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Stock Assessment and Rebuilding of Two Major Shrimp Fisheries (*Penaeus monodon* and *Metapenaeus monoceros*) from the Industrial Fishing Zone of Bangladesh

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Abstract: The two economically important shrimp species in Bangladesh are the tiger shrimp, *Penaeus monodon*, and the brown shrimp, *Metapenaeus monoceros*. However, a continuous decline in the landing of these species from the industrial trawling made it critical to assess their stock biomass status to explore their response to the present degree of removal. Given the minimum data requirement and robustness, this study employed the depletion-based stock reduction analysis (DB-SRA) to assess these fisheries rigorously. For the industrial fishing zone (beyond the 40 m depth in the EEZ of Bangladesh), the estimated historic mean carrying capacity (*K*) was 5015 metric tons for the *Penaeus monodon* and 35,871 metric tons for *Metapenaeus monoceros*. The estimated overfishing limits (*OFL*), which were much smaller than the reported catches throughout the time series, indicate the overfishing status of these fisheries. As a result, the estimated biomass for the reference year (B_{2020}) for both species was lower than B_{MSY}, indicating that these fisheries are not producing *MSY*. Therefore, for the rebuilding and sustainable management of these stocks, this study recommended a catch limit of 100 metric tons for *P. monodon* and 750 metric tons for *M. monoceros* for the next ten years from biomass projections.

Keywords: tiger shrimp; brown shrimp; depletion-based stock reduction analysis; stock assessment; overfishing

1. Introduction

Marine fisheries are critical to the economic and well-being of coastal communities in terms of food, employment, income, and livelihoods [1,2]. However, in today's world, it is increasingly recognized that a significant number of marine fish stocks have already been depleted, particularly in developing countries, due to their ever-growing population, increased demand, over-exploitation, and/or insufficient fisheries management ability [3–6]. Given these situations, to sustain these resources and rebuild the depleted stocks, science-based stock assessments that will provide necessary information for effective management policies are urgent [7–12]. Furthermore, stock assessments provide the basis to evaluate the effectiveness of existing management policies for sustainable harvesting or rebuilding a depleted fish stock [13,14].

In Bangladesh, industrial trawling beyond 40 m depth in the exclusive economic zone (EEZ) for shrimp and demersal fishes significantly contributes to the country's total marine landings [15,16], with shrimp playing a pivotal role. In 2019, shrimp contributed approximately 7% (42,749 metric tons) of total marine landings [17]. Despite the fact that 37 shrimp species have been reported from Bangladesh's maritime waters, the most economically important shrimp species include tiger shrimp (*Penaeus monodon*), brown shrimp (*Metapenaeus monoceros*), and white shrimp (*Penaeus indicus*) [17–21]. However, in terms of commercial importance, the tiger shrimp, *P. monodon*, outperform others [22]. With the growing number of tiger shrimp hatcheries along the coast of Bangladesh, extensive collections of postlarvae (PL) and broodstock (matured shrimp) from the wild have made this fishery vulnerable [23]. On the other hand, the brown shrimp is a major contributor to the shrimp trawling landing, and in 2019, it was accounted for over half of the total shrimp landing [24]. Even though the number of shrimp trawlers has remained constant for nearly two decades, a continuous decline in total shrimp landings since the beginning of the fishery was observed, i.e., 12% lower than the previous year in 2019 [24]. Given their significant economic importance, the sustainability of these fisheries must be ensured through appropriate management strategies based on scientific advice following a complete and formal stock assessment. But a traditional stock assessment method requires detailed information on the population, time-series of catch data, mortality, age structure, stock-recruitment relationships, catch per unit effort, and other life-history parameters [25,26]. Unfortunately, like most of the world's fish stocks, the marine fisheries of Bangladesh lack these data and are classified as data-poor fisheries. Though several data-poor stock assessment methods based on surplus production models (SPMs) have been developed [26–33], the primary indices of abundance essential for these methods as input parameters are based on catch and effort data [34,35]. However, these indices can be misleading in a multi-gear and multi-species fishery (i.e., marine fisheries of Bangladesh) if a proper standardization technique for the catch and effort data is not employed [36]. Studies that assessed shrimp populations using catch and effort data from the marine water of Bangladesh reported the over-exploitation and depleted stock biomass [23,37–43]. Unfortunately, these studies used the effort data presented in the "Yearbook of Fisheries Statistics of Bangladesh" [17] without any evidence of standardization, which could be affected the estimation of fisheries reference points. Furthermore, they mainly focused on estimating maximum sustainable yield (*MSY*), but other reference points, such as the overfishing limit (*OFL*) and information on population trends, remained ignored, which are indispensable for fish stock management [44].

To minimize the data requirement, Walters et al. (2006) [45] proposed an alternative based on a stock reduction analysis (SRA) that predicts the historical abundance required to sustain the observed fishery catches without extinction based on life-history parameters (primarily the intrinsic population growth rate r, carrying capacity K, and natural mortality rate M) rather than effort data. Dick and MacCall (2011) [46] later developed the depletion-based stock reduction analysis (DB-SRA) by introducing a depletion rate (the ratio between present biomass and the initial carrying capacity of the stock) in the procedures of SRA. However, this method requires an actual time series of catch data and basic life-history parameters of the exploited stock. Given the availability of some life-history parameters of *P. monodon* and *M. monocereos* in literature and time-series of catch data, the objective of this study was to evaluate the stock status of these two shrimp stocks using the DB-SRA method to determine the reasonable yield and management reference points including overfishing limit (*OFL*). Because of its robustness, this method is approved by the Pacific Fisheries Management Council (PFMC) for the assessment of data-poor fish stocks and recommended for Only Reliable Catch Stocks (ORCS) by the national oceanic and atmospheric administration (NOAA) [47,48]. Based on the results, this study also ran biomass projections for both species to identify the catch limit that will actively rebuild the stock biomass and defined the limit as the total allowable catch (*TAC*) for the respective species for the next ten years.

2. Materials and Methods

2.1. Study Area and Data Source

Bangladesh's marine industrial fishing zone defines the area beyond 40 m depth in the EEZ (Figure 1), and the fishing activities in this area are mainly characterized by demersal trawling for fish and shrimp. Shrimp trawlers ranged in length from 20.5 to 44.5 m, had outriggers, and operated 2–4 nets at once with modern shrimp trawl nets. The cod-end mesh sizes of trawl nets range from 4.5–6 cm and head rope lengths 15–35 m. [49,50]. These trawlers typically have a gross tonnage capacity of 150–250 metric tons and a main engine power range of 500–900 BHP. Although trawl fishing in Bangladesh was introduced in 1972, the commercially based demersal trawling for shrimp has been in full swing since 1986 [22]. Therefore, from 1987 to 2019, 33 years of time-series catch data of two commercially important shrimp species, *P. monodon* and *M. monoceros*, were collected from the catch logbook data sheets of the Marine Fisheries Office and Fisheries Resources Survey System's (FRSS) publications [24]. The catches are expressed in metric tons.

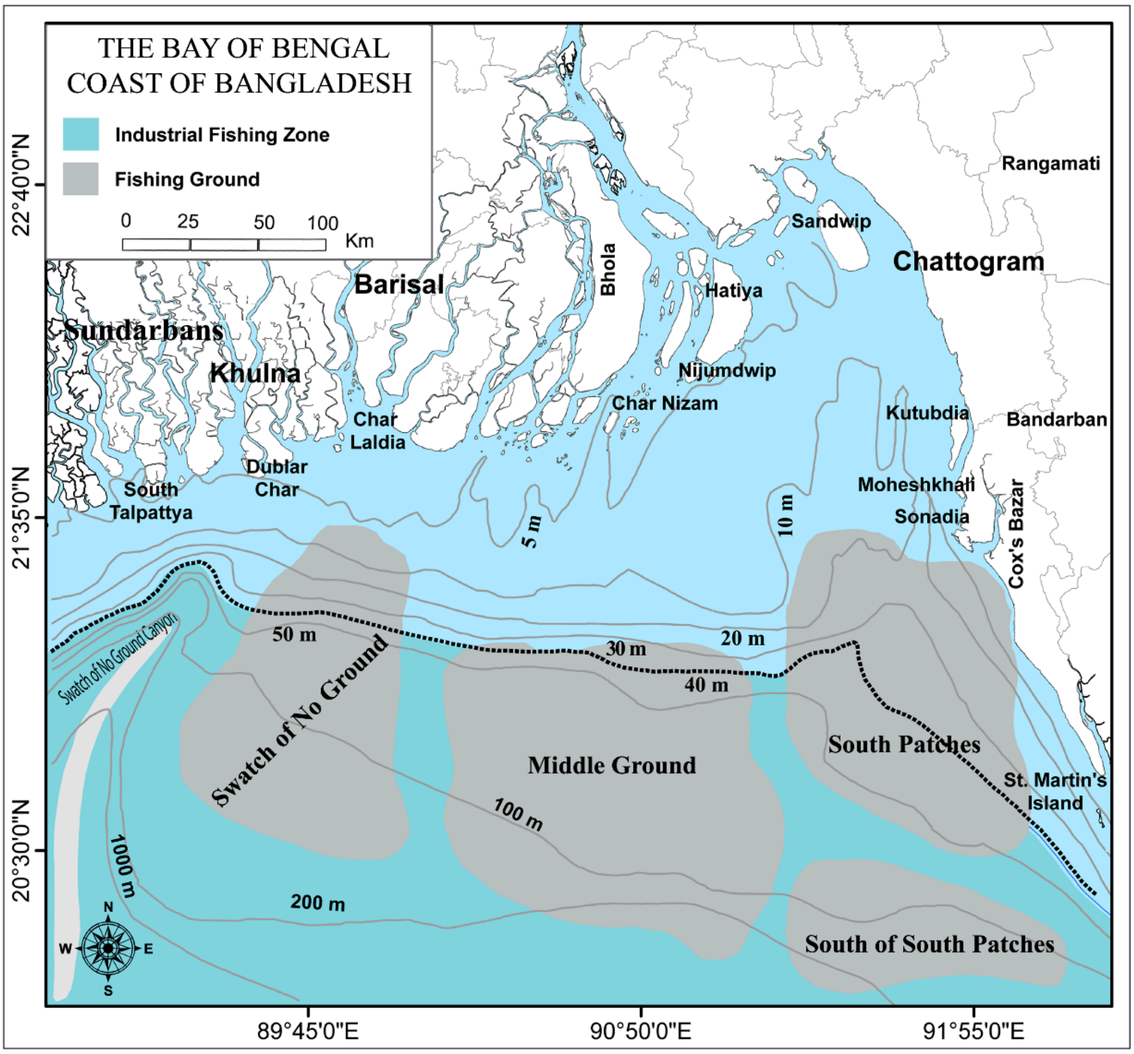

Figure 1. Map showing the Bay of Bengal coast of Bangladesh. The area beyond the black dotted line (40 m depth contour) is the industrial fishing zone. Shaded regions indicate the four major fishing grounds, i.e., South Patches, South of South Patches, Middle Ground, and Swatch of No Ground.

2.2. The DB-SRA Model

The DB-SRA model [46] uses a surplus production model in the form of

$$B_t = B_{t-1} + P(B_{t-a}) - C_{t\text{-}1} \quad (1)$$

where B_t and C_t are the biomass and catch at time t, $P(B_{t-a})$ is the latent annual production based on the initial biomass a (median age at sexual maturity) years earlier. In the DB-SRA model, annual production follows a Pella-Tomlinson-Fletcher production model [51] that allows flexible specification of peak latent productivity and MSY, which is

$$P(B_{t-a}) = \gamma m(B_{t-a}/K) - \gamma m(B_{t-a}/K)^n \quad (2)$$

where n is the Pella-Tomlinson shape parameter that defines the magnitude of the maximum productivity of the stock concerning its carrying capacity (K) based on the following assumptions:

a. when $n = 2$, the biomass at maximum sustainable yield (B_{MSY}) equals $K/2$;
b. when $n < 2$, B_{MSY} is less than half of K; and
c. when $n > 2$, B_{MSY} is higher than half of K [52].

From n, the parameter γ can be calculated as:

$$\gamma = n^{(n/n-1)}/n-1 \quad (3)$$

m denotes the stock's maximum sustainable yield (MSY) and is a function of n, K, and exploitation at maximum sustainable yield (U_{MSY})

$$m = Kn^{(n/n-1)}U_{MSY} \quad (4)$$

The DB-SRA model starts its analysis with a set of four Monte Carlo-drawn life history-based input parameters [46] and projects the population forward based on the number of removals each time, equaling the observed time series of catches with some uncertainty in those catches [46,52]. The life history- parameters that are used as input parameters in the model run are nature mortality (M), the ratio of fishing mortality that is required to produce MSY to M (F_{MSY}/M), the relative biomass at maximum latent productivity (B_{MSY}/K), and the relative biomass depletion level (B_t/K) for a specific recent year t. t doesn't need to be the final year in the time series, and this study assigned t to the following year of the final year of the time series (2020) and defined it as the reference year.

Based on the observed catches, the model estimates the stock's virgin population size required to prevent the extinction of the population and end up at some fraction of K by year t. The DB-SRA model proceeds iteratively, and the iterations that end in extinction are rejected, while iterations that allow the population to survive till the end of the time series are accepted. Therefore, final distributions of K, MSY, B_{MSY}, U_{MSY}, and a harvest control rule, overfishing limit (OFL), can be estimated from the distributions of the accepted parameter sets.

2.3. Estimation of Input Parameters

The initial carrying capacity (K) for the model run was assumed to be ten times the maximum catch in the time series data.

Due to the unavailability of age at sexual maturity and the difference in estimated length at sexual maturity (L_m) in different studies [53–58], this study used the following empirical equation proposed by Froese and Binohlan (2000) [59] to estimate the length at maturity (L_m) of both shrimp species from the asymptotic length (L_∞):

$$log\ L_m = 0.8979(log\ L_\infty) - 0.0782 \quad (5)$$

The following equation derived from the von Bertalanffy (1938) [60] growth formula was then used to estimate the age at maturity (t_m) from growth coefficient (K), L_∞, and estimated L_m:

$$t_m = t_0 - (1/K)ln[1 - (Lm/L_\infty)] \quad (6)$$

Based on the estimated values of L_∞ and K by Mustafa et al. (2006) [61], this study calculated the age at sexual maturity for *P. monodon* to be 0.91 years and 0.63 years for *M. monoceros*. Therefore, the age of maturity for both species was set to 1 year for the model run.

The reported maximum age for *P. monodon* was three years [62] and 2.5 years for *M. monoceros* [63]. Therefore, natural mortality (M) for both species was estimated using the following equation proposed by Hoenig's (1983) [64];

$$ln(M) = 1.44 - 0.982 \times ln(\text{maximum age}) \quad (7)$$

The M for *P. monodon* was calculated to be 1.43 year^{-1} and 1.70 year^{-1} for *M. monoceros*, assumed a log-normal distribution with a standard deviation (*sd*) of 0.4, and bounded from 0.001 to 3. The upper bound was set to cover other estimates reported in the literature for both species [61,65]. According to the rule of thumb, in a sustainably managed fishery, the F_{MSY}/M ratio should equal 1; therefore, this value was used in the base model run. However, Walters and Martel (2004) [66] suggested that the F_{MSY}/M ratio should be 0.8, and this study used this value in the model sensitivity runs (see description of sensitivity runs below). Based on the assumption that the target biomass (B_{MSY}/K) is 40% of unfished biomass (0.4 K), the input value for B_{MSY}/K was set to 0.4 for the base model run. Because of their relatively fast sexual maturity, shrimp species show high productivity, which results in a low value for B_{MSY}/K [52] and, thus, the input value of B_{MSY}/K was decreased to 0.25 for sensitivity analysis [52], assuming a beta distribution with *sd* = 0.05 and bounded from 0.05 to 0.95 (Table 1). The time-series data showed a significant decrease in catches, and therefore, this study assumed a high level of depletion and set B_t/K at 0.30 following a beta distribution with *sd* = 0.1 and bounded by 0.01 and 0.99. The relative biomass to K (B_1/K) in the first year when the fisheries began was set to 1 (assuming the initial biomass was equal to the carrying capacity), assuming that B_1/K) equals the mean and *sd* = 0.1 and bounded from 0.01 to 1 (Table 1).

Table 1. Input distribution for the DB-SRA analysis base model and sensitivity runs.

Parameters	Base Model Distribution	Sensitivity Perturbation
Initial K	Ten times of maximum catch.	------
Age at maturity	One year.	------
M	Lognormal, low = 0.001, up = 3, mean = 1.43 for *Penaeus monodon* and 1.71 for *Metapenaeus monoceros*, sd = 0.4.	Increase to 2.
B_1/K	None, low = 0.01, up = 1, mean = 1, sd = 0.1).	Decrease to 0.80.
B_t/K	Beta, low = 0.01, up = 0.99, mean = 0.3, sd = 0.1, refyr = max(final year of time-series) + 1).	Decrease to 0.2.
F_{MSY}/M	Lognormal, low = 0.1, up = 2, mean = 1, sd = 0.2.	Decrease to 0.80.
B_{MSY}/K	Beta, low = 0.05, up = 0.95, mean = 0.4, sd = 0.05.	Decrease to 0.25.

2.4. Sensitivity Analysis of DB-SRA

A sensitivity analysis was carried out to investigate the ability of the DB-SRA model to predict the true value for each reference point (MSY, B_{MSY}, B_{refer}, U_{MSY}, F_{MSY}, OFL, and K) with varying levels of input parameters, and thus to investigate uncertainty in those parameters. Table 1 describes the input settings for the sensitivity run. For each sensitivity run, the value of one input parameter was modified at a time while the remaining values remained unchanged.

After the analysis of the DB-SRA model, this study ran biomass projections with different yearly catch limits and DB-SRA results using the *dlproj* function of R statistical software [67] described by Nelson (2013) [68] to obtain a positive trend in stock biomass. The key inputs for this function are

dlobj: the output object from DB-SRA.
projyears: the number of projection years (10 years).
projtype: 2 (user-specified catch)
projcatch: projected catches (different catch limits including *MSY* and *OFL* were used).

3. Results

3.1. Landing Trend

The industrial landing data for *P. monodon* and *M. monoceros* was first recorded in the statistical yearbook of Bangladesh in 1987. Therefore, a 33-years (1987 to 2019) review of yearly landings from the industrial trawlers observed a similar declining trend for both species (Figure 2).

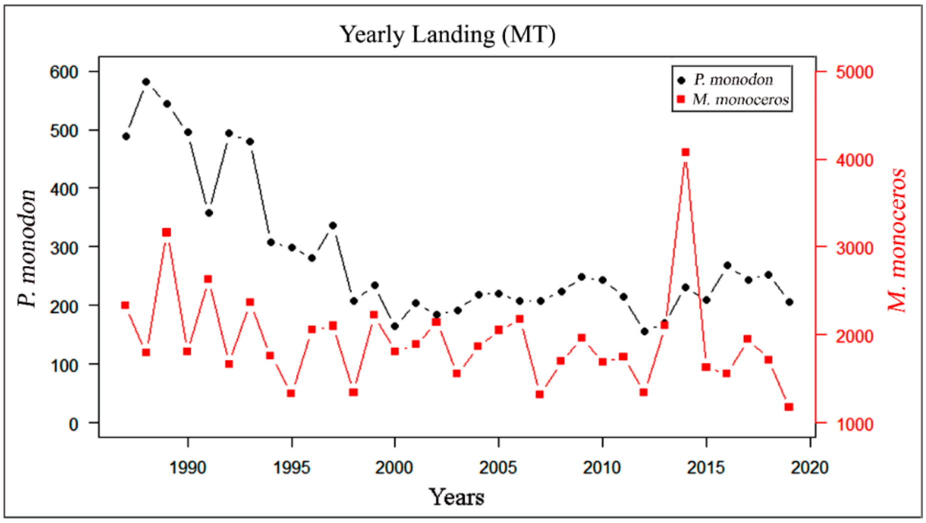

Figure 2. Catches of *Penaeus monodon* and *Metapenaeus monoceros* in metric tons from 1987–2019 from industrial trawling in the EEZ of Bangladesh.

The maximum catch for *P. monodon* was in 1988, while for *M. monoceros* in 2014. Catches in the final year were 58 and 50 percent lower than catches in the first year of the data set for both species. Despite a sudden increase in *M. monoceros* capture in 2013 and 2014, it began to decline again in 2015.

3.2. Stock Analysis Based on DB-SRA Model Results

The distributions of input parameter values from accepted and rejected model runs were significantly overlapped (Figure 3).

For all parameters, including F_{MSY}/M, B_{MSY}/K, B_t/K, and M, the distributions of accepted and rejected model runs were highly diverged, with accepted runs moving towards the lower values for both species.

The DB-SRA model estimated the fisheries reference points from the accepted model runs that allowed both shrimp populations to survive for the modeled period (Figure 4). The estimated mean carrying capacity (K) for the *P. monodon* population was 5015 metric tons and 35,871 metric tons for *M. monoceros*, before the beginning of the fishery. Thus, the fishing reduced the population biomass by more than 70 percent of the initial biomass for both species (assuming that K = initial biomass). In addition, the estimated *OFL* values, which were much smaller than the reported catches throughout the time series, indicate the overfishing status of these fisheries from the start of the time series data (Table 2, Figure 2).

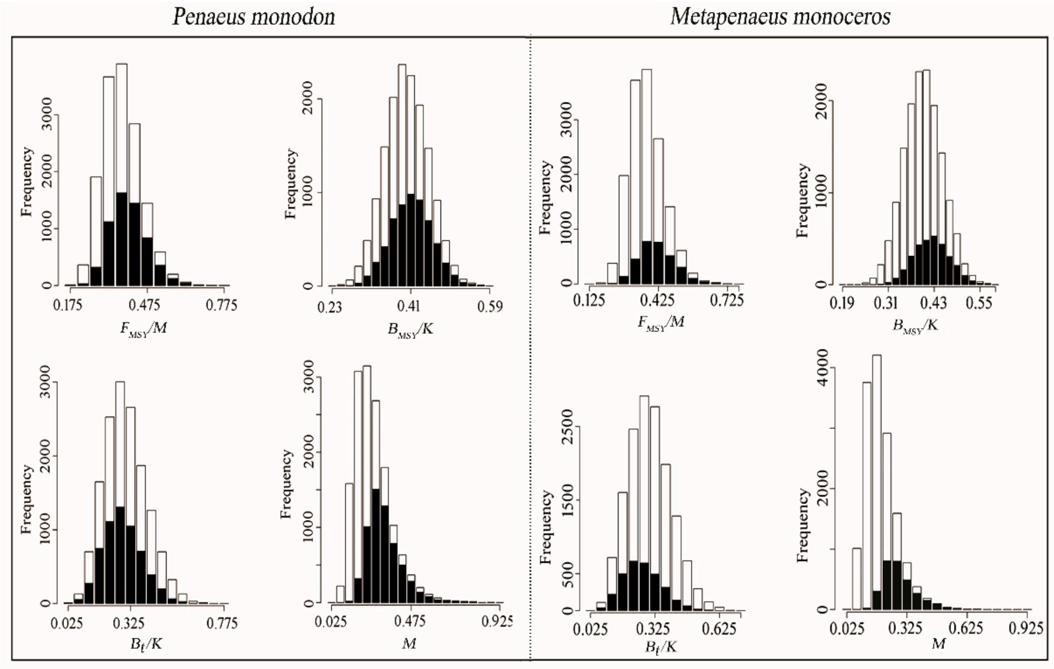

Figure 3. Input parameters distributions from accepted (black) and rejected (white) model runs.

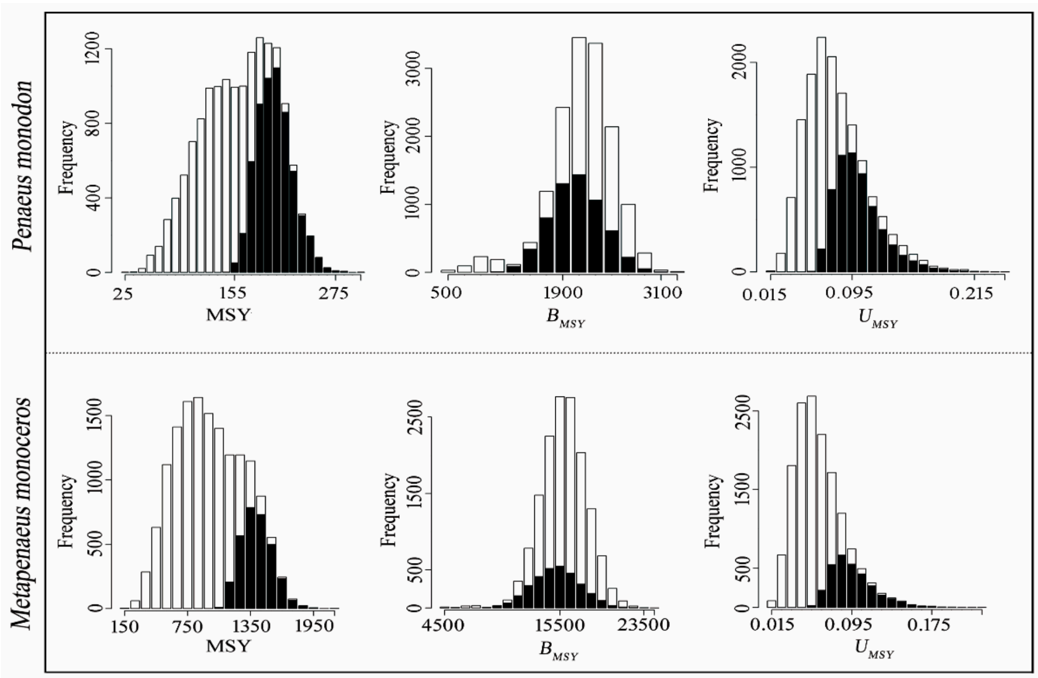

Figure 4. Estimated reference points by the DB-SRA model from accepted (black) and rejected (white) model runs.

The estimated mean MSY for tiger shrimp is 203 metric tons and 1408 metric tons for brown shrimp, but this level was exceeded in nearly all years until 1996 (Figure 5), and as a consequence, population biomass fell below the mean estimate of B_{MSY} of 2062 metric tons for *P. monodon* and 15,140 metric tons for *M. monoceros* from 1996 (Figure 6), (Table 2).

Table 2. Parameters estimate from DB-SRA model with 95% CI.

Parameters	*P. monodon*			*M. monoceros*		
	Mean	**LCI(2.5%)**	**UCI (97.5%)**	**Mean**	**LCI (2.5%)**	**UCI (97.5%)**
MSY	203	166	250	1408	1155	1715
B_{MSY}	2062	1451	2694	15,140	10,795	19,320
F_{MSY}	0.13	0.08	0.23	0.12	0.07	0.20
U_{MSY}	0.10	0.07	0.16	0.10	0.06	0.15
OFL	146	53	279	912	334	1871
B_{2020}	1429	626	2458	9470	4200	17,097
K	5015	3635	5808	35,871	26,192	40,750

Note: LCI and UCL indicate lower and upper confidence intervals.

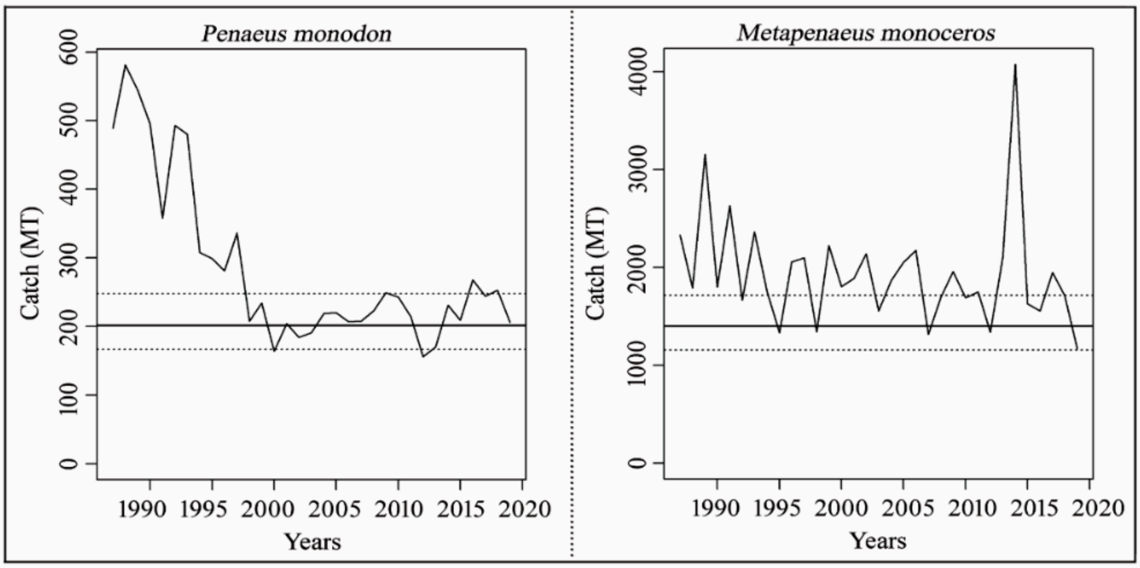

Figure 5. Historical catches of *Penaeus monodon* and *Metapenaeus monoceros* with *MSY* estimates.

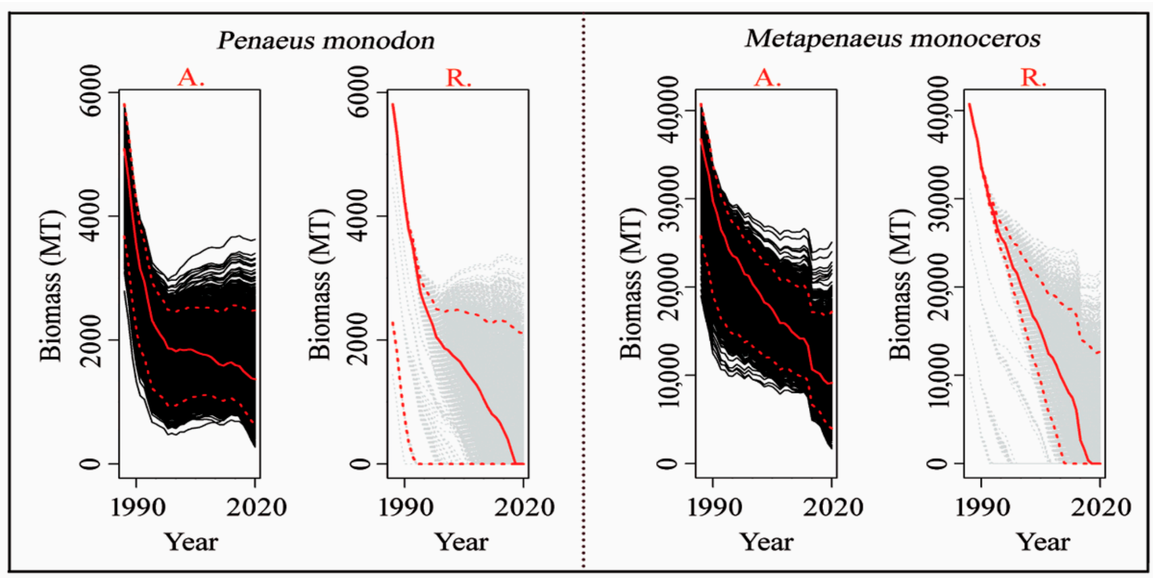

Figure 6. Biomass projections for *Penaeus monodon* and *Metapeneaus monoceros* from accepted (black) and rejected (white) model runs.

The model results show that these fisheries are inherently overfished, with a yearly exploitation rate much greater than the mean U_{MSY} estimates of 0.10 for both species. In 2019, the biomass of both species reached its minimum, and for the reference year (2020), the estimated biomass indicates that these two fisheries are not currently able to produce MSY ($B_{2020} < B_{MSY}$) (Table 2 & Figure 6).

The DB-SRA model showed robustness in model sensitivity runs, producing similar results with different input parameter values across diverse scenarios. The outputs from the sensitivity tests mostly overlapped the base model's output; however, in some instances, heterogeneity in models' outputs were observed (Figure 7). The predicted mean MSY values for both species were more or less steady in all sensitivity runs and varied from 3 to 12% for *P. monodon* and 1 to 17% for *M. monoceros* from the base model run. Similarly, mean estimates of B_{MSY} varied only 2 to 8% from the baseline model with one significant deviance (25% from the base model) when input parameter B_{MSY}/K was reduced to 0.25 but did not significantly affect other reference points estimation. Therefore, like the basic model run, the mean estimates of B_{MSY} from the sensitivity runs have remained much higher than the biomass in the reference year (B_{2020}).

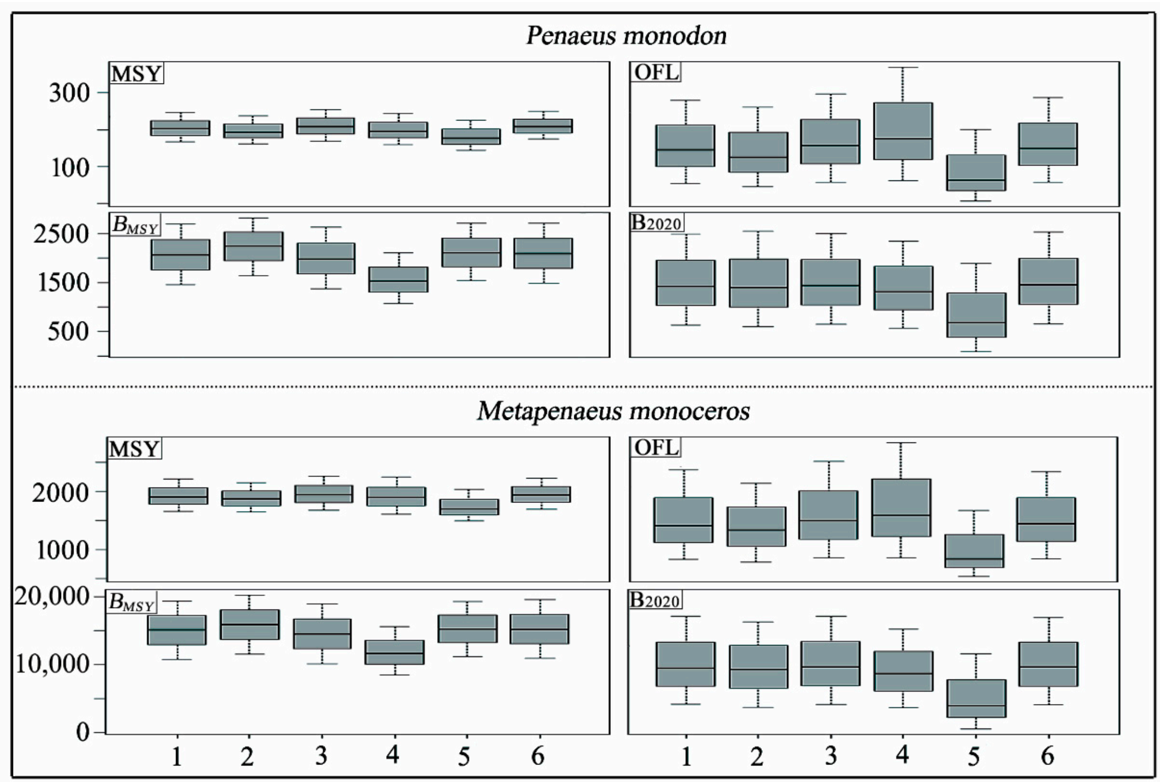

Figure 7. Sensitivity analysis for both *Penaeus monodon* and *Metapenaeus monoceros.* The scenarios are 1. The base model outputs; 2. M increases to 2; 3. F_{MSY}/M decreases to 0.8; 4. B_{MSY}/K decreases to 0.25; 5. B_t/K decreases to 0.2; 6. B_1/K decreases to 0.8.

Different values (50–500 metric tons for *P. monodon* and 500–1500 metric tons for *M. monoceros*), including the estimated MSY and OFL from the base model run, were considered for the biomass projection. However, 100 metric tons for *P. monodon* and 750 metric tons for *M. monoceros* as yearly landing limits resulted in continuous biomass growth, reversing the declining trend of stock biomass (Figure 8). With these annual capture limits, the biomass of these two species will be yielded 61 percent (2293 metric tons) and 52 percent (14,512 metric tons) growth after ten years, respectively (Figure 8).

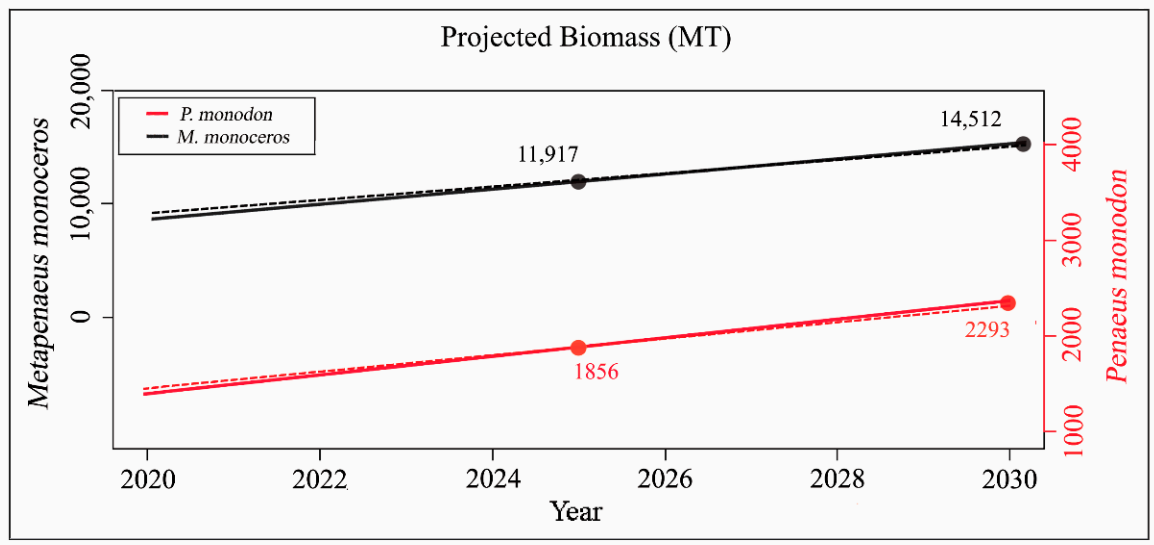

Figure 8. Biomass projections for both *Penaeus monodon* and *Metapenaeus monoceros* in metric tons (MT). Dots indicate the B_{MSY} for the respective years.

4. Discussion

With the number of trawlers nearly constant over time, the captures with a continuous fall for both species could be a sign of stock biomass depletion (Figure 1). Therefore, this study used a robust assessment approach to evaluate the stocks' current biomass status with other fisheries reference points. Due to the lack of species-specific total marine landing data for shrimp, only the catch data from commercial landings from 1987 to 2019 was used in this study. Most traditional stock assessment methods require catch and effort data in combination; however, in Bangladesh, effort statistics from the capture fisheries are incomplete and misreported. As a result, using these data may result in perplexing findings. Even though these two shrimp species have enormous importance, the stock assessment of these species from Bangladesh marine water is lacking in international literature, with only two published studies identified during this study, one for each species [23,43]. Those two studies, like this study, also used catch data from industrial trawl landings but were based on catch per unit effort (*CPUE*) data. Given the limitations in *CPUE* data in multi-species and multi-gears fisheries, this study employed a stock reduction analysis (DB-SRA) that is well suited to analyzing stocks that exhibit a monotonic decline in abundance [46] over the historical harvest period and can provide useful information on current stock status from catch history despite a lack of current abundance knowledge. For the best possible evaluation of the stock status, the DB-SRA method requires the complete history of the catches from the beginning of the fisheries [46]. Though offshore fish trawling in Bangladesh began in 1972 [19], industrial shrimp trawling beyond the 40 m depth was started in 1981 with only eight shrimp trawlers and gained traction in 1986 when the number of shrimp trawlers increased to 36 [22]. Therefore, the historical catch data used in this study from 1987 was assumed to be the complete capture history for these fisheries.

With a high degree of removal, where catches were much higher than the *OFL* for every year since the start of the fisheries, the biomass of the stocks has already been depleted. But, more importantly, the ongoing depletion of stock biomass exacerbated the problem to the point where these fisheries were unable to produce *MSY* in the following year of the data set (2020), with biomass less than the required biomass to produce *MSY* (B_{MSY}).

Estimating *MSY* is critical for policymakers when developing a sustainable harvest strategy [69], and DB-SRA can reduce uncertainty in estimating this quantity [46]. However, there was a large discrepancy observed in the estimates of *MSY* between the present and previous studies of Barua (2020 and 2021) [23,43]. The estimated *MSY* by Barua (2020 and 2021) [23,43] was much higher than in the present study (Table 3). Though the 95% confidence intervals of his estimates of B_{MSY} for *P. monodon* overlapped the range of this study's estimates, for *M. monoceros*, it was much lower than the present study. Similarly, the estimated mean biomass for *M. monoceros* for the reference year 2017 is significantly lower than this study's estimate (Table 3). The estimates of K also revealed a similar disparity with a very low value estimated by Barua (2020) [43] for *M. monoceros* (Table 3). He also showed that the stock status of *M. monoceros* was healthy in terms of B_{MSY}, despite a steep decline in capture. In the stock evaluation of a multi-gear and multi-species fishery with the methods that require effort data, efforts standardization is essential to get a reliable result. However, Barua (2020 and 2021) [23,43] used the same effort data to analyze both species, which could be resulting in erroneous estimates of the reference points. Using the DB-SRA model, this study did not need to use the effort data to analyze the stocks. Nevertheless, the results of this study and those of Barua (2021) [23] demonstrate that the harvest of *P. monodon* far surpassed the sustainable level and is responsible for the depleted biomass.

Table 3. The mean of the estimated reference points for *Penaeus monodon* and *Metapenaeus monoceros* by Barua et al. (2020 and 2021) [23,43] and the present study with 95% confidence intervals.

Species Name	K	MSY	B_{MSY}	B_{2020} *	F_{MSY}	Reference
Penaeus monodon	4720 (3350–6650)	527 (388–717)	2360 (1670–3320)	1250 (885–1550)	0.22 (0.16–0.31	[23]
	5015 (3635–5808)	203 (166–250)	2062 (1451–2694)	1429 (626–2458)	0.13 (0.08–0.23)	Present
Metapenaeus monoceros	10,000 (8380–12,200)	3090 (2920–3260)	5060 (4990–6110)	5960 (4760–6830)	0.61 (0.51–0.73)	[43]
	35871 (26,192–40,750)	1408 (1155–1715)	15140 (10,795–19,320)	9470 (4200–17,097)	0.12 (0.07–0.20)	Present

* B_{2020} stands for biomass in the reference year of 2020.

Given the high level of pollution in Bangladesh's marine water [70,71], the natural mortality of shrimp can be considered higher than the value used in the base model analysis. Demersal trawling for fish and shrimp began in 1981 with a few trawlers in Bangladesh's EEZ [19]. Thus, considering the stock biomass equal to unfished biomass (B_1/K = 1) in 1987 is not safe. The rapid decline in catch could be attributed to a rapid decline in stock biomass, indicating a high level of depletion and lowering the value of B_t/K. Again, short-lived shrimp species can exhibit high productivity, producing MSY even with lightly depleted biomass, resulting in a much lower value for B_{MSY}/K used in this study. Again, many scientists suggested that F_{MSY} should not be greater than 80% of natural mortality to ensure the stock's long-term viability [45]. Therefore, given all those uncertainties in input parameters, alternative values to address all the issues mentioned above were used for the DB-SRA model's sensitivity analysis.

Since the values of the different estimated reference points varied with different input parameters, the overall results showed a similar pattern, the depleted biomass for both stocks, due to historic overexploitation. Therefore, in DB-SRA analysis, the results have little possibility of deviating if the true distribution of M is greater than the base model run, the true productivity of both species is significantly higher, or F_{MSY}/M is significantly lower than the values used in the base model runs. Wetzel and Punt (2011) [72] reported a high sensitiveness of the DB-SRA model to the B_t/K. Although this study found a significant influence of changing B_t/K on OFL and B_{2020}, the impact was very little on MSY and B_{MSY}, similar to Sweka et al. (2018) [52]. Since the consistency of estimated reference points across all sensitivity runs of the model is desired for managers when determining what management plan should be taken to restore stocks biomass, the consistent findings of this study across all scenarios showed the rationality and effectiveness of the DB-SRA model for the assessment of data-poor fisheries of Bangladesh.

Based on the results of the DB-SRA model, it is possible to conclude that the stocks' biomass of these two shrimp species in the offshore (beyond 40 m depth) water of Bangladesh are depleted, and hence stock rebuilding strategies need to be adopted. To get the stocks' biomass above the B_{MSY}, it is likely that a trawling ban should be imposed. However, given the high resilience of the species (population doubling time < 15 months) [73] and increased demand and unemployment problem, this study conducted projections using different catch limits to ensure the consistent growth of the stocks' biomass. Based on the projections, an annual catch of 100 metric tons of *P. monodon* and 750 metric tons of *M. monoceros* will shift the biomass trend from down to upwards, and with these catch limits, biomass will exceed the B_{MSY} level in 2030. Therefore, this study recommends those catch limits as the total allowable catches (*TACs*) to sustain both shrimp populations in the marine water of Bangladesh that are assigned for industrial fishing for the next ten years. After ten years, another rigorous stock assessment should be carried out using the same methodology and set the *OFLs* as *TACs* for another ten years. The *OFL* is a strong tool that can ensure the sustainability of the stock biomass with optimum yield.

5. Conclusions

Due to the unavailability of reliable effort data, this study conducted a stock assessment of two shrimp species, *P. monodon,* and *M. monoceros,* using the depletion-based stock reduction analysis (DB-SRA) with catch and life-history data to get robust results. Depending on the outputs, this study concluded that due to the historic overexploitation, stocks' biomass of both shrimp species had been depleted in Bangladesh's industrial fishing zone (beyond 40 m depth) and that action to rebuild the stock biomass is urgent. Therefore, this study recommended annual catch limits of 100 metric tons for *P. monodon* and 750 metric tons for *M. monoceres*. These catches will actively rebuild and raise the stocks' biomass above the B_{MSY} within the next ten years. After successfully implementing this recommendation, a further rigorous stock assessment should be carried out after ten years to evaluate the impact of implemented management policy and adopt new strategies to manage these fisheries in the future sustainably.

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References

1. FAO. Key Features of Small-Scale and Artisanal Fishing [online]. 2011. Available online: http://www.fao.org/fish-ery/topic/14753/en (accessed on 13 October 2021).
2. Barman, P.P.; Karim, E.; Khatun, M.H.; Rahman, M.F.; Alam, M.S.; Liu, Q. Application of CMSY to estimate biological reference points of Bombay Duck (Harpadon neherus) from the Bay of Bengal, Bangladesh. *Appl. Ecol. Environ. Res.* **2020**, *18*, 8023–8034. [CrossRef]
3. FAO. The State of World Fisheries and Aquaculture. In *Food and Agriculture Organization of the United Nations*; FAO: Rome, Italy, 2014; 223p.

4. Pauly, D.; Zeller, D. Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. *Nat. Commun.* **2016**, *7*, 10244. [CrossRef] [PubMed]
5. Watson, R.; Pauly, D. Systematic distortions in world fisheries catch trends. *Nature* **2001**, *414*, 534–536. [CrossRef] [PubMed]
6. Watson, R.A.; Cheung, W.W.L.; Anticamara, J.A.; Sumaila, R.U.; Zeller, D.; Pauly, D. Global marine yield halved as fishing intensity redoubles. *Fish Fish.* **2013**, *14*, 493–503. [CrossRef]
7. Froese, R.; Zeller, D.; Kleisner, K.; Pauly, D. What catch data can tell us about the status of global fisheries. *Mar. Biol.* **2012**, *159*, 1283–1292. [CrossRef]
8. Ricard, D.; Minto, C.; Jensen, O.P.; Baum, J.K. Examining the knowledge base and status of commercially exploited marine species with the RAM Legacy Stock Assessment Database. *Fish Fish.* **2012**, *13*, 380–398. [CrossRef]
9. Lockerbie, E.M.; Shannon, L.J.; Jarre, A. The use of ecological, fishing and environmental indicators in support of decision making in southern Benguela fisheries. *Ecol. Indic.* **2016**, *69*, 473–487. [CrossRef]
10. Begg, G.A.; Friedland, K.D.; Pearce, J.B. Stock identification and its role in stock assessment and fisheries management: An overview. *Fish. Res.* **1999**, *43*, 1–8. [CrossRef]
11. Benson, A.J.; Stephenson, R.L. Options for integrating ecological, economic, and social objectives in evaluation and management of fisheries. *Fish Fish.* **2018**, *19*, 40–56. [CrossRef]
12. Punt, A.E. Spatial stock assessment methods: A viewpoint on current issues and assumptions. *Fish. Res.* **2019**, *213*, 132–143. [CrossRef]
13. Butterworth, D.S.; Johnston, S.J.; Brandao, A. Pretesting the Likely Efficacy of Suggested Management Approaches to Data-Poor Fisheries. *Mar. Coast. Fish.* **2010**, *2*, 131–145. [CrossRef]
14. Punt, A.E.; Hilborn, R. Fisheries stock assessment and decision analysis: The Bayesian approach. *Rev. Fish Biol. Fish.* **1997**, *7*, 35–63. [CrossRef]
15. Islam, M.M.; Shamsuzzaman, M.M.; Mozumder, M.M.H.; Xiangmin, X.; Ming, Y.; Jewel, M.A.S. Exploitation and conservation of coastal and marine fisheries in Bangladesh: Do the fishery laws matter? *Mar. Policy* **2017**, *76*, 143–151. [CrossRef]
16. Shamsuzzaman, M.M.; Xiangmin, X.; Islam, M.M. Legal status of Bangladesh fisheries: Issues and responses. *Indian J. Geo Mar. Sci.* **2016**, *45*, 1474–1480.
17. DoF (Department of Fisheries). *Marine Fisheries Survey Reports and Stock Assessment 2019 Based on R/V Meen Sandhani Surveys from 2016 to 2019*; Bangladesh Marine Fisheries Capacity Building Project; Department of Fisheries, Ministry of Fisheries and Livestock: Dhaka, Bangladesh, 2019.
18. Hussain, Z.; Archarya, G. (Eds.) *Mangroves of the Sundarbans*; IUCN: Bangkok, Thailand, 1994; Volume 2.
19. Rahman, A.K.A.; Khan, M.G.; Chowdhury, Z.A.; Hussain, M.M. *Economically Important Marine Fishes and Shellfishes of Bangladesh*; Department of Fisheries: Dhaka, Bangladesh, 1995.
20. Lamboeuf, M. *Bangladesh Demersal Fish Resources of the Continental Shelf*; R/V Anusandhani Trawling Survey Results (September 1984–June 1986); FAO: Rome, Italy, 1987; 26p.
21. Khan, M.G.; Mustafa, M.G.; Sada, M.N.U.; Chowdhury, Z.A. *Bangladesh Offshore Marine Fishery Resources Studies with Special Reference to the Penaeid Shrimp Stocks, 1988–1989*; Annual Report; Marine Fisheries Survey, Management and Development Project, GOB: Chittagong, Bangladesh, 1989; 213p.
22. Islam, M.S. Perspectives of the coastal and marine fisheries of the Bay of Bengal, Bangladesh. *Ocean Coast. Manag.* **2003**, *46*, 763–796. [CrossRef]
23. Barua, S.; Al Mamun, M.A.; Nazrul, K.M.S.; Mamun, A.; Das, J. Maximum sustainable yield estimate for Tiger shrimp, Penaeus monodon off Bangladesh coast using trawl catch log. *Bangladesh Marit. J.* **2021**, *4*, 135–144.
24. FRSS. *Fisheries Resources Survey System: Fisheries Statistical Report of Bangladesh*; Department of Fisheries (DoF), Ministry of Fisheries and Livestock (MoFL): Dhaka, Bangladesh, 2019; Volume 31, pp. 1–57.
25. Smith, D.; Punt, A.; Dowling, N.; Smith, A.; Tuck, G. Reconciling approaches to the assessment and management of data-poor species and fisheries with Australia's harvest strategy policy. *Mar. Coast. Fish. Dyn. Manag. Ecosyst. Sci.* **2009**, *1*, 244–254. [CrossRef]
26. Honey, K.; Moxley, J.; Fujita, R. From rags to fishes: Data-poor methods for fishery managers. *Managing data-poor fisheries: Case studies Models Simul.* **2010**, *1*, 159–184.
27. Prager, M.H. ASPIC: A Surplus-Production Model Incorporating Covariates. *Coll. Vol. Sci. Pap. Int. Comm. Conserv. Atl. Tunas* **1992**, *28*, 218–229.
28. Martell, S.; Froese, R. A simple method for estimating MSY from catch and resilience. *Fish Fish.* **2013**, *14*, 504–514. [CrossRef]
29. Rosenberg, A.A.; Fogarty, M.J.; Cooper, A.B.; Dickey-Collas, M.; Fulton, E.A.; Gutiérrez, N.L.; Hyde, K.J.W.; Kleisner, K.M.; Kristiansen, T.; Longo, C.; et al. *Developing New Approaches to Global Stock Status Assessment and Fishery Production Potential of the Seas*; FAO Fisheries and Aquaculture Circular No. 1086; FAO: Rome, Italy, 2014; 175p.
30. Froese, R.; Demirel, N.; Coro, G.; Kleisner, M.K.; Winker, H. Estimating fisheries reference points from catch and resilience. *Fish Fish.* **2017**, *18*, 506–526. [CrossRef]
31. Winker, H.; Carvalho, F.; Kapur, M. JABBA: Just Another Bayesian Biomass Assessment. *Fish. Res.* **2018**, *204*, 275–288. [CrossRef]
32. Cope, J.; Punt, A.E. Length-based reference points for data-limited situations: Applications and restrictions. *Mar. Coast. Fish. Dyn. Manag. Ecosyst. Sci.* **2009**, *1*, 169–186. [CrossRef]

33. Reuter, R.F.; Conners, M.E.; Discosimo, J.; Gaichas, S.; Ormseth, O.; TenBrink, T. Managing non-target, data-poor species using catch limits: Lessons from the Alaskan groundfish fishery. *Fish. Manag. Ecol.* **2010**, *17*, 323–335. [CrossRef]
34. Agnew, D.J.; Gutiérrez, N.L.; Butterworth, D.S. Fish catch data: Less than what meets the eye. *Mar. Policy* **2013**, *42*, 268–269. [CrossRef]
35. Branch, T.A.; Jensen, O.P.; Ricard, D.; Ye, Y.; Hilborn, R. Contrasting Global Trends in Marine Fishery Status Obtained from Catches and from Stock Assessments. *Conserv. Biol.* **2011**, *25*, 777–786. [CrossRef]
36. Maunder, M.N.; Punt, A.E. Standardizing catch and effort data: A review of recent approaches. *Fish. Res.* **2004**, *70*, 141–159. [CrossRef]
37. Khan, M. Optimal stock, harvest and effort level of Bangladesh trawl shrimp fishery-a nonlinear dynamic approach. *J. Agric. Rural. Dev.* **2007**, *5*, 143–149. [CrossRef]
38. Khan, M.G.; Islam, M.S.; Chowdhury, Z.A.; Paul, S.C. *Shrimp Resources of Bangladesh—Jour Crates of Exploitation and Its Comparative Effect on the Stock*; Marine Fisheries Research Management & Development Project; DoF: Dhaka, Bangladesh, 1998; 12p.
39. Ray, A.; Khan, M. Estimating some parameters of shrimp fishery in Bangladesh. *Indian J. Fish.* **2003**, *50*, 251–257.
40. Amin, S.M.N.; Ara, R.; Zafar, M. Conservation of marine and coastal shrimp resources and sustainable aquaculture. *Res. J. Fish. Hydrobiol.* **2006**, *1*, 18–22.
41. Uddin, M.S.; Karim, E.; Hasan, S.J.; Barua, S.; Humayun, N.M. Catch Composition for Main Marine Shrimp Species in Bangladesh. *Bangladesh Res. Pub. J.* **2012**, *7*, 91–98.
42. Barua, S.; Magnuson, A.; Humayun, N.M. Assessment of offshore shrimp stocks of Bangladesh based on commercial shrimp trawl logbook data. *Indian J. Fish.* **2018**, *65*, 1–6. [CrossRef]
43. Barua, S. Maximum sustainable yield estimate for Brown shrimp, Metapenaeus monoceros (Fabricius 1798) in marine waters of Bangladesh using trawl catch log. *Indian J. Geo-Mar. Sci.* **2020**, *50*, 258–261.
44. Pacific Fisheries Management Council (PFMC). *Pacific Coast Groundfish Fishery Management Plan for the California, Oregon, and Washington Groundfish Fishery*; Pacific Fisheries Management Council (PFMC): Portland, OR, USA, 2011; 177p.
45. Walters, C.J.; Martell, S.J.D.; Korman, J. A stochastic approach to stock reduction analysis. *Can. J. Fish. Aquat. Sci.* **2006**, *63*, 212–223. [CrossRef]
46. Dick, E.J.; MacCall, A.D. Depletion-based stock reduction analysis: A catch-based method for determining sustainable yields for data-poor fish stocks. *Fish. Res.* **2011**, *110*, 331–341. [CrossRef]
47. Berkson, J.; Barbieri, L.; Cadrin, S.; Cass-Calay, S.; Crone, P.; Dorn, M.; Friess, C.; Kobayash, D.; Miller, T.J.; Patrick, W.S.; et al. *Calculating Acceptable Biological Catch for Stocks that Have Reliable Catch Data Only (Only Reliable Catch Stocks-ORCS)*; NOAA Technical Memorandum NMFS-SEFSC-616; National Oceanic and Atmospheric Administration: Washington, DC, USA, 2011; 56p.
48. Arnold, L.M.; Heppell, S.S. Testing the robustness of data-poor assessment methods to uncertainty in catch and biology: A retrospective approach. *ICES J. Mar. Sci.* **2015**, *72*, 243–250. [CrossRef]
49. Hoq, M.E.; Haroon, A.K.Y.; Chakraborty, S.C. *Marine Fisheries of Bangladesh: Prospect and Potentilities*; Support to Sustainable Management of the BOBLME Project; Bangladesh Fisheries Research Institute: Mymensingh, Bangladesh, 2013; 120p.
50. Huntington, T.; Khan, M.G.; Islam, S.; van Brakel, M.; Miller, A. *Towards Sustainable Coastal and Marine Fisheries in Bangladesh: Initiating a Precautionary Approach*; Report submitted by the WorldFish Center-Bangladesh Office to the Ministry of Fisheries and Livestock, Government of Bangladesh; WorldFish Center-Bangladesh Office: Dhaka, Bangladesh, 2008; 86p.
51. Fletcher, R.I. On the restructuring of the Pella-Tomlinson system. *Fish. Bull.* **1978**, *76*, 515–521.
52. Sweka, J.A.; Neuenhoff, R.; Withers, J.; Davis, L. Application of a Depletion-Based Stock Reduction Analysis (DB-SRA) to Lake Sturgeon in Lake Erie. *J. Great Lakes Res.* **2018**, *44*, 311–318. [CrossRef]
53. Nalini, C. Observations on the maturity and spawning of Metapenaeus monoceros (Fabricius) at Cochin. *Indian J. Fish.* **1976**, *23*, 23–30.
54. Rao, G.S. Studies on the reproductive biology of the brown prawn Metapenaeus monoceros (Fabricius: 1798) along the Kakinada coast. *Indian J. Fish.* **1989**, *36*, 107–123.
55. Rao, G.S. The Indian Tiger Prawn Penaeus Monodon Fabricius. In *Marine Fisheries Research and Management*; CMFRI: Kochi, India, 2000; pp. 511–524.
56. Nandakumar, G. Reproductive biology of the speckled shrimp *Metapenaeus monoceros* (Fabricius). *Indian J. Fish.* **2001**, *48*, 1–8.
57. Rameshbabu, K. Fecundity variations of black tiger shrimp Penaeus monodon from two different geographical locations, east coast of Andhra Pradesh. *India. J. Glob. Biosci.* **2014**, *3*, 725–730.
58. Sk Uddin, N.; Ghosh, S.; Maity, J. Reproductive biology, maturation size and sex ratio of black tiger shrimp (Penaeus monodon Fabricus, 1798) from fishing grounds of Digha coast, West Bengal. India. *Indian J. Aqua. Res.* **2015**, *2*, 372–378.
59. Froese, R.; Binohlan, C. Empirical relationship to estimate asymptotic length, length at first maturity and length at maximum yield per recruit in fishes, with a simple method to evaluate length-frequency data. *J. Fish Biol.* **2000**, *56*, 758–773. [CrossRef]
60. von Bertalanffy, L. A quantitative theory of organic growth (inquiries on growth laws. II.). *Hum. Biol.* **1938**, *10*, 181–213.
61. Mustafa, M.G.; Ali, S.; Azadi, M.A. Some aspect of population dynamics of three penaeid shrimp (P.monodon, P.semisulcatus and M.monoceros) from the Bay of Bengal, Bangladesh. *Chittagong Univ. J. Sci.* **2006**, *30*, 97–102.
62. McCann, J.A.; Arkin, L.N.; Williams, J.D. *Nonindigenous Aquatic and Selected Terrestrial Species of Florida*; University of Florida, Center for Aquatic Plants: Gainesville, FL, USA, 1996.

63. Dineshbabu, A.P. Length-weight relationship and growth of the speckled shrimp, Metapenaeus monoceros (Fabricius) off Saurashtra. *J. Mar. Biol. Assoc. India* **2006**, *48*, 180–184.
64. Hoenig, J.M. Empirical use of longevity data to estimate mortality rates. *Fish. Bull.* **1983**, *82*, 898–903.
65. Manasirli, M.; Kiyaga, V.B.; Perker, M. Reproduction, growth, mortality and exploitation rate of *Penaeus semisulcatus* De Haan, 1844 (Decapoda, Penaeidae) from iskenderun bay (northeastern mediterranean). *Crustaceana* **2014**, *87*, 385–400. [CrossRef]
66. Walters, C.; Martel, S. *Fisheries Ecology and Management*; Princeton University Press: Princeton, NJ, USA, 2004; 399p.
67. R Core Team. *A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2016.
68. Nelson, G.A. Fisheries Methods and Models in R. Version: 1.4-0. 2013. Available online: http://www2.uaem.mx/r-mirror/web/packages/fishmethods/fishmethods.pdf (accessed on 12 May 2021).
69. Alam, M.S.; Liu, Q.; Nabi, M.; Al-Mamun, M. Fish Stock Assessment for Data-Poor Fisheries, with a Case Study of Tropical Hilsa Shad (*Tenualosa ilisha*) in the Water of Bangladesh. *Sustainability* **2021**, *13*, 3604. [CrossRef]
70. Alam, M.S.; Hossain, M.S.; Monwar, M.M.; Hoque, M.E. Assessment of fish distribution and biodiversity status in Upper Halda River, Chittagong, Bangladesh. *Int. J. Biodivers. Conserv.* **2013**, *5*, 349–357.
71. Alam, M.W.; Xiangmin, X. Marine Pollution Prevention in Bangladesh: A Way Forward for Implement Comprehensive National Legal Framework. *Thalassas* **2019**, *35*, 17–27. [CrossRef]
72. Wetzel, C.R.; Punt, A.E. Model performance for the determination of appropriate harvest levels in the case of data-poor stocks. *Fish. Res.* **2011**, *110*, 342–355. [CrossRef]
73. Froese, R.; Pauly, D. (Eds.) *FishBase 2000: Concepts, Design, and Data Sources*; WorldFish: Penang, Malaysia, 2000; 344p.