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Stock Assessment of Long Whisker Catfish (*Mystus gulio*): Ensuring the Fisheries' Sustainability in the Sundarbans Mangrove, Bangladesh

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Abstract

The world's largest mangrove, Sundarbans, Bangladesh, is the habitat of the euryhaline catfish Nona Tengra (*Mystus gulio*). This study aimed to assess the stock status of *M. gulio* and provide reference points for sustainable fisheries' management. One-year length–frequency (LF) data were collected from the Sundarbans region of Bangladesh and analyzed using the Length-Based Bayesian Biomass (LBB) method and the Length-Based Spawning Potential Ratio (LBSPR) model. The findings showed healthy biomass (B/B_{MSY} = 1.2), with 57% of the wild stock of this species being harvested (B/B_0 = 0.43). The calculated fishing mortality ratio indicated the underfishing conditions (F/M = 0.9). Safe exploitation (E = 0.46) was depicted, as E was smaller than the permitted level of 0.5. The value of capture length (L_c = 12.8 cm) was larger than the optimum capture length (L_{c_opt} = 10.0 cm) and the optimum length for maximum yield per recruit (L_{opt} = 12.0 cm) and larger than the maturity length (L_m = 9.16 cm), indicating the capture of mature individuals. The calculated Spawning Potential Ratio (SPR = 48%) was higher than the target reference points (SPR = 40%). This research evaluated the sustainable stock status. Although the margin between L_{c_opt} and L_m is very narrow, setting the minimum capture size at L_{opt} would be a conservative buffer to ensure long-term sustainability. The recommended minimum harvest size is 12 cm for *M. gulio*. Current fishing gear selectivity can ensure the sustainability of *M. gulio* in Sundarbans, Bangladesh; however, maintaining current fishing practice through careful management is suggested. Further assessments with length-based and other low-data methods should be conducted to refine exploitation estimates and trends.

Keywords: Nona Tengra; healthy biomass; safe exploitation; SPR; fisheries' management

Key Contribution: Healthy biomass and safe exploitation level of *Mystus gulio* was assessed in Sundarbans, Bangladesh, using LBB and LBSPR models. The observed capture size was

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larger than the optimum length (L_{c_opt}) and maturity length (L_m). The Spawning Potential Ratio (SPR) was above the target reference point (SPR = 40%). This study recommends maintaining current fishing pressure and minimum capture size of 10 cm for sustainability.

1. Introduction

The Sundarbans Ramsar site is the world's most diverse contiguous wetland ecosystem. This unique ecosystem is situated in the delta of the Ganges, Brahmaputra, and Meghna rivers, covering approximately 1 million hectares across the southwestern areas of Bangladesh in the districts of Bagerhat, Khulna, and Satkhira and the southeastern portion of West Bengal in India [1]. This mangrove has high biodiversity and species richness. It is home to a wide array of aquatic life, including 322 species of fish, 44 species of crabs, and 20 species of prawns [2]. The fishery resources of Sundarbans are the most significant non-wood element of the forest and play a crucial role in the livelihoods of millions living in the region, supporting the local economy and food security. In the fiscal year 2022–2023, fish production in Sundarbans totaled 26,047 metric tons, contributing 0.53% of the overall inland capture fishery sector of Bangladesh, and it generated a revenue of USD 5.16 million during this period [3].

Mystus gulio, commonly known as the Long Whiskers Catfish, belongs to the family Bagridae under the order of Siluriformes. This euryhaline catfish primarily inhabits brackish water environments, and it can venture into freshwater habitats [4]. It is available in canals, wetlands, haors, oxbow lakes, rivers, and estuaries across Bangladesh, including the Sundarbans delta [5]. This small indigenous fish species (SIS) possesses considerable nutritional benefits [6]. Because of its exceptional taste and high nutritional content, this species has gained widespread popularity among consumers, leading to significant market demand in many Asian countries, specifically in Bangladesh and India [7–10].

However, the rapid growth of human populations, along with limited alternative livelihood options, pose significant challenges to the integrity of Bangladesh's Sundarbans ecosystem. The overexploitation of fish to fulfil rising demand is one of the major reasons for the depletion of wild stocks. In addition to overexploitation, Sundarbans fisheries are also facing a combination of anthropogenic and natural pressures, including illegal fishing, destructive fishing practices, mangrove destruction, pollution, invasive species, sea level rise, siltation, and natural disasters [11]. The decline in fish productivity in Sundarbans is alarming, as indicated by recent studies [12,13]. For example, between 1960 and 2000, the capture of *M. gulio* in the southern coastal region of Bangladesh declined by 33.6% [14]. This decline not only threatens the biodiversity of the region but also the economic stability of the communities that depend on fisheries for their livelihoods. Given the crucial role of this species in the livelihoods of local communities and national economic growth, it is imperative to assess stock status. Stock assessment serves as a vital tool that provides valuable insights into the stock's health and assists policymakers in providing evidence-based reference points to maintain sustainable fishery production.

Currently, accurate and up-to-date stock data for this finfish species are limited in Bangladesh. Several studies have addressed length–weight relationships, food and feeding behavior, reproduction, culture potential, and stocking density of *M. gulio* [8,15–18]. Furthermore, a recent study touched on some variables of stock assessment, such as growth parameters, biomass, exploitation rate, and maximum sustainable yield of *M. gulio* in the Satkhira region [19]. Nevertheless, the application of advanced stock assessment tools, such as Length-Based Bayesian Biomass (LBB) and Length-Based Spawning Potential Ratio (LB-SPR), remains limited in the Sundarbans region. These modern techniques allow us to estimate some key factors and reference points, including the current biomass status relative to MSY, the length of capture (L_c), length at maturity (L_m), minimum and maximum catch size, and the Spawning Potential Ratio (SPR) of this species. Estimation of these parameters is necessary to maintain fishing pressure at a level that ensures fisheries' sustainability.

Addressing the existing research gap, this research aimed to evaluate the stock status of *M. gulio* in Sundarbans by applying Length-Based Bayesian Biomass (LBB) and Length-Based Spawning Potential Ratio (LB-SPR) models. This study collected one-year length–frequency (LF) data to assess stock health and the Spawning Potential Ratio of *M. gulio* utilizing widely accepted LBB and LB-SPR models [20,21]. The findings of this research will contribute to the development of evidence-based policies and management strategies aiming at ensuring the long-term sustainability and economic viability of *M. gulio* in Sundarbans, Bangladesh.

2. Materials and Methods

2.1. Sampling Sites

The study was conducted in Sundarbans, Bangladesh. Length–frequency (LF) data were collected from the six sampling sites, namely, Sarankhola fishery ghat (22°12′43″ N, 89°48′30″ E) and Mongla ghat (22°29′12″ N, 89°35′26″ E) in Bagerhat district, Paikgacha fishery ghat (22°35′22″ N, 89°19′30″ E) and Koyra landing site (22°21′08″ N, 89°17′33″ E) from Khulna district, and Hajrakhali fishery ghat (22°25′38″ N, 89°11′39″ E) and Shyamnagar's fishery ghat (22°14′54″ N, 89°14′17″ E) in Satkhira district (Figure 1).

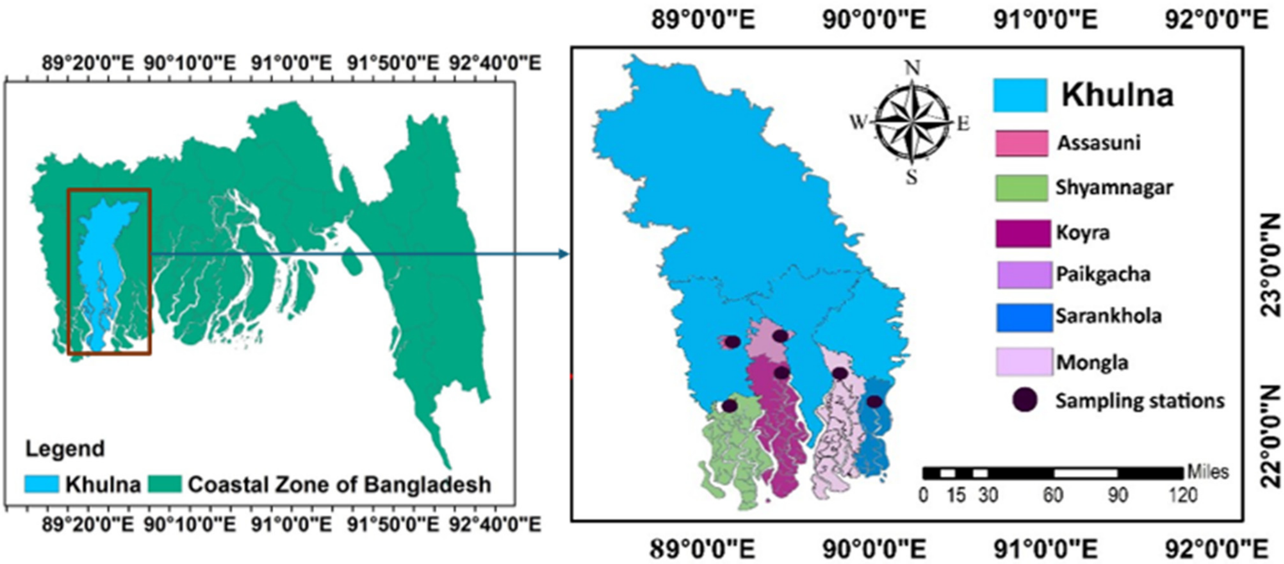

Figure 1. Map of the study area (source: authors, 2025).

These sites were selected to ensure representative spatial coverage of the Sundarbans mangrove in Bangladesh. The divers' estuarine condition of the sampling locations was considered to ensure the availability of euryhaline *M. gulio* species. Thus, these sites are the major artisanal fishing and landing center of this species. Also, their consistent accessibility and prior use in fishery studies support reliable and year-round length–frequency (LF) data collection.

2.2. Data Collection and Analysis

In Sundarbans, Bangladesh, *M. gulio* is primarily harvested by artisanal fishers using small-scale and traditional fishing gear like the monofilament nylon gill net (*Current jal* with mesh size 1.5–2.5 cm), the polyethylene drag net (*Behundi jal* with mesh size 2.0 cm), and the lift net (*Dharma jal*). One-year length–frequency (LF) data were collected from January to December 2023 from artisanal fishing. Monthly sampling was conducted on board condition before landing from each sampling site. During sampling, the total length (TL) of each sampled fish was measured using the measuring wooden scale in millimeter (mm) units. To avoid sampling bias, a random sampling method was carefully chosen to ensure maximum representation across all age classes and length classes, from smaller to larger individuals.

A total of 1180 individual samples of *M. gulio* were collected during the study period. Among them, 145 samples were collected from Sarankhola, with the maximum and minimum length sizes recorded 5 cm to 20 cm, and 191 samples were collected from the Mongla site, with sample sizes ranging from 6 to 19 cm in the Bagerhat district. A total of 177 samples were collected from Paikgacha, with sample size ranging from 6.5 to 19.5 cm, and 177 samples were collected from Koyra, with sample sizes ranging from 8 to 19 cm in the Khulna district. A total of 165 samples were collected from Hajrakhali, with sample sizes ranging from 7 to 19 cm, and 325 samples from the Shyamnagar site, with sample sizes ranging from 5 to 19.5 cm in the Satkhira district (Figure 2).

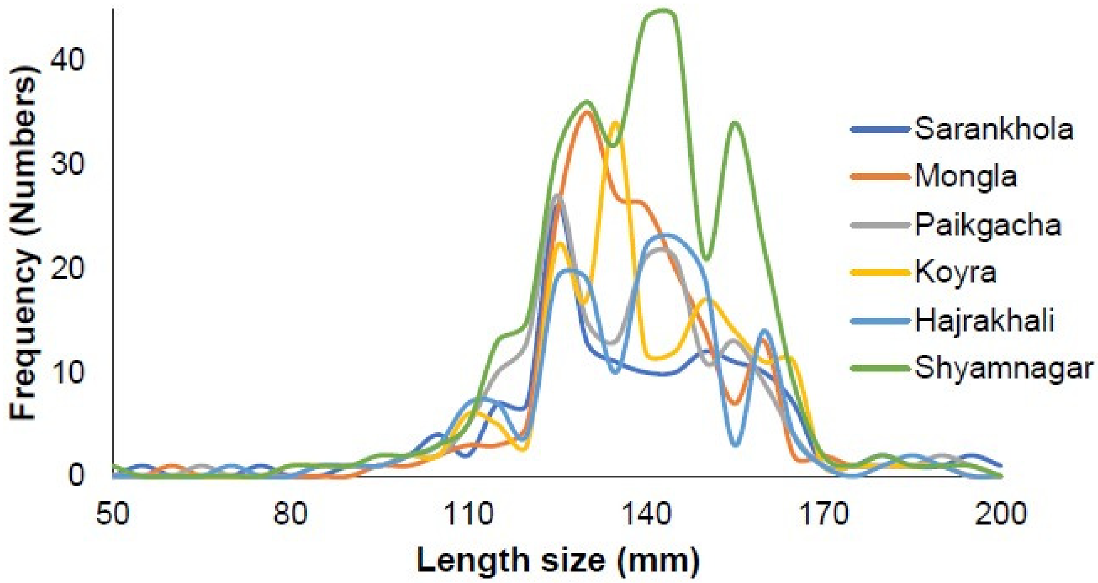

Figure 2. Length–frequency distribution of *M. gulio* collected from six sampling sites.

The collected LFs were than grouped into different length classes based on 5 mm class intervals (CIs). Furthermore, both Length-based Bayesian Biomass (LBB) and Length-Based Spawning Potential Ratio (LB-SPR) methods were applied to analyze the LF data. R-codes for LBB (LBB33a.R) and LBSPR (LB-SPR package) were downloaded from http://oceanrep.geomar.de/44832/ (accessed on 10 July 2021) and https://cran.r-project.org/web/packages/LBSPR/index.html (accessed on 30 March 2022), respectively, and R studio (2024.12.1) was used to run the R codes.

2.3. Description of Length-Based Bayesian Biomass (LBB) Method

The Length-Based Bayesian Biomass (LBB) method was developed as a data limited stock assessment approach designed to evaluate the fish population using simple LF data [20]. The LBB method is particularly suitable in regions or conditions where traditional time series catch data and detailed age structure data are unavailable. This method uses a Bayesian Monte Carlo Markova Chain (MCMC) approach to evaluate the relevant population parameters, including asymptotic length or length infinity (L_{inf}), natural mortality (M), fishing mortality (F), and the ratio between current biomass and biomass producing maximum sustainable yield (B/B_{MSY}). This method also assumes steady-state population dynamics and applies length–base indicators to assess the stock status. Other important biological reference points (BRPs) like ratio of current biomass to virgin biomass (B/B_0), exploitation (E), and mortality ratio (F/M) were also estimated through LBB. The LBB is a cost-effective and reliable stock assessment approach, particularly for small-scale and data-poor fisheries, and it offers guidance for management decisions under uncertainty.

The Von Bertalanffy Growth Function (VBGF) is fundamental to the LBB method to estimate the growth of aquatic organisms, including fish, in terms of length over time [22,23]. This VBGF (Equation (1)) provides a robust framework to describe individual growth trajectories from LF data.

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

Here, length at t is indicated by L_t, the L_{inf} is the asymptotic length, k is the rate at which the L_{inf} is approached, and t_0 is the hypothetical length at zero age.

When a specific type of gear is predominantly used for fishing, the catch curve in the LF distribution is principally influenced by total mortality ($Z = F + M$) relative to the growth coefficient (K), resulting in the rightward skew of the catch distribution by the Equation (2).

$$N_L = N_{L_{start}}\left(\frac{L_{inf} - L}{L_{inf} - L_{start}}\right)^{Z/K} \tag{2}$$

Here, N_L is the number of survivors at L length, N_{Lstart} is the number of samples at L_{start} length, L_{inf} is the asymptotic length, and Z/K is the ratio between total mortality and growth coefficient.

Fishing gears typically exhibit characteristic selection patterns, which are incorporated into the LBB method through a selectivity ogive [24,25]. This ogive function describes the probability of capture as a function of fish length, and it is represented by Equation (3).

$$S_L = \frac{1}{\left[1 + e^{-\alpha(L-L_c)}\right]} \tag{3}$$

Here, S_L is the fraction of an individuals captured at L length, α is the gradient of the ogive, and L_C is the length at first capture.

Through the integration of Equations (1)–(3), the LBB method formulates additional expressions of Equations (4) and (5) to enable the simultaneous estimation of key BRPs, including the ratio of natural mortality to growth (M/K), the ratio of fishing mortality to growth (F/K), the length at first capture (L_c), asymptotic length (L_∞), and the shape parameter of selectivity ogive (α). These equations provide the framework for estimating stock status based on LF data alone.

$$N_{L_i} = N_{L_{i-1}}\left(\frac{L_{inf} - L_i}{L_{inf} - L_{i-1}}\right)^{\frac{M}{K} + \frac{F}{K}\ S_{L_i}} \tag{4}$$

$$C_{L_i} = N_{L_i} S_{L_i} \tag{5}$$

Here, the L_i is the number of individuals at the length i, L_{i-1} is the number at the previous length, and C is the number of individuals vulnerable to fishing gear.

The optimum length (L_{opt}), defined as the length at which the biomass of a cohort is maximized, can be calculated from L_∞ and M/K using Equation (6) [26]. Subsequently, the optimal length at first capture (L_{c_opt}), which corresponds to the maximum yield and biomass under sustainable fishing pressure, is estimated using Equation (7), incorporating values of L_{opt} and the F/M ratio.

$$L_{opt} = L_{inf}(\frac{3}{3+\frac{M}{K}}) \tag{6}$$

$$L_{c\_opt} = \frac{L_{inf}(2+3\frac{F}{M})}{(1+\frac{F}{M})(3+\frac{M}{K})} \tag{7}$$

For the virgin (unfished condition) fisheries, the $Z/K = M/K$, where N_{Lstar} is 1 and L_{star} is 0. Furthermore, the result of L_{c_opt} was used for relative biomass to produce MSY [20]. Table 1 represents the basic information and prior values (L_{inf}, L_c, Z/K, M/K, F/K, and α) for the LBB analysis.

Table 1. Inputs and prior values of LBB and LB-SPR analysis for *M. gulio* in Sundarbans, Bangladesh.

Methods	Parameters	Values
Input values for LBB	Min (mm)	50
	Max (mm)	200
	Class Interval (mm)	5.0
	Individual Number	1180
	L_{inf} Prior (cm)	20.0
	Z/K Prior	1.80
	M/K Prior	1.50
	F/K Prior	0.27
	L_c Prior	11.7
	Alpha Prior	44.7
Input values for LB-SPR	L_∞ (cm)	21.0
	M/K	1.98
	L_{50} (cm)/L_m	9.16
	L_{95} (cm)	16.07

2.4. Description of Length-Based Spawning Potential Ratio (LB-SPR)

The Spawning Potential Ratio (SPR) is a widely recognized fishery reference point with a strong theoretical foundation for guiding sustainable fishery management. The LB-SPR approach is particularly effective for estimating SPR in aquatic species, especially when the natural mortality to growth ratio (M/K) exceeds 0.53 [27–30]. The LB-SPR method is distinguished from other equilibrium-based stock assessment models by several underlying assumptions: asymmetric selectivity; population length at age following the VBGF and being normally distributed; constant natural mortality across the adult population; and a stable growth rate within the stock cohort [31]. This method requires only length–frequency (LF) data for implementation [21]. The LB-SPR model also requires specific life history parameters as inputs: the asymptotic length (L_∞), the M/K ratio, the length at 50% maturity (L_{50}), and the length at 95% maturity (L_{95}). In this study, the L_∞ and M/K values were derived from the LBB analysis, while L_{50} and L_{95} were estimated using Equations (8) and (9), respectively [31,32], as presented in Table 1.

$$logL_{50} = 0.8979logL_\infty - 0.0782 \tag{8}$$

$$L_{95} = 1.1 \times L_{50} \tag{9}$$

The maximum likelihood technique is used to estimate the length of the first capture of a 50% population ($SL_{50\%}$) and a 95% population ($SL_{95\%}$) using the LB-SPR. Furthermore, the LB-SPR approach is used to estimate the relative fishing mortality (F/M) to determine the SPR value [21,31]. The target SPR set at SPR = 40% was set to run the LB-SPR method.

3. Results

3.1. Length-Based Reference Points of *Mystus gulio*

The length-based population parameters and stock status of *M. gulio* were evaluated using the LBB approach in Table 2 and Figure 3. The assessed values of L_{mean}/L_{opt} and L_c/L_{c_opt} were 1.2 and 1.3, respectively, denoting the healthy state of the *M. gulio* stock and the harvesting of prominent individuals. The existence of larger-sized fish within the stock was indicated by L_95th/L_{inf} = 0.93 (higher than unity of 0.9). Furthermore, the obtained value of L_c (12.8 cm) is higher than L_{c_opt} (10 cm) and L_{opt} (12.0 cm), which signifies the harvesting of larger fish at first capture in Sundarbans. However, the assessed $L_c > L_{c\_opt}$ and the $B/B_0 > B_{MSY}/B_0$ suggest that existing fishing pressure and gear have no impact on the biomass of *M. gulio* in Sundarbans, Bangladesh (Table 2).

Table 2. Stock information of *M. gulio* in Sundarbans, Bangladesh, from LBB analysis.

Length Parameters cm		Different Length Ratios		Stock Information	
L_{mean}	14.4	L_{c_opt}/L_{inf}	0.49	M/K	1.98
L_{inf}	21.0	L_{opt}/L_{inf}	0.57	F/M	0.90
L_c	12.8	L_c/L_{inf}	0.61	F/K	1.80
L_{c_opt}	10.0	L_{mean}/L_{opt}	1.20	Z/K	3.90
L_{c50}	12.8	L_c/L_{c_opt}	1.30	B/B_0	0.43
L_{c95}	15.0	L_95th/L_{inf}	0.93	B/B_{MSY}	1.20
L_95th	19.5	E	0.46	B_{MSY}/B_0	0.36
L_{opt}	12.0	L_c/L_{opt}	1.28		
Stock Status	Healthy stock and safe exploitation of *M. gulio* in Bangladesh.				

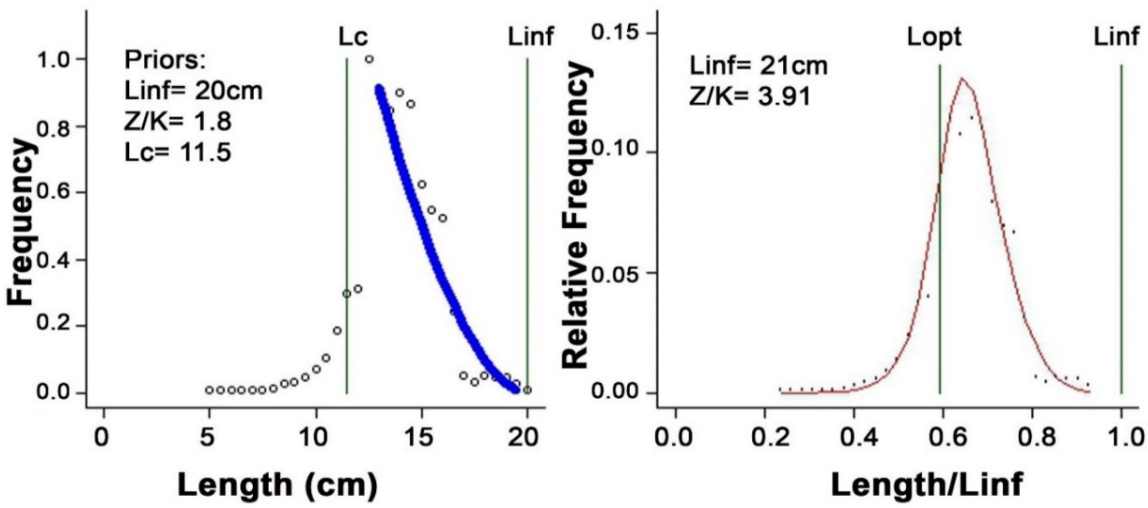

Figure 3. LBB-derived findings for *M. gulio* in Bangladesh's Sundarbans waters.

3.2. Stock Status and Exploitation of *Mystus gulio*

The length-based stock information of *M. gulio* was evaluated using the LBB approach in Table 2. The predicted B/B_{MSY} of 1.2 indicates the healthy condition of the *M. gulio* stock and denotes that the standing biomass is more than the level required to produce MSY. The computed B/B_0 (0.43) indicates the safe biomass of *M gulio* and signifies that only 57% of this stock has been harvested. Additionally, the estimated B/B_0 (0.43) was higher than the B_{MSY}/B_0 (0.36), which suggests that the wild stock of *M gulio* is being underharvested. The calculated F/M ratio was 0.9, which is very close to the optimum level of 1.0, providing further evidence that the *M. gulio* in Sundarbans is currently under sustainable fishing pressure. Moreover, the estimated exploitation rate (E = 0.46) was smaller than the permitted maximum rate of exploitation (E = 0.5), suggesting safe exploitation of *M. gulio* in Sundarbans, Bangladesh.

3.3. Life History, Selectivity, Maturity, and SPR of Mystus gulio

Table 3 and Figure 4 show the results of the LB-SPR analysis for *M. gulio*. The length–frequency distribution (top-left panel) shows a predominance of smaller to medium-sized individuals within the catch, with a clear distinction between unfished (light blue) and fished (pink) portions of the population. The figure highlights a Spawning Potential Ratio (SPR) of 0.40, indicating that approximately 40% of the unfished reproductive potential remains in the stock under current fishing pressure. The maturity length (L_m) was estimated as 9.16 cm (Table 2). The maturity and selectivity ogive curves (top-right panel) indicate that the size at 50% selectivity occurs at a slightly larger length than the size at 50% maturity. This suggests that fish are generally allowed to mature before being subject to high fishing mortality. This pattern is generally favorable from a management perspective, as it suggests that a substantial proportion of the population contributes to reproduction prior to being harvested.

Table 3. Output of LB-SPR model for *M. gulio* in Sundarbans, Bangladesh.

Parameters	Values
$SL_{50\%}$ (cm)	13.37
$SL_{95\%}$ (cm)	16.07
F/M	1.95
SPR	0.48

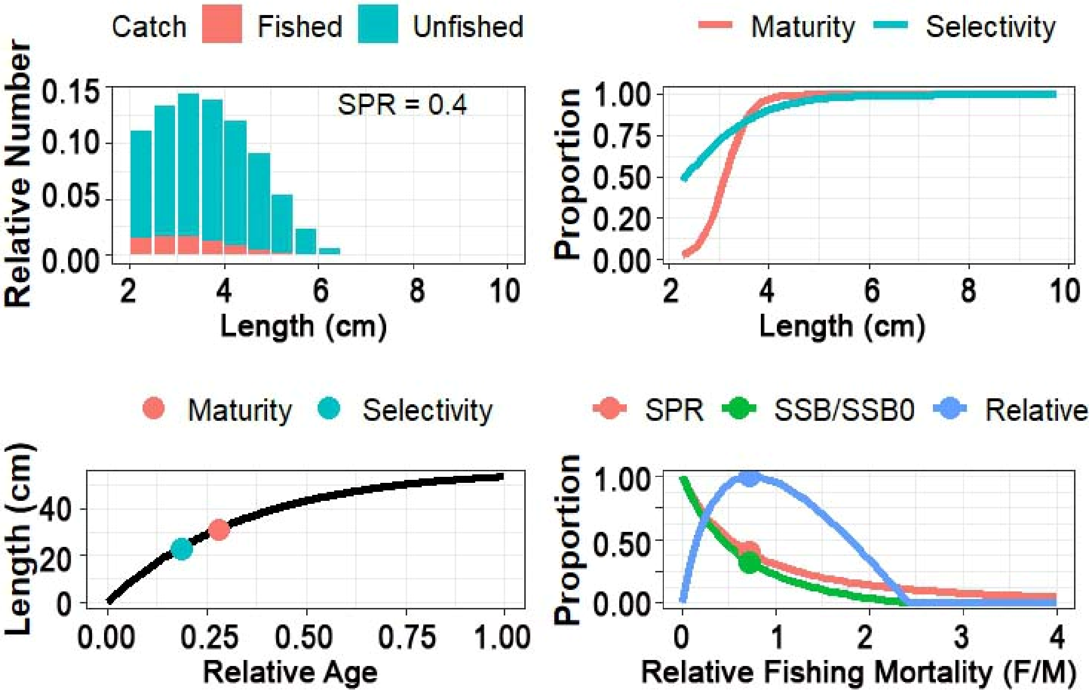

Figure 4. Output from the LB-SPR assessment for *M. gulio* in Sundarbans, Bangladesh, shows the length–frequency histogram with SPR overlay (in top-left panel), the selectivity and maturity ogives (in top-right panel), the length vs. relative age curve (in bottom-left panel), and the performance indicator vs. relative fishing mortality (F/M) (in bottom-right panel).

Figure 5 displays that the growth curve distribution skewed toward smaller size classes, and it was appropriately fitted to the observed length–frequency data for *M. gulio* in the Sundarbans region (Figure 5, left panel). The strong central peak suggests that the population is dominated by mid-sized individuals, potentially near or slightly below the size at first maturity ($L_{50\%}$). The estimated selectivity lengths at 50% (SL_{50}) and 95% (SL_{95}) capture were 13.37 cm and 16.07 cm, respectively (Figure 5, right panel). These values reflect the size ranges over which the majority of fishing mortality is exerted. The average relative fishing mortality (F/M) was estimated at 1.95 from the LB-SPR model, suggesting current overfishing, and the Spawning Potential Ratio (SPR) was estimated at 0.48 (48%), indicating a relatively healthy stock status (Figure 5, right panel). The SPR value indicates that the population retains nearly half of its unexploited reproductive capacity, signifying a relatively healthy stock status. The LB-SPR analysis indicated that the modeled growth curve was appropriately fitted to the observed length–frequency data (Figure 5, right panel), showing a distribution skewed toward smaller size classes for *M. gulio* in the Sundarbans region.

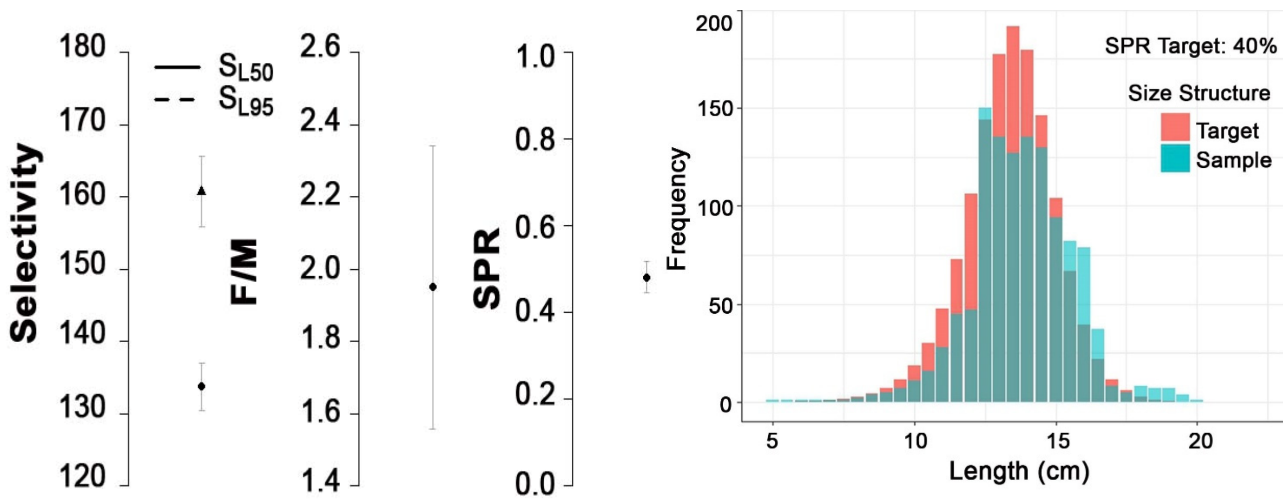

Figure 5. Output from the LB-SPR assessment for *M. gulio* in Sundarbans, Bangladesh, shows the distribution of selectivity for $SL_{50\%}$ and $SL_{95\%}$, relative fishing mortality (F/M), and SPR (in **left** panel). **Right** panel shows the sample observed vs. the target size structure, with the target SPR limit set at 40%.

4. Discussion

4.1. Suitability of LBB and LB-SPR for Mystus gulio

The stock assessment of *Mystus gulio* in Sundarbans using one year of length–frequency (LF) data highlights the effectiveness and applicability of length-based methods—particularly the Length-Based Bayesian Biomass (LBB) and Length-Based Spawning Potential Ratio (LB-SPR)—for evaluating data-poor fisheries. These approaches are increasingly recognized as practical and reliable alternatives to traditional age-structured models, especially where historical catch data, age composition, and fishery-independent surveys are unavailable [20,21,33].

The LBB method is well-suited for fish species, such as *M. gulio*, that exhibit indeterminate growth and are subject to continuous exploitation across various size classes. The method requires only LF data from the exploited population and relies on key life history traits, such as length at first capture and asymptotic length, to estimate biomass status and fishing pressure indicators [20]. In this study, LF data collected over twelve months were stratified into 5 mm length class intervals to ensure high resolution in size structure, and a random sampling strategy was adopted to reduce bias and enhance representativeness across all size classes.

The robustness of the LBB approach is evident from its ability to yield reliable estimates of biological reference points (e.g., B/B_{MSY}, F/M) with minimal data input. Previous studies comparing the LBB method with classical models, such as the Pella–Tomlinson and Beverton–Holt yield-per-recruit approaches, have found that LBB produces consistent and biologically interpretable results even under severe data constraints [20,34]. These strengths make the LBB particularly advantageous for tropical multispecies fisheries and small-scale artisanal sectors, where systematic data collection is often limited.

In parallel, the LB-SPR method proved effective in estimating the Spawning Potential Ratio (SPR), a key indicator of reproductive sustainability. LB-SPR utilizes LF data to infer the proportion of the spawning biomass relative to an unfished population, incorporating parameters for size-selective fishing and maturity. Its reliance on length-based inputs rather than age composition or catch effort data makes it an accessible and scientifically rigorous option for resource-limited settings [21,31]. The successful application of this method to *M. gulio* provides critical insights into the reproductive dynamics of the stock and confirms that the majority of individuals are harvested after reaching maturity—a favorable outcome for ensuring recruitment success.

Together, these methods support a precautionary approach to fisheries' management by offering quantitative estimates of stock status that are grounded in observed data yet require minimal assumptions [24,28,33,35]. They are particularly well-suited for *M. gulio*, a non-target but locally significant species in Sundarbans, where dedicated stock monitoring programs are scarce. Moreover, the findings from both models are consistent, reinforcing confidence in their applicability and reinforcing the reliability of LF-based assessments for data-poor fisheries. The outcomes of the LBB analysis provide not only an assessment of stock status and exploitation level but may also serve as prior information for more complex, data-demanding models. Previous studies have shown that even with limited data, results from the LBB model align well with those obtained from conventional approaches, such as the Pella–Tomlinson surplus production model and Beverton–Holt yield-per-recruit analysis [36,37]. Consequently, the use of LF data for *M. gulio* in this study is justified, and the model's outputs are consistent with expectations for lightly exploited stocks, exhibiting asymmetrical distributions in line with patterns reported in earlier research [20].

4.2. Length-Based Reference Points of *Mystus gulio*

Length-based indicators offer insights into fish stock status and are essential in fisheries' management, particularly for data-poor fisheries or developing areas [34,38,39]. Indicators like mean length, length at first capture (L_c), length at maturity (L_m), and ratios, such as L_{mean}/L_{opt} or L_c/L_{c_opt}, directly inform population size structure. Changes in these indicators indicate overfishing, growth overfishing, recruitment overfishing, or recovery trends, aiding timely management decisions [21,40].

The L_{mean}/L_{opt} ratio is a widely used biological indicator in length-based stock assessment methods. It helps evaluate whether a fish population is optimally exploited, overfished, or underfished. $L_{mean}/L_{opt} \approx 1.0$ suggests that the stock is optimally exploited, L_{mean}/L_{opt} suggests that the stock is overfished, meaning fish are caught too early before reaching optimal size, and $L_{mean}/L_{opt} > 1.0$ may suggest underfishing, meaning fish are generally older/larger and harvesting could be increased [40]. The estimated L_{mean}/L_{opt} was 1.2 and the L_c/L_{c_opt} was 1.3, indicating a population skewed toward larger individuals, which suggests low fishing mortality and selective harvesting of larger fish [21,34].

If $L_c < L_{c\_opt}$, fish are caught before they reach their optimum size of harvest, leading to growth overfishing. If $L_c > L_{c\_opt}$, fish are caught later than an ideal size, possibly causing stock underutilization. When $L_c \approx L_{c\_opt}$, fishing mortality is balanced better to maximize sustainable yield without harming recruitment or growth [32]. The estimated L_c (12.8 cm) was higher than the L_{c_opt} (10 cm), indicating that the gear selectivity or mesh size currently employed enables fish to attain larger sizes before being captured, which is generally favorable for stock sustainability. The findings of this research are supported by different studies conducted in Bangladesh and India (Table 4).

The L_95th/L_∞ ratio is a valuable indicator derived from LF data to evaluate the exploitation status of a fish population [34]. It compares the 95th percentile of observed fish lengths (L_95th) to the theoretical asymptotic length (L_∞) estimated from growth models, such as the VBGF. A ratio of $L_95th/L_\infty > 0.9$ indicates a healthy size structure and the presence of large individuals, while $L_95th/L_\infty < 0.7$ indicates a truncated size structure, potential overfishing, or high selectivity pressure on large fish [34,38,41]. Large individuals within the stock are also supported by a high L_95th/L_∞ ratio of 0.93, exceeding the precautionary value of 0.9, further emphasizing the low harvest pressure.

Selectivity refers to the probability that the fishing gear catches fish of a specific size (length). It is fundamental to understanding how fishing affects different size classes in the population. Length at 50% selectivity ($S_{L50\%}$) is the length at which 50% of the fish are vulnerable or caught by the gear, and length at 95% selectivity ($S_{L95\%}$) is the length at which 95% of the fish are vulnerable to capture [42–44]. This information allows managers to estimate the impact of fishing on spawning biomass and recruitment, influencing stock sustainability. Accurate selectivity estimates improve the precision of BRPs, such as SPR and MSY [43]. Selectivity helps detect growth or recruitment overfishing, guiding adaptive management actions [44]. The estimated size at $S_{L50\%}$ and $S_{L95\%}$ was 13.37 cm and 16.07 cm, respectively. These values suggest that the fishing gear is likely targeting larger individuals, allowing smaller and potentially immature fish to escape. This selectivity pattern aligns with best practices in fisheries' management, promoting stock sustainability by reducing the capture of juvenile fish and allowing them to contribute to future generations [33]. Length parameters help to design the practical size limits, mesh regulations, and harvest control rules to protect spawning biomass and ensure sustainable yields [45]. Fishery managers use this ratio to establish minimum size limits or gear regulations to ensure fish are harvested near the optimal size for productivity [23]. Based on the estimated life history parameters (L_m = 9.16 cm, L_{opt} = 12.0 cm, L_{c_opt} = 10.0 cm, L_{c50} = 12.8 cm), this research recommends a minimum harvest size of 12 cm for *M. gulio*. Although the margin between L_{c_opt} and L_m is very narrow, setting the minimum capture size at L_{opt} (12 cm) would be a conservative buffer to ensure long-term sustainability [23,38]. This precautionary threshold ensures that most individuals have the opportunity to reproduce at least once before capture, while also aligning with the optimum yield length (L_{opt}). Because L_{c50} is larger than L_m and L_{opt}, the gear starts capturing fish significantly above maturity, suggesting that current fishing gear is relatively selective and precautionary to support long-term sustainability of the *M. gulio* stock in Sundarbans, Bangladesh [38].

Table 4. Growth coefficient and length parameters (in cm) of *M. gulio* in different studies.

Study Location	L_∞	K	L_c	L_{c_opt}	Reference
Sundarbans, Bangladesh	21.0	-	12.8	10.0	Present Study (2025)
The Malancha River, Bangladesh	19.3	0.94	-	-	[19]
Sundarbans, Bangladesh	23.0	0.75	8.53	-	[46]
The Meghna estuary, Bangladesh	18.5	0.80	9.80	9.50	[47]
The Krishna estuary, India	21.0	0.68	10.5	10.0	[48]
The Ganga delta, India	20.2	0.70	10.2	10.0	[49]
The Hoogly estuary, India	17.6	0.85	9.50	9.20	[50]

4.3. Stock Status and Exploitation of Mystus gulio

This study offers important insights into the exploitation pattern and stock status of *M. gulio* in Sundarbans, Bangladesh. The fishing mortality (F) relative to natural mortality (M) ratio is expressed as F/M, which is a widely used metric in fisheries' stock assessment because it provides a standardized and biologically meaningful measure of fishing pressure relative to the natural loss of fish from the population [20]. $F/M < 1$ denotes that the fishing is considered sustainable or underexploited, $F/M \approx 1$ indicates sustainable limits, and $F/M > 1$ indicates unsustainable depletion or collapse [31]. The F/M ratio was calculated at 0.90, well below the optimal benchmark of 1.0 [51]. This assessed low F/M value indicates minimal fishing pressure and reflects responsible regional harvesting practices. Supporting this, the exploitation rate (E = 0.46) also remains close but lower than the commonly accepted threshold of E = 0.5 for sustainable exploitation [52–55]. Together, these indicators underscore a low level of exploitation of *M. gulio* in Sundarbans, affirming its role as a relatively undisturbed habitat for this species, as supported by different studies conducted in Bangladesh and India (Table 5).

Table 5. Mortality and exploitation status of *M. gulio* in different studies.

Study Location	*M/K*	*Z/K*	*F/K*	*F/M*	*E*	Reference
Sundarbans, Bangladesh	1.98	3.9	1.8	0.9	0.46	Present Study (2025)
The Malancha River, Bangladesh	1.60	3.6	2.9	1.8	0.63	[19]
Sundarbans, Bangladesh	2.12	4.0	1.9	0.9	0.47	[46]
The Meghna estuary, Bangladesh	1.20	2.3	1.1	0.9	0.48	[47]
The Krishna estuary, India	1.00	1.6	0.9	0.9	0.40	[48]
The Ganga delta, India	1.10	1.9	1.0	0.9	0.47	[49]
The Hoogly estuary, India	1.3	2.5	1.2	0.9	0.49	[50]

The biomass to biomass producing MSY (B/B_{MSY}) ratio and current biomass to virgin biomass (B/B_0) were analyzed using the LBB method to clarify the fishery stock's condition. Stocks were classified according to the B/B_{MSY} values as follows: healthy stock ($B/B_{MSY} > 1.1$), slightly overfished ($0.8 < B/B_{MSY} \leq 1.1$), overfished ($0.5 < B/B_{MSY} \leq 0.8$), grossly overfished ($0.2 < B/B_{MSY} \leq 0.5$), and collapsed ($B/B_{MSY} \leq 0.2$) [20]. The estimated B/B_{MSY} ratio in this research was 1.2, indicating a biomass level exceeding the required amount to reach the MSY, suggesting a healthy stock [20]. The healthy stock status of this research is supported by different studies (Table 6).

Table 6. Stock health condition of *M. gulio* in different studies.

Study Location	Stock Status	Reference
Sundarbans, Bangladesh	Healthy	Present Study (2025)
The Malancha River, Bangladesh	Overexploited	[19]
Sundarbans, Bangladesh	Fully exploited	[46]
The Meghna estuary, Bangladesh	Fully exploited	[47]
The Krishna estuary, India	Healthy	[48]
The Ganga delta, India	Healthy	[49]
The Hoogly estuary, India	Fully exploited	[50]

B/B_0 is commonly used in data-limited stock assessments to evaluate how much of the original population remains, and it helps to quantify the depletion of fish stocks to guide management decisions and conservation strategies [20]. A B/B_0 range from 0.4 to 0.5 is the precautionary biomass level that maintains sustainable yields without risking stock collapse [51]. The computed B/B_0 value of 0.43 is within the biological limit threshold, which denotes that the current biomass retains 57% of its unexploited level. This suggests that only a tiny fraction of the stock has been harvested [20]. Similarly, the observed B/B_0 (0.43) surpasses the B_{MSY}/B_0 reference value (0.36), further indicating that the stock is underharvested and exists in a biologically safe state [21].

4.4. Spawning Potential Ratio of Mystus gulio

The Spawning Potential Ratio (SPR) serves as an essential reference point in fisheries' management indicating the reproductive capacity of a fish stock compared to its unfished state. The SPR is a dependable biological benchmark for evaluating how current fishing pressures affect a stock's reproductive ability [21,31]. Various species have different SPR limits that act as biological reference points for sustainable fishing practices. The 30% SPR (0.3) often functions as a proxy limit below which recruitment can be hindered; this is commonly applied to multiple fish stocks worldwide [56]. A SPR range of 20–30% is frequently recommended to prevent recruitment overfishing, particularly in fisheries with limited data [57]. A 40% SPR (0.4) may serve as a target or more precautionary limit, especially for heavily fished stocks or vulnerable stocks [21]. Additionally, a 35% SPR is proposed as a reference for certain species where some reduction in spawning biomass is deemed acceptable [58], while a 50% SPR is regarded as a conservative target for sustainable fisheries to ensure strong reproductive capacity [59]. The LB-SPR model for *M. gulio* in Sundarbans indicated an SPR of 0.48, suggesting that the stock retains around 48% of its unfished reproductive capacity and can maintain adequate reproductive output for long-term sustainability. Consequently, the SPR value for *M. gulio* indicates a healthy spawning biomass, affirming that current fishing methods do not significantly threaten the population's reproductive potential.

5. Conclusions

The current evaluation shows that *M. gulio*'s stock status is healthy. The exploitation rate (E) and the mortality ratio (F/M) suggest moderate fishing pressure close to the upper limits. With B/B_{MSY} (1.20), stock biomass exceeds the level necessary for MSY, indicating sustainable fishing practices. The length at $L_c > L_{c\_opt}$ shows that fish are harvested after reaching an optimal size. B/B_0 (0.43) and B_{MSY}/B_0 (0.36) indicate that biomass has dropped to 43% of unexploited levels, presenting an opportunity to rebuild stock resilience. SPR (0.48) suggests the stock is near the critical threshold of 0.4, below which reproduction could be at risk. Thus, E (0.46) is acceptable, allowing current fishing pressure to be sustained but not increased. However, metrics like SPR and B/B_0 indicate a need for precautionary management for long-term sustainability. A minimum harvest size of 12 cm is recommended for *M. gulio* based on the estimated life history parameters. The current fishing gear is relatively selective and precautionary, which allows the majority of individuals to reproduce at least once prior to capture. Though the current fishing practice can promote the long-term sustainability of *M. gulio* stock in Sundarbans, Bangladesh, maintaining or enhancing the SPR ratio through careful management is advised. Ongoing assessments with length-based and other low-data methods should be conducted to refine exploitation estimates and monitor trends.

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