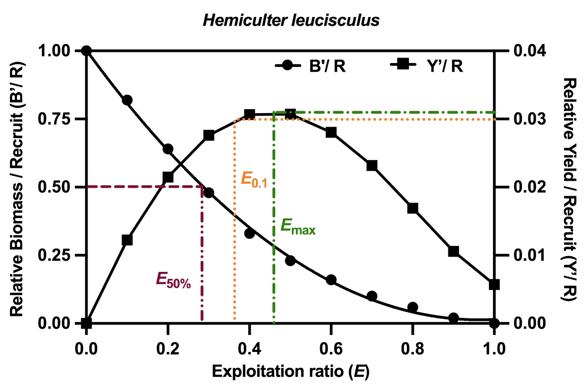

FIGURE 3
Two-dimensional analysis for Y′/R and B′/R of Hemiculter leucisculus when Lc = 40 mm.

addition, growth characteristics and populations of the same species of fish changed over time and space. It has been reported showed that *Carassius auratus*, *Gyprinus carpio*, *Hemiculter leucisculus*, *Leuciscus waleckii* (Dybowski, 1869), and *Cultrichthys erythropterus* (Cultrichthys erythropterus) were the dominant species in the lower reaches of the Songhua River in 2012 (Yang et al., 2015). In the past 10 years, the growth rate of *Hemiculter leucisculus* changed from moderate to rapid, accompanied by a decrease in growth potential and survival rate (Table 4). In fact, anthropogenic factors such as construction of water-related projects, disturbance of agroforestry industries and increased intensity of commercial fishing have led to changes in the dominant fish from large and medium-sized and commercially valuable fish to small and low-value fish.

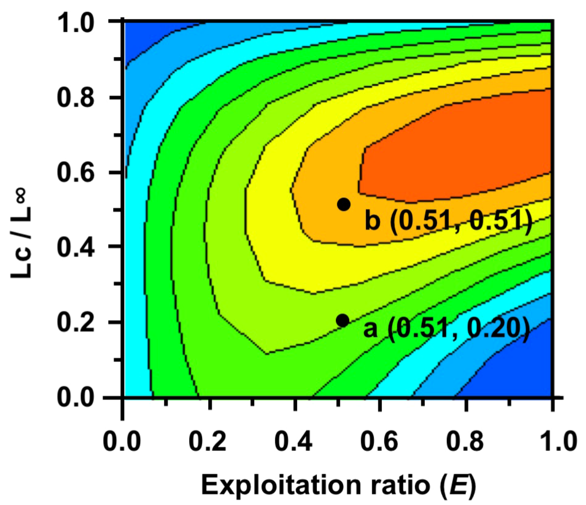

FIGURE 4
Relationship between relative yield per recruit Y′/R, exploitation ratio, and catchable size of Hemiculter leucisculus. The point a represents the Y′/R value in the current state. The point b represents the maximum Y′/R value when changing the body length of different start catches in the current exploitation state. Each loop in this figure is the equivalent of the Y′/R value. It means that the Y′/R values of the same loop are equal for the same starting catch length, different exploitation states or different starting catch lengths in the same exploitation state. The redder the color, the higher the Y′/R value, and conversely, the bluer the color, the lower the Y′/R value.

4.2 Prey fish resource management strategy in the lower reaches of the Songhua River

As a secondary productivity of the ecosystem, changes in prey fish populations have profound effects on fish at the higher trophic levels of the food chain, including endangered fish such as *Acipenser schrencki* (Li et al., 2020), *Hucho taimen*, *Coregonus ussuriensis* (Bochkarev et al., 2017), and medium and large fish with high economic value such as *Channa argus* (Liu et al., 2000) and *Silurus asotus* (Jiang et al., 2022). With the increase in current commercial fishing intensity and the reduction in mesh size, the former bycatch of prey fish has gradually become the target of fishing and made into fishmeal for profit. Gulland (1989) indicated that the optimal exploitation intensity should be 0.5. In addition, Mehanna (2007) suggested that the population is in a safe state of exploitation when the exploitation intensity is not higher than E_{max}. However, our results demonstrated that *Hemiculter leucisculus* and *Squalidus argentatus* were in an overexploited state. Pauly also suggested that the optimal exploitation point should be 0.286 (Pauly, 1987), where all resources are in a state of overexploitation. Based on the results of the population parameters and the Y'/R values fitted for different exploitation states, the $E_{50\%}$ for all five prey fish species in the current exploitation state was close to the optimal value (Table 5). To ensure biomass loss below 75%, the catch with E_{Lopt} is the largest, and the manipulation of adjusting the fishing size is much less difficult than setting the exploitation intensity. Therefore, the optimal management specifications for the *Hemiculter leucisculus*, *Acheilognathus macropterus*, *Rhodeus sericeus*, *Pseudorasbora parva*, and *Squalidus argentatus* population were defined as 101.08, 55.93, 43.58, 42.89, and 44.63 mm, respectively. Based on these estimates, it is possible to determine the minimum mesh size to be used in the lower reaches of the Songhua River. Considering convenience of operation, the mesh specifications could be controlled above 45 mm. However, when the opening and catching specifications are controlled at 45 mm, the above results will not be materially affected by the confirmatory calculation. Especially considering the small changes in the catch and the biomass loss of *Hemiculter leucisculus* and *Acheilognathus macropterus* populations at this stage, it is recommended that the mesh size of all nets in the lower reaches of the Songhua River should be controlled at 45 mm or greater.

4.3 Upstream effects of prey fish in the lower reaches of the Songhua River

The upward effect is a "bottom-up" effect, where the quantities of resources and biomass at lower trophic levels determine the population structure at higher trophic levels (Ware and Thomson, 2005; Buchheister et al., 2015; Maitra et al., 2018). Therefore, it is reasonable to assume that the

TABLE 4 Comparison of growth characteristics and population change parameters of the *Hemiculter leucisculus* population in the lower reaches of the Songhua River over 10 years.

Year of survey	L_∞	K	E	$P_{1/a}$	$P_{2/a}$	$P_{3/a}$	$P_{4/a}$	Data source
2012	255.00	0.15	0.81	0.67	0.55	0.46	0.38	(Yang et al., 2015)
2020–2021	198.20	0.60	0.51	0.29	0.11	0.04	0.02	This study

$P_{t/a}$, Probability of surviving to age t.

TABLE 5 Y_r/R value for prey fish in different states.

Species	*Hemiculter leucisculus*	*Acheilognathus macropterus*	*Rhodeus sericeus*	*Pseudorasbora parva*	*Squalidus argentatus*
E_{curr}	0.031	0.025	0.014	0.022	0.027
E_{ttp}	0.025	0.022	0.012	0.018	0.025
E_{cr}	0.026	0.024	0.013	0.020	0.026
E_{max}	0.031	0.026	0.014	0.023	0.027
$E_{50\%}$	0.027	0.022	0.012	0.019	0.022
E_{Lopt}	0.042	0.032	0.017	0.027	0.034

E_{curr}, Development rate in the current state (L_{curr}).
E_{ttp}, Open-catch body length for weight inflection point at age corresponding to body length (L_{ttp}).
E_{cr}, Open-catch body length is the corresponding body length at critical age (L_{cr}).
E_{Lopt}, Open-catch body length for the optimal body length (L_{Lopt}).

population size and variation patterns of prey fish play a key role in the recovery and rebuilding of their predator populations. From a feeding perspective, most species have similar feeding habits to their juvenile predators, leading to the formation of a competitive relationship for feeding. Therefore, when small-sized fish proliferate uncontrollably, this will have a greater impact on their predator populations, thereby affecting the rationality of the fish community structure and ultimately the balance of the entire ecosystem. Similarly, the feeding habits of prey fish are close to those of the juvenile fish of their predators, thus forming another competitive relationship (Sharp, 2001). A previous study has proved that a decline in jellyfish-feeding fish resources caused an increase in the number of jellyfish species, which instead led to a decrease in the number of juvenile fish in the East Sea and Yellow Sea of China (Greve, 1994). As a representative of large economic fish and endangered fish, *Huso dauricus* (Georgi, 1775) in the Songhua River, for example, its egg stage is also a food source for other fish (including some other prey fish).The juvenile stage of *Huso dauricus* (before 1 year of age) is in competition with other prey fish, such as *Hemiculter leucisculus*. *Hemiculter leucisculus* and *Squalidus argentatus* are the main baits for adult *Huso dauricus*. Therefore, the upward effect triggered by the population size of prey fish in the Songhua River had a direct impact on zoophagous commercial fish and endangered fish.

In addition to the upstream effect of prey fish, there are also factors affecting the community structure of their predatory fish, such as the physical and chemical environment of the habitat waters themselves, human intervention, and commercial fishing. A previous study showed that *Hemiculter leucisculus*, *Parabotia fasciatus*, *Saurogobio dabryi*, and *Rostrogobio amurensis* were the dominant species among the drifting eggs and juvenile fry in the lower reaches of the Songhua River in recent years (Huo et al., 2022). Therefore, the number of prey fish can be expected to remain dominant in the coming years.

5 Conclusion

Currently, the fish resources in the lower reaches of the Songhua River are in a state of high intensity exploitation. Unless effective management measures are taken in time, the structure of the fish community in the lower Songhua River will gradually homogenize, the fish individuals will become smaller and younger, causing the reduction of fishery resources in the Songhua River basin. Therefore, all mesh sizes should be controlled above 45 mm in accordance with the above management strategy to control the size of prey fish populations. At the same time, the authorities and local people need to reduce the frequency of commercial fishing boat operations and the use of banned nets. In addition, the construction of water-related projects and sewage discharge should be reduced to ensure the survival space of commercial fish, which will be beneficial to restore the balance and integrity of the Songhua River ecosystem.

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 author.

Ethics statement

The animal study was reviewed and approved by the Committee for the Welfare and Ethics of Laboratory Animals of Heilongjiang River Fisheries Research Institute of Chinese Academy of Fishery Sciences.

Author contributions

WL: Methodology, Formal analysis, Visualization, Writing - original draft. PL: Investigation. BM: Validation. TH: Data curation. FT: Conceptualization, Writing - review and editing. ZY: Software, Writing - review and editing. JW Funding acquisition and Supervision. All authors contributed to the article and approved the submitted version.

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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/fmars.2023.1166634/full#supplementary-material

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