

Article

Assessment of *Coilia mystus* and *C. nasus* in the Yangtze River Estuary, China, Using a Length-Based Approach

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Abstract: An assessment of the stock status and historical changes in abundance of *Coilia mystus* and *C. nasus* in the Yangtze River Estuary, China, was carried out based on field surveys conducted in 2019–2020 and published length-frequency (L/F) data from earlier periods. These two species' current and past relative biomasses (B/B_{MSY}) were estimated using a length-based Bayesian biomass estimation method (LBB). The LBB method also estimated their asymptotic lengths (L_{inf}), current and optimum mean lengths at first capture (L_c ; L_{opt_c}), and their ratios of natural and fishing mortality to growth (M/K ; F/K). In response to increasing fishing pressure, both species' maximum lengths declined, along with their B/B_{MSY} ratio, which declined for *C. mystus* from 1.7 in 1982 to 0.47 in 2020 and for *C. nasus* from 1.7 in 2006 (or earlier) to 0.17 in 2020. These assessments show that both of the two *Coilia* species are overfished, with *C. nasus* impacted more severely than *C. mystus*. The prospect for the recovery of these two species is briefly discussed. This contribution will help toward the management of the population of these two *Coilia* species and provides a basis for evaluating the effect of the 10-year fishing ban in the Yangtze River.

Keywords: anchovies; biomass declines; LBB method; overfishing; dam effects; fisheries management and conservation



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1. Introduction

Due to their productivity and location, estuaries provide habitats and migratory routes to many species exploited by fisheries [1–3]. However, despite the immense ecological services they provide, estuaries are threatened habitats throughout the world, mainly by riverine pollution and human settlements [4]. Indeed, these traditional threats to estuaries and their resource are now intensified worldwide by ocean warming, deoxygenation, and acidification [5–9].

The Yangtze is the largest river in China and the third-largest river in the world. The Yangtze River Estuary (Figure 1) is the most important estuary in China and functions as a feeding and wintering ground for hundreds of species exploited by fisheries [10,11]. The depletion of fishery resources due to overfishing and environmental degradation in the Yangtze River Estuary has been relatively well documented in recent years [12–16].

Osbeck's grenadier anchovy (*Coilia mystus*) and Japanese grenadier anchovy (*Coilia nasus*) are small pelagic fish of the family Engraulidae. *C. mystus* is widely distributed in the coastal seas of countries in the Indo-Pacific, ranging from India in the West to China and Japan in the East [17], while *C. nasus*, also known as Japanese tapertail anchovy, has a more restricted distribution centered along the coastal seas of China, Japan, and South Korea in the Northwest Pacific (www.fishbase.org, accessed on 23 January 2022) [18].

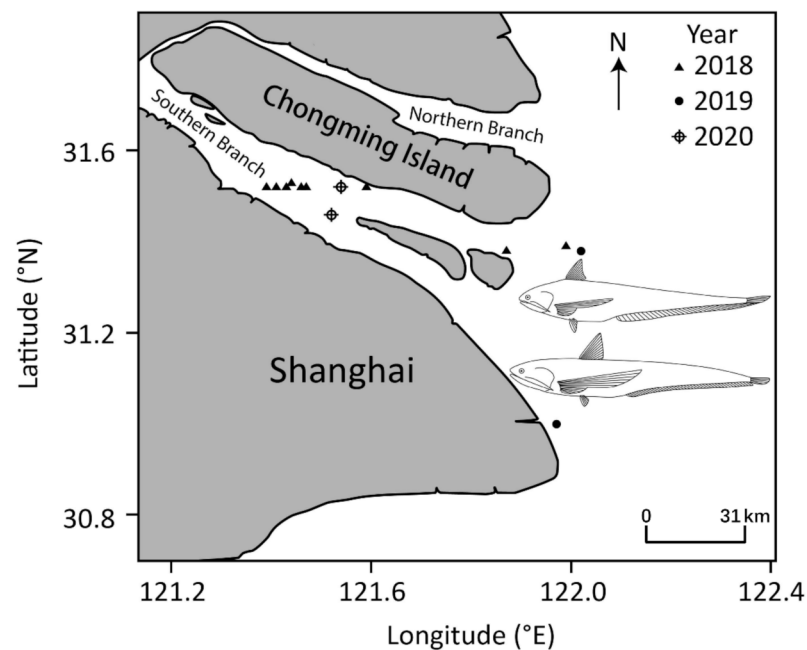


Figure 1. Survey sites for *C. mystus* (2018–2020) and *C. nasus* (2019–2020) in the Yangtze River Estuary, China.

These two species are commercially important [19,20], but in recent years, both declined in China and Japan, which is manifested in the decline of their catch and relative biomass (B/B_0 , i.e., current biomass relative to the estimated carrying capacity), in their catch consisting of younger individuals, and in a trend toward the miniaturization of body size [15,21–24]. Also, *C. nasus* is listed as an endangered species by the IUCN [25].

The Yangtze River and its estuary were the most important habitats for the two *Coilia* species, which supported two of the five major fisheries in the Yangtze River in the past decades. *C. nasus* was a fish sought-after by consumers in the Yangtze Basin, which resulted in a high market price for this species. *C. nasus* was mainly fished by drift net in Yangtze River Estuary. The catch of Shanghai in this area peaked in 1973 at 391 tonnes, then dropped to 49 tonnes by 1988 (Figure 2, right panel).

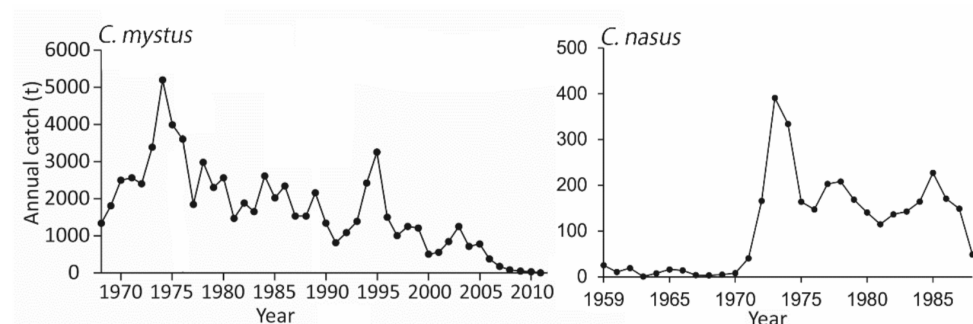


Figure 2. Annual catch of two *Coilia* species in the Yangtze River Estuary (Left panel: catches of *C. mystus* by fishing season (April–July) from 1968 to 2011 [21,26–30]; right panel: catches of *C. nasus* of Shanghai in the Yangtze River Estuary from 1959 to 1988 [31]).

The main gears for *C. mystus* are gill nets and trap nets in the Yangtze River and its estuary. *C. mystus* accounted for almost half of China's total domestic fishery catches before the 1960s [23,26]. Since the 1960s, the production of *C. mystus* has shown a fluctuating decrease in catch, which dropped from more than 5000 tonnes in 1973 to less than 20 tonnes in 2011 (Figure 2, left panel).

The stock of *C. mystus* in the Yangtze River can be clearly separated from the stocks in the Minjiang River and the Pearl River based on morphological, biochemical, and molecular criteria [32,33]. As for *C. nasus*, it is generally divided into three stocks according to ecotypes, i.e., landlocked stock, freshwater-resident stock, and anadromous stock [34,35]; the third stock is the focus of this study.

Scientific stock assessments of exploited fish populations are increasingly required in most countries to provide input for fisheries management [36,37]. A critical output of such assessments is the estimation of time series of mortality, from which the biomass of the exploited fish population can be determined and management or rehabilitation policies formulated.

In China, stock assessments have recently received a boost through the publications of robust methods for use in data-sparse situations, notably the CMSY and LBB approaches [38,39]. The latter approach—formally a length-based Bayesian biomass estimation method—has been successfully applied to over 60 populations of fish and invertebrates along the coast of China [40–44] and in other areas as well [45–47].

The LBB method applies a Bayesian Monte Carlo Markov Chain (MCMC) procedure to one (or several) length-frequency (L/F) sample(s) representative of an exploited population (over time) to estimate the population's biomass (B) relative to its environmental carrying capacity (k), i.e., B/k , where k is roughly equivalent to unfished biomass (B_0). Thus, we report here on B/B_0 .

Simultaneously, other key parameters are estimated by LBB from L/F samples. These include asymptotic length (L_{inf}), length at 50% selectivity (L_c), and natural and fishing mortality relative to the K -parameter of the von Bertalanffy Growth Function, or VBGF (i.e., M/K and F/K). Since catch data, especially for recent years, is not available for *C. mystus* and *C. nasus*, we applied a length-based method to estimate their stock status. Thus, applying the LBB model to the two *Coilia* species presented above should help the management department to better understand their population and fisheries status, and provide a data basis for the evaluation of the effect of the 10-year fishing ban in the Yangtze River.

2. Materials and Methods

2.1. Data Sources

The L/F samples available for this analysis are presented in Tables S1 and S2 (see Supplementary Materials). The samples obtained from 2018 to 2020 originated from surveys of the South Branch of the Yangtze River Estuary in May, June, and July 2018, May 2019, and May 2020 by local fishers hired for the purpose and using set gillnets. Samples of more than 30 kg were split into subsamples, and individuals making up 10% of a sample or subsample were randomly selected and individually measured (standard and total lengths) and weighted. The collection and processing of the samples were carried out in accordance with the Specifications for oceanographic survey-Part 6: Marine biological survey (GB/T 12763.6-2007) [48].

The recent L/F that we obtained were then complemented with L/F data from the published literature to serve as a temporal contrast to the current data.

All the analyses in this paper were implemented using the R-code (version LBB_33. R), which can be downloaded from the website (<http://oceanrep.geomar.de/id/eprint/44832/>, accessed on 23 January 2022); their description and usage are documented in a User Guide [49]. The analyses and visualization were mainly based on the R package R2jags, Formula and ggplot2.

2.2. The LBB Method

The LBB method, as proposed by Froese et al. [39] assumes that the growth of fish is correctly described by the VBGF (see www.fishbase.org, accessed on 23 January 2022) [18,50,51], which has the form:

$$L_t = L_{inf} \left[1 - e^{-k(t-t_0)} \right] \quad (1)$$

where L_t is the fish length at age t , L_{inf} is the asymptotic length, i.e., the mean fish body length at an infinite age, K is a growth coefficient (here in year⁻¹), and t_0 is the theoretical age at zero length.

The LBB further assumes that the fraction of fish individuals that are retained by the fishing gear at length L , i.e., the selectivity of the fishing gear can be represented by

$$S_L = 1 / (1 + e^{-a(L-L_c)}) \quad (2)$$

Also, it is assumed that the selectivity of the gear that produced the L/F samples is the same as that of the major gear in the commercial fishery, which was the case here.

From the length (L_{start}) where $S \approx 1$, when 100% of the fish coming in contact with the gear are retained, the numbers of length L_i left in the population are given by

$$N_{L_i} = N_{L_{i-1}} \left((L_{inf} - L_i) / (L_{inf} - L_{i-1}) \right)^{\left(\frac{M}{K} + \frac{F}{K} S_{L_i} \right)} \quad (3)$$

and

$$C_{L_i} = N_{L_i} S_{L_i} \quad (4)$$

where N_{L_i} is the number of survivors at length L_i , $N_{L_{i-1}}$ is their number at length L_{i-1} , M and F are the instantaneous rates of natural and fishing mortality to which the population is exposed, and C_{L_i} is the number of individuals vulnerable to the gear, computed using the selection probabilities from Equation (2).

The maximum biomass of the unexploited population [52] is computed from

$$L_{opt} = L_{inf} (3 / (3 + M/K)) \quad (5)$$

The optimum length at first capture L_{c_opt} that produces the maximum catch and biomass and leads to L_{c_opt} obtained from the equation

$$L_{c_opt} = L_{inf} (2 + 3(F/M)) / ((1 + F/M)(M/K)) \quad (6)$$

As shown by [39], relative yield-per-recruit (Y'/R) [53], can be re-expressed as

$$\frac{Y'}{R} = \frac{F/M}{1 + F/M} \left(1 - \frac{L_c}{L_{inf}} \right)^{\frac{M}{K}} \left(1 - \frac{3(1 - L_c/L_{inf})}{1 + \frac{1}{M/K + F/K}} + \frac{3(1 - L_c/L_{inf})^2}{1 + \frac{2}{M/K + F/K}} - \frac{(1 - L_c/L_{inf})^3}{1 + \frac{3}{M/K + F/K}} \right) \quad (7)$$

As CPUE is proportional to biomass, and fishing mortality is proportional to fishing effort, $CPUE'/R$ could be obtained from Equation (6) by dividing it by F/M :

$$\frac{CPUE'}{R} = \left(\frac{Y'}{R} \right) / \left(\frac{F}{M} \right) = \left(\frac{1}{1 + \frac{F}{M}} \right) \left(1 - \frac{L_c}{L_{inf}} \right)^{\frac{M}{K}} \left(1 - \frac{3(1 - L_c/L_{inf})}{1 + \frac{1}{M/K + F/K}} + \frac{3(1 - L_c/L_{inf})^2}{1 + \frac{2}{M/K + F/K}} - \frac{(1 - L_c/L_{inf})^3}{1 + \frac{3}{M/K + F/K}} \right) \quad (8)$$

Then, the relative biomass ($>L_c$) when $F = 0$, i.e., before fisheries started, is given by

$$\frac{B_{0>L_c}}{R} = \left(1 - \frac{L_c}{L_{inf}} \right)^{\frac{M}{K}} \left(1 - \frac{3(1 - L_c/L_{inf})}{1 + \frac{1}{M/K}} + \frac{3(1 - L_c/L_{inf})^2}{1 + \frac{2}{M/K}} - \frac{(1 - L_c/L_{inf})^3}{1 + \frac{3}{M/K}} \right) \quad (9)$$

Thus, the relative biomass of exploited fishery can be obtained by

$$B/B_0 = \left(\frac{CPUE'}{R} \right) / \left(\frac{B'_{0>L_c}}{R} \right) \quad (10)$$

3. Results

L/F samples covering six periods were available for *C. mystus* (Figure 3) against three for *C. nasus* (Figure 4). As may be seen, the L/F data (left panels) were well fitted when the LBB model was applied to them (right panels).

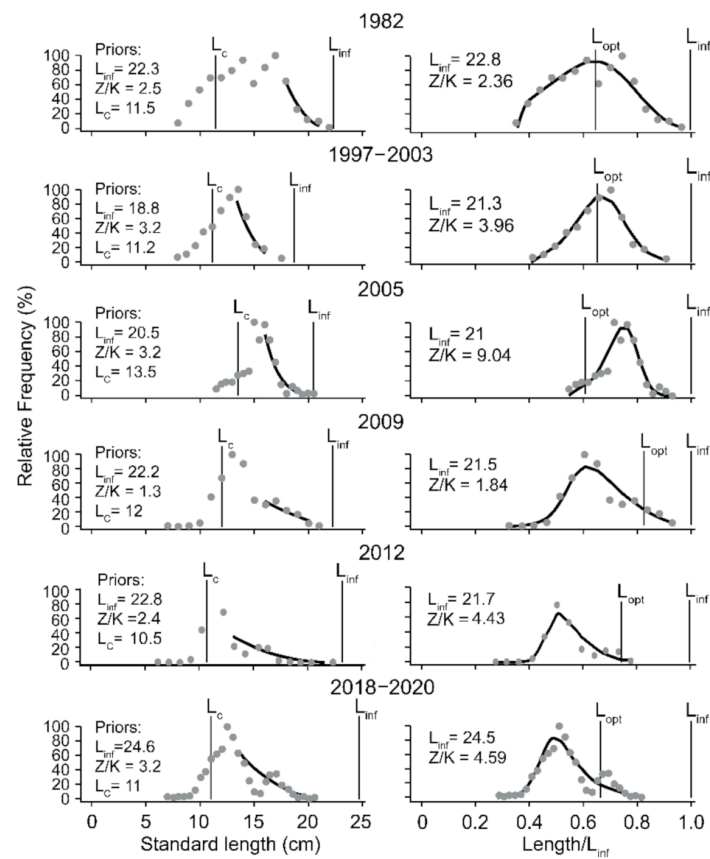


Figure 3. LBB estimation of *C. mystus* from the Yangtze River Estuary. The panels on the left show the length-frequency (L/F) data from which priors are estimated for L_c , L_{inf} , and Z/K . The panels on the right show the fit of the LBB master equation to the L/F data, which provides estimates of Z/K , M/K , F/K , L_c , and L_{inf} , with L_{opt} computed from L_{inf} and M/K .

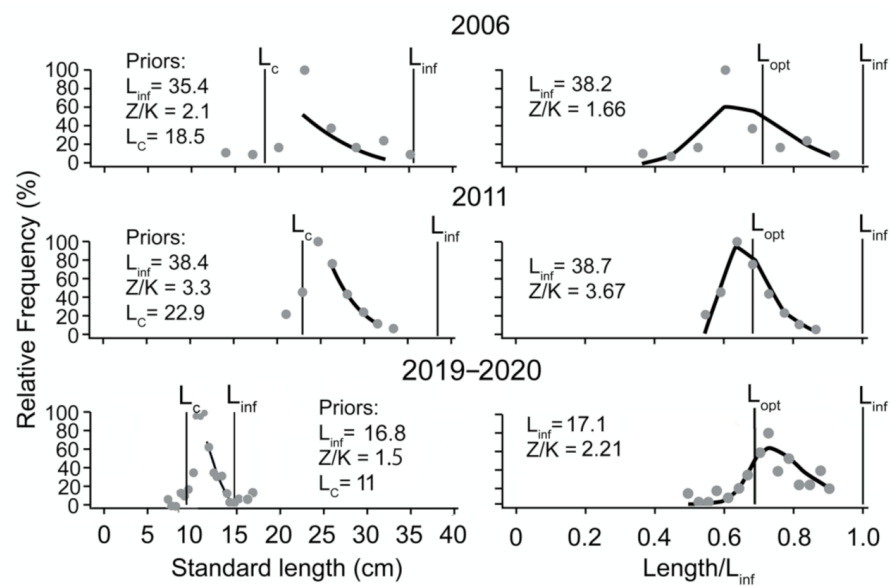


Figure 4. LBB estimation of *C. nasus* in the Yangtze River Estuary. The panels on the left show the length-frequency (L/F) data from which priors are estimated for L_c , L_{inf} and Z/K . The panels on the right show the fit of the LBB master equation to the L/F data, which provides estimates of Z/K , M/K , F/K , L_c , and L_{inf} , with L_{opt} computed from L_{inf} and M/K .

The estimated parameters, i.e., L_{inf} , $L_{c,opt}$, F/K , Z/K , and F/M , are presented in Table 1. They show that the L_{inf} estimates and the maximum length from each sample (L_{max}) for both species have declined in recent years. This effect is particularly strong in *C. nasus*, whose L_{max} of 350 mm in 2006 was reduced to 170 mm in 2019, while its L_{inf} estimates went from 282 to 171 mm in the same time span.

Table 1. Parameters estimates and their 95% confidence limits (brackets) obtained via the LBB method applied to length-frequency samples covering different periods.

Species	Year	L_{max} (cm)	L_{inf} (cm)	$L_{c,opt}$ (cm)	F/K	Z/K	F/M
Osbeck's grenadier anchovy (<i>Coilia mystus</i>)	1982	22.0	22.8 (22.6–23.0)	11.0	0.72 (0.43–1.10)	2.37 (2.03–2.79)	0.44 (0.25–0.72)
	1997–2003	19.4	21.3 (20.9–21.5)	12.0	2.37 (1.96–2.85)	3.98 (3.61–4.41)	1.48 (1.15–1.98)
	2005	20.5	21.0 (20.6–21.4)	12.0	7.11 (5.33–9.02)	9.08 (7.28–10.9)	3.62 (2.77–4.83)
	2009	20.0	21.5 (21.2–21.8)	16.0	1.22 (0.876–1.45)	1.84 (1.70–1.97)	1.95 (0.989–3.25)
	2012	22.0	21.7 (21.3–22.0)	16.0	3.40 (3.03–3.82)	4.43 (4.18–4.76)	3.3 (2.31–4.80)
Japanese grenadier anchovy (<i>Coilia nasus</i>)	2018–2020	20.5	24.5 (24.0–25.0)	14.0	3.06 (2.66–3.45)	4.56 (4.24–4.87)	1.98 (1.54–2.83)
	2006	35.0	38.2 (37.8–38.6)	20.0	0.44 (0.23–0.72)	1.67 (1.53–1.79)	0.36 (0.17–0.76)
	2011	33.4	38.7 (38.2–39.3)	23.0	2.28 (1.76–2.64)	3.68 (3.43–3.95)	1.62 (0.93–2.11)
	2019–2020	16.2	17.1 (16.7–17.2)	12.0	1.5 (1.16–2.19)	2.21 (2.00–2.53)	0.55 (0.35–0.90)

The length decline occurred with a sharp drop in relative biomass for both species (Table 2). For *C. mystus*, B/B_{MSY} dropped from 1.7 in 1982 to 0.25 in 2012, then bounced back to 0.47 in 2020. The B/B_{MSY} of *C. nasus* dropped from 1.70 in 2006 to 0.17 in 2020. This effect was caused by excessive fishing pressure, as expressed by the F/M ratio. For *C. mystus*, F/M increased from 0.44 in 1982, underwent some violent fluctuations, and stabilized at near 2 in recent years, and for *C. nasus* from 0.36 in 2006 to 1.62 in 2011, then declined to 0.55 along with fishing pressure reduced in 2020 (Table 2).

Table 2. Estimated relative biomass (B/B_0) and their 95% confidence limits (in brackets) as obtained by the LBB method.

Species	Year	Y'/R	B/B_0	B/B_{MSY}	Stock Status
Osbeck's grenadier anchovy (<i>Coilia mystus</i>)	1982	0.022 (0.009–0.041)	0.64 (0.25–1.20)	1.70 (0.70–3.20)	Healthy
	1997–2003	0.042 (0.029–0.059)	0.31 (0.21–0.44)	0.85 (0.58–1.20)	Fully/overfished
	2005	0.021 (0.014–0.031)	0.20 (0.13–0.30)	0.55 (0.35–0.79)	Fully/overfished
	2009	0.120 (0.043–0.227)	0.21 (0.07–0.38)	0.50 (0.18–0.92)	Fully/overfished
	2012	0.029 (0.017–0.046)	0.10 (0.06–0.15)	0.25 (0.15–0.4)	Stocks outside of safe biological limits
Japanese grenadier anchovy (<i>Coilia nasus</i>)	2018–2020	0.032 (0.021–0.047)	0.17 (0.11–0.25)	0.47 (0.31–0.69)	Outside of safe biological limits
	2006	0.040 (0.010–0.090)	0.63 (0.16–1.40)	1.7 (0.42–3.80)	Healthy
	2011	0.057 (0.028–0.084)	0.26 (0.13–0.39)	0.71 (0.35–1.10)	Fully/overfished
	2019–2020	0.110 (−0.460–1.200)	0.08 (−0.33–0.86)	0.17 (−0.72–1.90)	Stocks outside of safe biological limits

According to the definitions in Table 3, the stock status for *C. mystus* in 1982 and *C. nasus* in 2006 was 'healthy.' However, after 2006, the status dropped to 'overfished' for both of the two fish species (Figure 5).

Table 3. Definition of fish stock status, based on the estimation of B/B_{MSY} in a given periods.

B/B_{MSY}	F/M	Stock Status
≥ 1	≤ 1	Healthy stocks
0.5–1.0	≤ 1	Recovering stocks
< 0.5	≤ 1	Stocks outside of safe biological limits
0.5–1.0	> 1	Fully/overfished stocks
0.2–0.5	> 1	Stocks outside of safe biological limits
< 0.2	> 1	Severely depleted stocks

Modified from Froese et al. [39] and Zhai et al. [15].

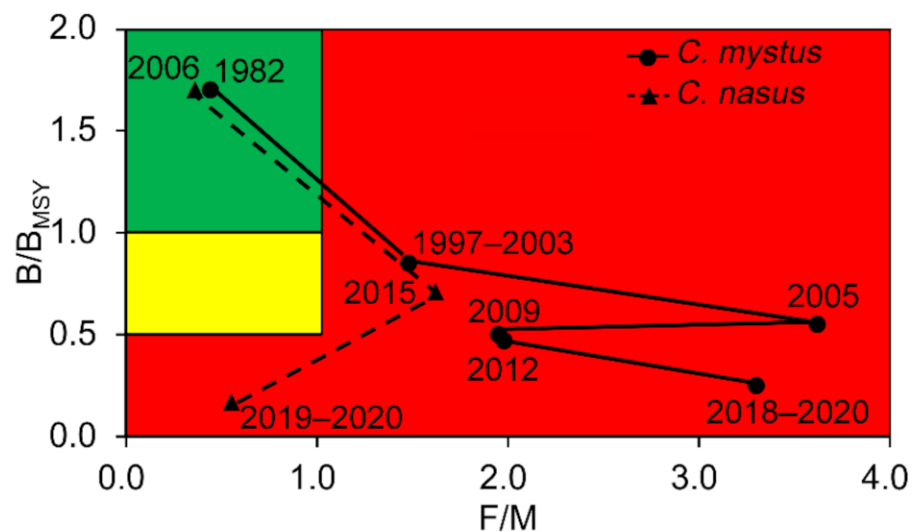


Figure 5. Trajectories of the relative biomass (B/B_{MSY}) and fishing pressure (F/M) for *C. mystus* and *C. nasus* in the Yangtze River Estuary, China. Red area: stocks that are being overfished and/or are outside of safe biological limits; yellow area: recovering stocks; green area: stocks subject to sustainable fishing pressure and/or a healthy stock biomass that can produce high yields close to MSY. Note that the location of 2006 data point for *C. nasus* is very questionable (see Discussion).

4. Discussion

A comparison of the results based on recent L/F samples suggests a worrying stock status for both *Coilia* species. This confirms the trend reported by other authors of worsening conditions for exploited fish populations in the Yangtze River Estuary, here illustrated by the much better state of the same fish population a few years or decades ago (Figure 5). When performing stock assessments, this illustrates the need to utilize data going as far back as possible, to avoid shifting baselines [54] and overly optimistic status assignments [55].

The B/B_{MSY} values for *C. mystus* estimated here are consistent with other studies, based on different data and methods in the same period in the Yangtze River Estuary [16,56].

On the other hand, in the same period, the status of other stock of *C. mystus* in the Minjiang River Estuary (25°45' N–26°30' N and 119°30' E–120°00' E), another important estuary in southeastern China, was in much better shape [41,43]. It had a low F/M of 0.78 and a high B/B_{MSY} of 1.3 in 2014 [41] and 1.9 in 2018 [43], having recovered from overfishing in the late 1980s and early 1990s [57]. This analysis illustrates that the fishing pressure in the Yangtze River Estuary far exceeds that in other parts of China's coast, and that it is urgent to better manage the fishery resources of the Yangtze River Estuary.

What is comforting is that our data suggest that the status of *C. mystus* in recent years may have slightly recovered, possibly because of an early 2019 government ban on the issuance of special fishing licenses for *C. mystus* and *C. nasus* [58].

The available L/F data on *C. nasus* in the Yangtze River Estuary suggest that the stock had remained at a healthy level until 2006 and that its biomass declined only thereafter. However, the value of B/B_0 for *C. nasus* in 2006 may well be an overestimate, because the L/F data used for its estimation was obtained during the spawning season [59], which led to an overrepresentation of adult fish in the sample.

This analysis is supported by the observation that 3–4-year-old individuals accounted for more than 80% of the spawning population in the 1970s, while it is reported to consist of 1–2-year-olds in more recent studies [60,61]. Similar truncations of population structure have been reported from other overexploited fish species [29,62].

In addition to fishing pressure, two other reasons have been attributed to the rapid depletion of the *C. nasus* population: (a) juveniles were caught as bycatch of the glass eel fishery [63], and (b) the construction of a dam led to a reduction of the spawning habitat

and a shortening of the migration channel of *C. nasus* [64]. Indeed, similar causes have been attributed to the decline of *C. nasus* in the Ariake Sea, Japan [65].

The impact of the new dam on *C. nasus* was much more severe than on *C. mystus* because the former species migrates much further upstream than the latter [17,22]. With its biomass currently reduced to less than 20% of B_0 , *C. nasus* now probably suffers from depensation [66], which reduces recruitment when biomasses are low [39]. This situation was different even in the recent past, where the implementation of moderate control measures sufficed and led to a (slight) restoration of the stock [67].

Since the 1980s, China has adopted several management measures to control the fishing effort of the fisheries targeting *Coilia* spp., including limiting the number of fishing boats and nets, banning fishing in the spring, controlling the number of fishing licenses, and strengthening law enforcement (see Table S3 in Supplementary Materials). However, since the failure in the 1990s to ban the deep-water nets and glass eel nets that were extremely harmful to juveniles, fish stocks, especially for *C. nasus*, have been declining continuously. Furthermore, the 2003 dam project affected fish habitat downstream and altered the salinity and sediment supply to the estuary [61]. Thus, the dam added to the damage from legal and illegal overfishing.

Although we applaud the significant progress in the artificial propagation of *C. nasus* [68], we must point to the loss of genetic diversity that a massive reduction of the biomass as sea implies [69–72]. Since early 2020, much of the Yangtze River, including parts of the estuary, is officially declared protected by a ten-year fishing ban. This ban, implemented to recover the fishery resources of the Yangtze River, is the longest and strictest fishery ban in China's history. We hope that its implementation is effective, as this would greatly improve the status of the fish of the Yangtze River and estuary.

5. Conclusions

Length-frequency data, when covering a longer time span and analyzed with the LBB method, can help straightforward inference on changes in the status of exploited fisheries resources. This is illustrated here in the case of two anchovy species, *Coilia mystus* and *C. nasus*, which are both overexploited by various fishing gears in the Yangtze Estuary. However, the life history of species must be considered when performing such assessments, as illustrated here by the fact that *C. nasus*, which performs longer upstream migrations than *C. mystus*, is, therefore, more affected by the construction of dams.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/fishes7030095/s1>, Table S1: Types and sources of the data available for this study, Table S2: Summary of the length data and sampling size for *C. mystus* and *C. nasus* in the Yangtze River Estuary used in this paper, Table S3: The main management measures and the fisheries events of *C. mystus* and *C. nasus* in the Yangtze River Estuary (1960s).

Author Contributions: L.Z.: Methodology, Formal analysis, Writing—Original draft; Z.L.: Data curation, Formal analysis; Y.H. and C.H.: Data curation, Investigation; S.T. and R.W.: Investigation, Supervision; D.P.: Methodology, Writing—review & editing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data that support this study is derived from published papers and available in accompanying online Supplementary Materials.

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Conflicts 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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