



RESEARCH ARTICLE

Age, growth, and mortality of silver carp *Hypophthalmichthys molitrix* (Valenciennes, 1844) in the middle and lower reaches of the Pearl River, and implications for management and conservation

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Abstract – This study aimed to determine the age, growth, mortality, and population structure of the economically important cyprinid silver carp *Hypophthalmichthys molitrix* (Valenciennes, 1844) in the middle and lower reaches of the Pearl River. A total of 297 silver carp were sampled quarterly from the catches of gillnet fishermen, at six sites, between June 2019 and September 2020. Standard length of the specimens ranged from 130 to 585 mm, and body weight ranged from 45.5 to 3930 g. The length–weight relationship parameter b values reached 3.015. Age was determined through examination and measurements of fish scales, and the age composition of the sampled silver carp varied from 0+ to 4+. Fitting the new data to the von Bertalanffy growth model, we obtained an asymptotic size (L_{∞}) of 1107 mm, k of 0.135, and t_0 of -0.666 for silver carp in this stretch of the river. The calculated growth performance index ϕ and estimated longevity t_{\max} were 5.22 and 21.56, respectively. The rates of total mortality, natural mortality, and fishing mortality were calculated as 0.4997, 0.1621, and 0.3377, respectively, while the exploitation ratio was evaluated as 0.6757. The overall results confirm overexploitation of this resource in the middle and lower reaches of the Pearl River. It was concluded that this species should be protected from capture until at least 790 mm in standard length, representing an optimal minimum size for capture to benefit conservation of the species and to sustainably develop this valuable fishery.

Keywords: Silver carp / length–weight / von Bertalanffy growth function / capture standard / conservation

1 Introduction

Freshwater fishes are largely overexploited worldwide, and many of the ecosystems that sustain them have become degraded (Dudgeon *et al.*, 2006). China's large population and thriving economy have correspondingly increased the demand for fish as food, leading to situations of severe overexploitation (Guo *et al.*, 2019; Chen *et al.*, 2020). Historically, poorly regulated fish harvesting, in conjunction with other anthropogenic pressures, has resulted in dramatic declines in fishery resources, total catches, and biodiversity (Chen *et al.*, 2020).

To address the sustainable development of freshwater fisheries, it is necessary to establish effective fisheries management. Depressed fishery resources and the declining conservation status (and even extinction) of some endemic fish species have led to instances of fishing bans in the Yangtze River and other river basins in China. The recent fishing bans are unprecedented in their duration and extent (Chen *et al.*, 2020). Determinations of fish growth parameters provide important and reliable scientific information to carry out regional assessments and conservation actions (de Santana *et al.*, 2020). Basic data from studies of growth and population dynamics are input into various models used to evaluate and manage exploited fish stocks (Ju *et al.*, 2016; Mehanna *et al.*, 2018).

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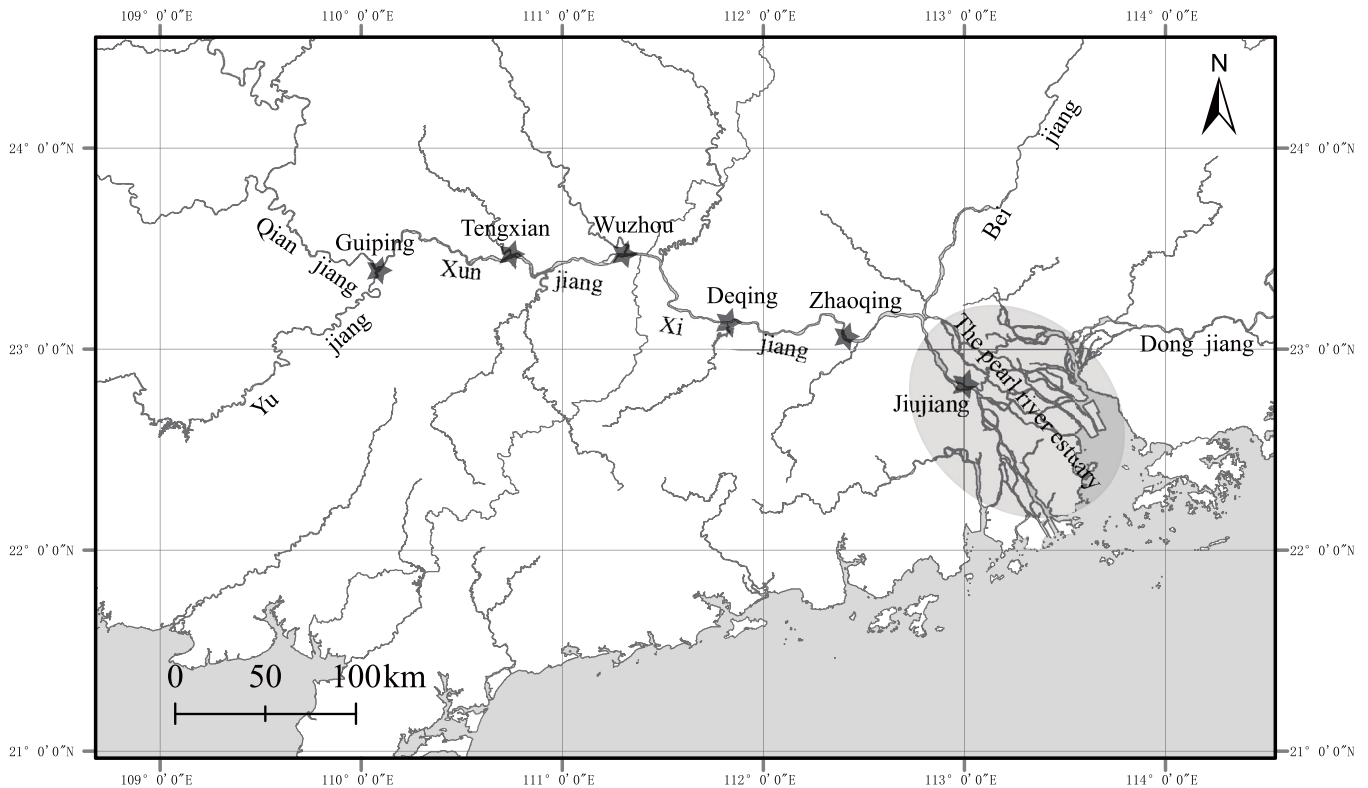


Fig. 1. Map showing the six sampling sites in the middle and lower reaches of the Pearl River.

The silver carp *Hypophthalmichthys molitrix* (Valenciennes, 1844) is a freshwater cyprinid native to East Asia, and it has been introduced worldwide for aquaculture and controlling algal blooms (Froese and Pauly, 2020). As one of the most economically important fishes in China, its resources have been in a state of continuous decline since the 1980s as a result of water conservancy construction, water pollution, overfishing, and other factors (Liu *et al.*, 2005; Tan *et al.*, 2010; Chen *et al.*, 2020). Conservation programs involving the silver carp, such as artificial fish propagation and release projects, have been implemented since 2006 (Chen *et al.*, 2009). The population structure and growth characteristics of silver carp have been studied in the Yangtze River, Songhua River, and Minjiang River (Xiong *et al.*, 2013; Pan *et al.*, 2019; Wang, 2020; Wang *et al.*, 2020). Studies of the biology and ecology of silver carp in the Pearl River have been undertaken since the 1980s (Lu, 1990), but few investigations have focused on decadal changes in its age, growth, and mortality.

The Pearl River is the longest river in southern China, exceeding 2000 km and stretching between 21°31'–26°49' N and 102°14'–115°53' E (Editorial Committee of *Encyclopedia of Rivers and Lakes in China*, 2013); it is located in tropical and subtropical climate zones having an annual mean temperature range of 14–22 °C and long-term annual average precipitation of 1525.1 mm (Deng *et al.*, 2018). Biological information on silver carp in the Pearl River would provide basic data that are needed for management of a sustainable fishery. Thus, this study aimed to (i) provide basic information on age, growth, mortality, and population structure of the silver carp, and (ii) propose reasonable management and protection measures for this species in the middle and lower reaches of the Pearl River.

2 Materials and methods

2.1 Fish sampling

This study was conducted in the middle and lower reaches of the Pearl River and included sites at Qianjiang, Xunjiang, Xijiang, and the Pearl River estuary. This extensive section of the Pearl River is an important fishing area for silver carp. Qianjiang and Xunjiang are main spawning grounds of silver carp; Xijiang and the Pearl River estuary are feeding ground and migration route. To determine current demographic parameters of silver carp, samples were collected quarterly, from June 2019 to September 2020, at six sites: Guiping, Tengxian, Wuzhou, Deqing, Zhaoqing, and Jiujiang (Fig. 1). Fish were obtained from local fishermen using gillnets (height 2 m × stretched length 100 m, 5–10-cm mesh). Each specimen collected was measured for standard length *SL* (to the nearest 1 mm) and body weight *W* (to the nearest 0.1 g), and 6–10 scales were removed from the region of the fish between the dorsal-fin origin and the lateral-line scales. The scales were then soaked in 4% sodium hydroxide solution and cleaned for investigation.

2.2 Age determination

To determine the age of the sampled silver carp, the collected scales were examined and measured under a stereomicroscope (Olympus SZX16). The total radius of each scale (*R*: distance from the focus to the *n*th annulus) was measured to the nearest 0.01 mm. The scale edge was also measured for backcalculating the fish length at the time of the

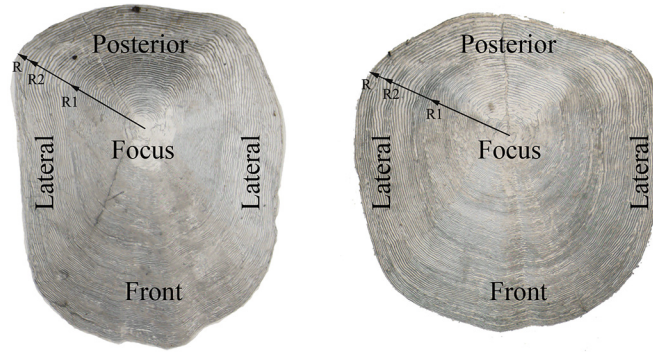


Fig. 2. Scale and annuli characteristics of silver carp sampled from the Pearl River.

annulus formation. The sampled silver carp were classified into age groups based on the number of completed annuli (Fig. 2).

The relationship of fish body length to scale radius was based on the assumption that scale growth is proportional to fish growth, calculated as: $L = a + b \times R$, where L is fish length (mm); R is scale radius (mm); b is slope value; and a is the initial fish length before scale formation (Lee, 1920; El-Nasr, 2017). Backcalculated fish length at the end of each year was calculated as: $L_n = (L - a) \times (R_n/R) + a$, where L_n is the length at n years; L is the standard length at capture (mm); R_n is the scale radius at annulus n ; R is total radius of the scale at the time of capture; and a is the intercept at y -axis (Lee, 1920; El-Nasr, 2017). To guarantee the independence of the data, only the last measurement was used for each individual.

2.3 Estimation of the growth parameters

The relationship between SL (mm) and W (g) for the silver carp specimens was expressed by the equation $W = \alpha \times L^b$, where α is a coefficient related to body form, and b is an exponent that indicates isometric growth when $b = 3$ (Leonart *et al.*, 2000; Froese, 2006). Student's t -tests were used to test significance of the difference between b and the value 3, implemented with the function 'hoCoef' in the package FAS in R software.

Absolute growth rate was calculated as: $(L_2 - L_1)/(t_2 - t_1)$ or $(W_2 - W_1)/(t_2 - t_1)$; relative growth rate as: $(L_2 - L_1)/L_1 \times (t_2 - t_1)$ or $(W_2 - W_1)/W_1 \times (t_2 - t_1)$; instantaneous growth rate as: $(\ln L_2 - \ln L_1)/(t_2 - t_1)$ or $(\ln W_2 - \ln W_1)/(t_2 - t_1)$; and the index of growth as: $C_e = (\log_{10} L_2 - \log_{10} L_1)/0.4343 \times (t_2 - t_1) \times L_1$, where W_2, W_1 and L_2, L_1 are the weights and lengths at ages t_2 and t_1 (Chen and Liu, 2017).

The von Bertalanffy growth function (VBGF) was used to determine the growth parameters as follows: $L_t = L_\infty \times (1 - e^{-k(t-t_0)})$, $W_t = W_\infty \times (1 - e^{-k(t-t_0)})^b$, where L_t and W_t are the SL (mm) and W (g) at age t (year); L_∞ and W_∞ are the mean asymptotic SL and W ; k is the body growth coefficient (year^{-1}); t is age; and t_0 is the theoretical age when the specimen's size was zero (Bertalanffy, 1938; El-Nasr, 2017). The inflection age of body growth was calculated as: $t_i = \ln b/k + t_0$. The growth performance index was calculated using the formula: $\varphi = \log_{10} k + 2 \times \log_{10} L_\infty$ (Pauly and Munro, 1984).

Longevity (t_{\max}) was estimated using the growth parameters k and t_0 as follows: $t_{\max} = 3/k + t_0$ (Pauly, 1983).

2.4 Mortality and exploitation rate

Following the Beverton–Holt (B-H) model (Beverton and Holt, 1956), total mortality (Z) was estimated based on coefficients related to average body lengths, thus: $Z = k \times (l_\infty - l)/(l - l')$, where l' is minimum fishery landing SL , and l is mean fishery landing SL . Natural mortality (M) was estimated using an empirical equation (Pauly, 1980): $\ln M = -0.0152 - 0.279 \times \ln L_\infty + 0.6543 \times \ln k + 0.463 \times \ln T$, where mean water temperature (T) is 23.48 °C. Fishing mortality (F) was calculated as $F = Z - M$. The exploitation ratio (E) was calculated as $E = F/Z$ (Temple *et al.*, 2020).

2.5 Critical age

The critical age (T_c , the optimum capture age) was determined using the equation of Yuan (1989): $T_c = (K \times t_0 - \ln M + \ln(3 \times K + M))/K$. The critical standard length (L_c , the optimum capture length) and the critical body weight (W_c , the optimum capture body weight) were calculated using the value of T_c and the von Bertalanffy equation.

2.6 Minimum capture standard

Minimum capture length (L_R) was estimated using the equation relating L_R to E and the mean fishery landing l , thus: $L_R = l \times E^{1/b}$ (Xu and Zhang, 1988; Ju *et al.*, 2016). Minimum capture body weight (W_R) was estimated using the equation relating W_R to E and the mean fishery landing weight W , thus: $W_R = E \times W$ (Radway, 1953).

3 Results

3.1 Size and age structure of the silver carp

A total of 297 silver carp specimens were collected. The length range was 130–585 mm SL , with an average of 342.85 ± 94.95 mm SL , and dominant range of 248.0–437.9 mm SL . Body weight ranged from 45.5 to 3,930.0 g, with an average

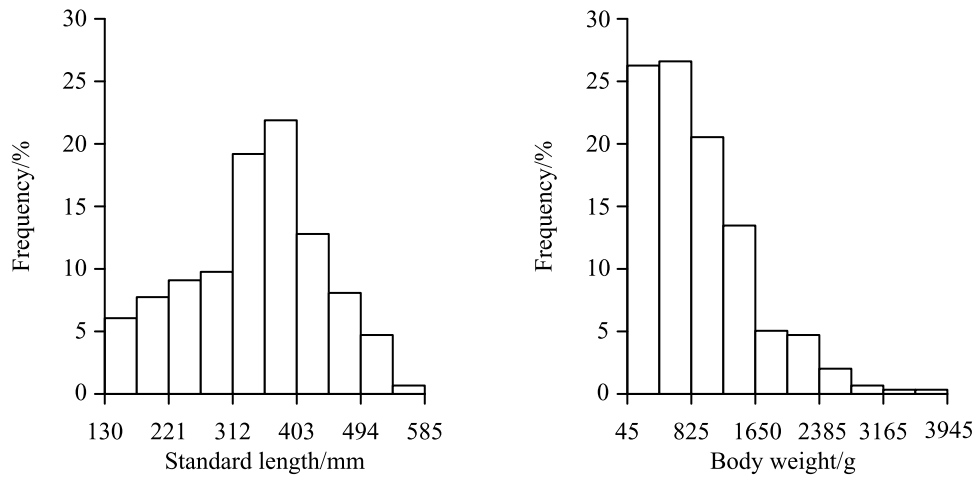


Fig. 3. Distributions of length frequency and weight frequency for the sampled silver carp.

Table 1. Age structure of the silver carp populations.

Age (year)	Body length (mm)	Range (mm)	Body weight (g)	Range (g)	Quantity percentage (%)
0 ⁺	188.13 ± 31.43	130–264	127.99 ± 63.28	45.5–311.4	16.21
1 ⁺	293.66 ± 43.31	200–373	486.37 ± 196.45	141.0–988.1	34.39
2 ⁺	389.81 ± 41.89	242–485	1098.73 ± 372.82	252.0–2204.2	33.20
3 ⁺	465.28 ± 39.94	347–525	1859.67 ± 504.02	738.8–3178.0	14.23
4 ⁺	543.00 ± 25.76	508–585	2909.06 ± 575.36	2265.9–3930.0	1.98

of 901.98 ± 673.61 g, and dominant range of 228.38–1,575.59 g (Fig. 3). The scales collected from 44 of the sampled silver carp were damaged, and therefore their age could not be determined; hence, 253 sampled fish were age-identified. The age range of the specimens was from 0⁺ to 4⁺ years. Among them, 41 fish (16.21%) were age 0⁺; 87 (34.39%) were age 1⁺; 84 (33.20%) were age 2⁺; 36 (14.23%) were age 3⁺; and 5 (1.98%) were age 4⁺ (Tab. 1). Fish in age groups 1⁺ and 2⁺ predominated. All the age 4⁺ silver carp were collected at Wuzhou.

3.2 Length–weight relationship

In this study, the standard length and body weight relationship of the silver carp is given as a power function expressed by the equation $W = 1.66 \times 10^{-5} \times L^{3.015}$ (Fig. 4). The results showed no significant difference between $b = 3.015$ and the value of 3 ($p = 0.49$), indicating that the growth rate of the silver carp was nearly isometric.

3.3 Growth

There is high correlation between scale radius and standard length in silver carp. The computed relationship between standard length and scale radius was expressed as $L = 140.87 \times R + 13.7$. Table 2 lists the backcalculated lengths and weights at different years of life for the sampled silver carp.

The von Bertalanffy growth model yielded the following parameters for the silver carp: $L_{\infty} = 1107$ mm, $k = 0.135$, $W_{\infty} = 25,015.73$ g, and $t_0 = -0.666$. The VBGF L_t is a non-inflection point curve that increases with age and then tends toward an asymptotic value (Fig. 5). The VBGF W_t is an S-type curve and has points of inflection, signifying that the body weight increases with age following a low–fast–low pattern, and then tends toward asymptotic (Fig. 5). Accordingly, the computed growth performance index (ϕ) was 5.22 for the silver carp. The age of growth inflection (t_i) was 7.51, and estimated longevity (t_{\max}) was 21.56.

3.4 Mortality

We determined $Z = 0.4997$ (evaluated with the *B-H* model), $M = 0.1621$, $F = 0.3377$, and $E = 0.6757$ for the sampled silver carp.

3.5 Capture standard

Optimum capture length L_c was calculated as 790.56 mm, and optimum capture body weight W_c was 9,065.29 g. Minimum capture length L_R and minimum capture body weight W_R were 296.64 mm SL and 609.47 g, respectively.

4 Discussion

The present study estimates the age, growth, mortality, and population structure of silver carp in the middle and lower

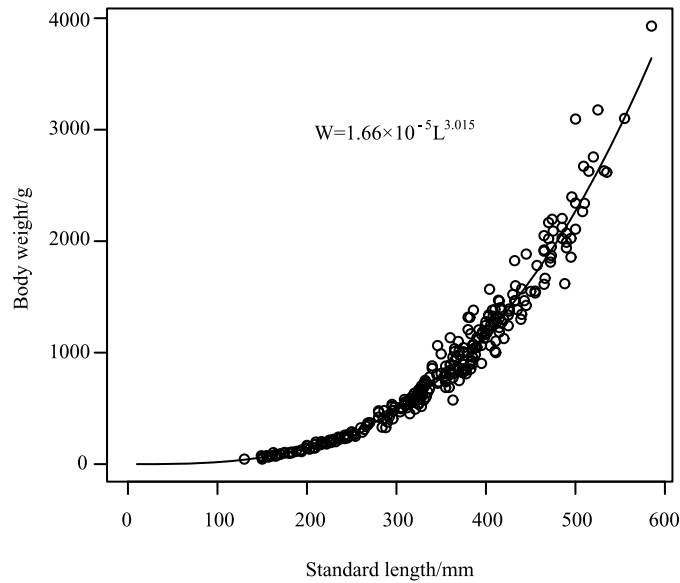


Fig. 4. Relationship between standard length and body weight in the sampled silver carp.

Table 2. Back-calculated and growth measurement of standard length and body weight of the silver carp.

Age	Back calculated body length (mm)	Absolute growth rate	Relative growth rate	Instantaneous growth rate	Index of growth	Back calculated body weight (g)	Absolute growth rate	Relative growth rate	Instantaneous growth rate
1	221.54					195.73			
2	339.51	117.97	0.53	0.43	94.57	708.97	513.24	2.62	1.29
3	426.91	87.40	0.26	0.23	77.77	1414.4	705.43	1.00	0.69
4	519.37	92.46	0.22	0.20	83.69	2554.29	1139.89	0.81	0.59

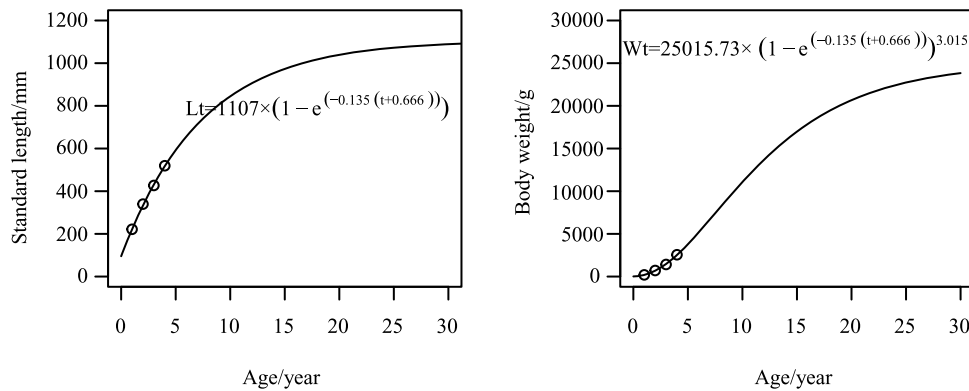


Fig. 5. Growth curves of standard length and body weight for silver carp from the Pearl River.

reaches of the Pearl River. The von Bertalanffy growth parameters L_{∞} , k and t_0 are basic data that are needed for input into the various models used for managing and assessing the status of exploited fish stocks; moreover, these parameters facilitate comparisons between the growth rates of different species or within the same species at different times or in different localities (Mehanna *et al.*, 2018). Table 3 presents the

growth parameters obtained for silver carp in this study alongside values presented by other authors. Parameters k and L_{∞} are interdependent (Gallucci and Quinn, 1979). In general, in this study the larger the value of k , then the smaller the value of L_{∞} . The asymptotic length (L_{∞}) of 1107 mm calculated here for silver carp in the Pearl River is relatively high compared with determinations for this species in other

Table 3. Growth parameters of the silver carp from different localities.

Author	<i>L</i>	<i>L</i> _∞ (mm)	<i>k</i> (/y)	<i>t</i> ₀	<i>b</i>	<i>t</i> _i	<i>φ</i>	Locality	Country
Xiong <i>et al.</i> , 2013	SL	1037	0.188	-0.217	2.9925	5.80	5.31	Upper Yangtze River	China
Pan <i>et al.</i> , 2019	SL	1047	0.160	-0.890	2.7546	5.40	5.24	Middle Yangtze River	China
Wang, 2020	SL	1067	0.147	-1.443	2.953	5.92	5.22	Minjiang River	China
Wang <i>et al.</i> , 2020	SL	746	0.258	0.113	3.0894	4.49	5.16	Songhua River	China
Williamson and Garvey (2005)	TL	778	0.629	-0.161	–	–	5.58	Middle Mississippi River	USA
Hayer <i>et al.</i> , 2014	TL	1224	0.173	0	–	–	5.41	Missouri River, South Dakota	USA
Present study	SL	1107	0.135	-0.666	3.015	7.51	5.22	Pearl River	China

areas, such as in the upper Yangtze River (1037 mm), middle Yangtze River (1047 mm), Minjiang River (1067 mm), and Songhua River (746 mm), whereas the value of *k* that was determined is relatively lower than that for silver carp in the other locations. These results indicate that the silver carp populations in the middle and lower reaches of the Pearl River grow slower as compared with fish in other locations in China. The difference in growth parameters for silver carp in different drainages might be caused by environmental and ecological factors in different regions, including differences in population density and water temperatures (Ju *et al.*, 2016).

In contrast, the values of parameter *b* remained within the expected range of 2.5–3.5 (Froese, 2006). The *b* value for silver carp in the middle and lower reaches of the Pearl River was 3.015, signifying nearly isometric growth. This value was close to that obtained for this species in the Upper Yangtze River (Xiong *et al.*, 2013), Minjiang River (Wang, 2020), and Songhua River (Wang *et al.*, 2020), but higher than that in the middle section of the Yangtze River (Pan *et al.*, 2019). Differences in *b* values for the same species might be attributable to several factors, including differences in environmental conditions, growth phase, stomach fullness, sampling size, and length range (Froese *et al.*, 2011).

Mortality coefficients for silver carp in the middle and lower reaches of the Pearl River are reported here for the first time. Determination of the natural mortality rate (*M*) is an important life-history parameter estimate for managing exploited fish populations (Gray *et al.*, 2017; Sippel *et al.*, 2017). Furthermore, *M* correlates with several other parameters, such as *F*, *E*, *T_c* and *L_R*. Together and individually, these parameters can greatly influence stock assessment outcomes and subsequent management decisions (Gray *et al.*, 2017; Sippel *et al.*, 2017; Newman *et al.*, 2000). In the current study, the estimates of *F* and *E* were greater than *M*, indicating that silver carp populations in this section of the Pearl River are heavily fished. Moreover, the exploitation rate (*E*) exceeded the value denoting optimal exploitation at *E*=0.5 (Patterson, 1992; Gray *et al.*, 2017); this further reveals that these stocks have been overfished.

The maximum age (*t*_{max}) of a fish species will be affected by the environmental conditions (Mehanna *et al.*, 2018). In this study, the estimated longevity for silver carp was 21.56 years, whereas the previously reported maximum age of silver carp was 20 years in Florida, USA (Froese and Pauly, 2020). Age at sexual maturity of silver carp was generally 3 years in the Pearl River (Lu, 1990). In the present study, the age composition of the sampled silver carp varied from 0⁺ to 4⁺, with fish aged 1⁺

(34.39%) and 2⁺ (33.20%) dominant. Moreover, the younger age groups were dominant across the sampling period, indicating the risk of growth overfishing. Juvenile fish are a driving force of recruitment, allowing fish stocks to endure and recover (Ju *et al.*, 2016). For instance, a break in the chain of recruitment will lead to collapse of a fishery if masses of juveniles are captured. Therefore, based on the data obtained here, it is recommended that the minimum capture size of silver carp in the Pearl River should be 790 mm SL.

The middle and lower reaches of the Pearl River are important habitats and fishing areas for silver carp, and all the samples in this study were collected in this section. However, because silver carp are widely distributed throughout the Pearl River, this study cannot reflect the situation of the stock in the whole basin; therefore, the age, growth, and mortality of silver carp in other regions of the Pearl River must likewise be studied.

5 Conclusion

This study of the age structure, von Bertalanffy growth parameters, mortality coefficients, and exploitation ratio of silver carp in the middle and lower reaches of the Pearl River provides vital data for managing the stock dynamics. To conserve this species and sustainably develop the fishery, in this stretch of the Pearl River, silver carp should be protected from capture until at least 790 mm in standard length.

Authors contributions

Zhu Shuli, Li Jie, and Li Xinhui designed the research and wrote the initial manuscript. Zhu Shuli, Wu Zhi, Zhang Yingqiu, Chen Weitao, and He Yujie performed the sampling and laboratory analyses.

Statement of conflict of interest

The authors declare no conflict of interest.

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