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Estimating Stock Status and Biological Reference Points of the Sardine Fishery Using the Surplus Production Model from the Bay of Bengal, Bangladesh

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Abstract: This research examined the biological reference points (BRPs) and stock status of the sardine fishery in the Bay of Bengal (BoB), Bangladesh, to determine the sustainability of this resource. The Monte Carlo method (CMSY), the Bayesian state-space Schaefer surplus production model (BSM), and the ASPIC (a Stock Production Model Incorporating Covariates) software suite, were used to analyze catch–effort data obtained from the Yearbook of Fisheries Statistics of Bangladesh. All models derived maximum sustainable yields (*MSY*) ranging from 37,900 to 41,280 t, which is quite near to the catch from the latest year (38,051 t in 2020), indicating the fully exploited status of sardines. The estimated $B < B_{MSY}$ and $F > F_{MSY}$ values from the BSM and Schaefer models indicate a poor biomass and an unsafe fishing status. For Schaefer and BSM, the calculated F/F_{MSY} values were 1.07 and 1.06, and the B/B_{MSY} values were 0.92 and 0.75, which also indicate the overexploited status of the sardine fishery in the BoB, Bangladesh. This information will aid in developing management strategies and conservation policies for the sustainability and rebuilding of this commercially important resource in the BoB on the Bangladesh coast.

Keywords: BRPs; overexploited; *MSY*; CMSY; ASPIC; sardine; Bay of Bengal

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1. Introduction

One-third of the world's assessed fisheries are overfished [1] and nearly half of harvesting fish stocks in Asia have been overexploited or have collapsed [2]. Fisheries management aims to find the best balance between ecological conservation, economic yield, and social considerations for marine living resources. For this goal, it is important to assess a stock's current condition and potential for exploitation with the help of biological and economic reference points [3]. Most commercially harvested fish stocks worldwide lack an accurate stock assessment due to a shortage of data for assessing the stock status and fishing mortality [4,5]. However, fish stock assessment is a difficult task for fisheries because of the enough data that is currently available and, according to the scarce available data, it is possible that only 12% of the world's fisheries are currently managed [6–8].

Herring, anchovies, and sardines (HAS) are a group of forage species. HAS are expected to produce 15.2 million tons of fish annually, or 18.6% of the world's total marine fisheries productivity [1,8]. Sardines are pelagic and comprise one of the major clupeid groups of commercial fishery targets in terms of biomass harvested from Bangladesh's coastal water. Fifteen species of Sardine are found in the Indo-Pacific region; however, sixty-one sardine species have been reported globally [8–10]. In addition, seven different sardine species have been reported in the Bay of Bengal, Bangladesh coast, where five species are under the genus *Sardinella* and two are from *Dussumieria* [11,12]. These fishery groups make up an average of 5.12% of Bangladesh's overall marine production, with 97% coming from commercial fishing and only 3% from artisanal fishing [13].

Data-limited fisheries, often known as fisheries with only catch and/or length frequency (*LFQ*) data, call for a certain set of models [14]. In the BoB, Bangladesh coastal waters, where only catch–effort data are available, sardine resources fall under the category of data-limited fisheries. Data-limited techniques have recently been created in response to the current issue, e.g., CMSY [15]. The current study analyzed 10-year-long catch and effort (CE) data from the commercial sardine fishery of the BoB, Bangladesh using two non-equilibrium SPMs. The SPMs, also known as biomass dynamics models, are frequently used to evaluate the *MSY*, which is one of the most commonly utilized biological reference points (BRPs), as a target for fisheries management [16,17]. Additionally, there are other modern methods, such as the Monte Carlo approach (CMSY) [15], for calculating *MSY* and BPRs in fisheries with limited data. The CMSY is more effective at evaluating BRPs than other methods and is especially useful for developing countries with little or no data on effort [15,17]. Attempts were made to determine the *MSY* and associated BRPs using catch statistics and supplemental data, using the CMSY approach and ASPIC software package [15,16].

From Bangladesh's standpoint, there are few, poor, or perhaps no commercial fisheries statistics for many species. Thus, the creation of a Marine Protected Area (MPA), mesh size limitations, and the closure of spawning grounds, were the main focuses of Bangladesh's marine fisheries management [17]. MPAs are a popular concept and may be an ultimate solution to the conservation and sustainable utilization of fishery resources. As in other parts of the world, Bangladesh should also seriously consider and implement this management option. Since Bangladesh has a small data collection of sardines, the stock status and total allowable catch (TAC) cannot be realized. No studies have yet been performed on the stock status and *MSY* of this fisheries resource using the latest commercial catch data in the Bay of Bengal (BoB) Bangladesh water.

The objective of this study was to estimate the BRPs and assess the stock status of sardine fishery, using CMSY and ASPIC approaches, for the sustainable management and conservation of this fishery resource in the coastal water of Bangladesh.

2. Materials and Methods

2.1. Data Sources

The Bay of Bengal (BoB) is roughly located between latitudes 5° and 22° N and longitudes 80° and 90° E, and is bordered by Sri Lanka, India, Bangladesh, Myanmar and the northern part of the Malay Peninsula. The coastal area of Bangladesh is located in the northern part of the BoB (Figure 1). The commercial fisheries sector of Bangladesh is broadly categorized as an artisanal and industrial fishery. The artisanal mechanized fishing boats have marine diesel engines with 20–75 horsepower (HP), while industrial trawlers are normally 20–40 m long and have marine diesel engines with 350–1450 horsepower (HP).

The sardine fishery was studied using ten years' (2011–2020) worth of time series catch–effort (CE) data in the BoB (Figure 2). The CE data of the commercial fisheries were collected from the Yearbook of Fisheries Statistics of Bangladesh, published by the Department of Fisheries, Ministry of Fisheries and Livestock, Government of the People's Republic of Bangladesh. Sardines were mostly caught with trawl nets, gill nets, and Set Bag Nets (SBNs) in the industrial and artisanal sectors of the BoB. Typically, the fish trawl nets' minimum code end mesh size was 60 mm. However, for the SBNs it was 45 mm, while for the gill nets (small mesh drift net) it was 100 mm [13]. The catch statistics were considered in tons (t), and the *CPUE* (catch per unit of effort) was figured in tons per gear per year (t/g/yr).

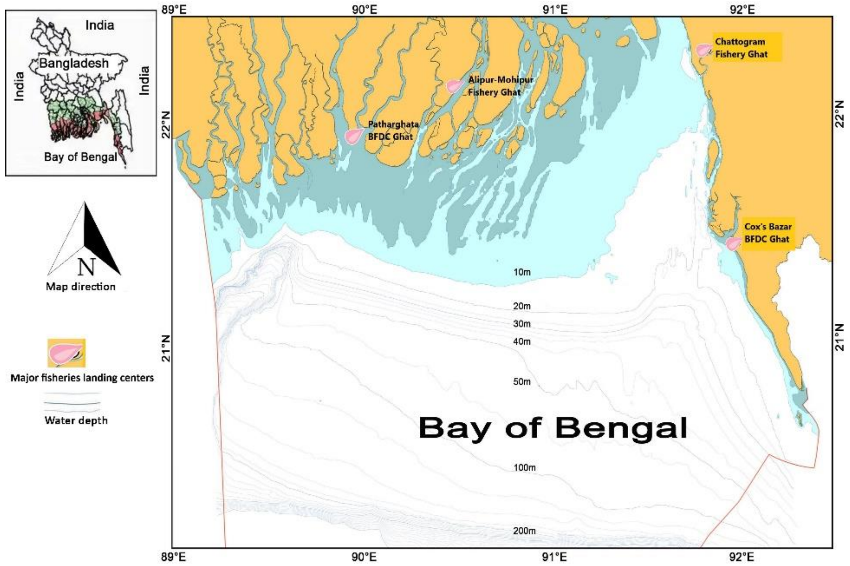

Figure 1. The coastal map of the BoB, Bangladesh.

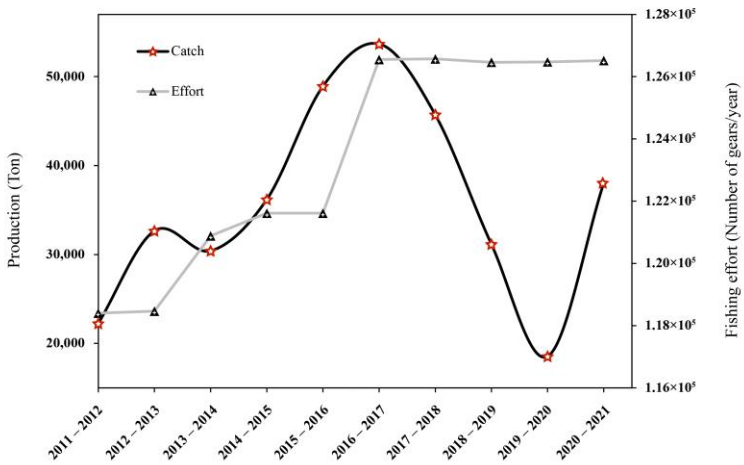

Figure 2. Diagrammatic representation of the catch and effort data (2011–2020) of the sardine fishery from the BoB, Bangladesh.

The CE data were analyzed using the R codes (CMSY_2019_9f.R), and were downloaded from https://oceanrep.geomar.de/33076/ (accessed on 10 June 2022) [18]. The Markov chain Monte Carlo method was employed during CMSY analysis on probability distributions using the JAGS program [19]. In addition, two non-equilibrium SPMs (Surplus Production Models) were also run using the ASPIC software to evaluate the BRPs [16].

2.2. CMSY and BSM Model

The CMSY and BSM methods were applied to estimate the important biological reference points (BRPs) of MSY, B/B_{MSY}, and F/F_{MSY}, using time series data on catch, CPUE, and resilience. While, for the productivity estimation, the catch and abundance information is required by the traditional surplus production models (such as the Fox and Schaefer model) [20,21], the CMSY can forecast biomass using data on catch and productivity [15]. The BSM that makes use of catch and CPUE data was also incorporated [22,23].

In the present study, the fish population dynamics are described below:

$$B_{t+1} = B_t + r(1 - {}^{B_t}/_{k})B_t - C_t \tag{1}$$

In the year (t + 1) the exploited biomass was B_{t+1}, the existing biomass and catch in year t was respectively B_t and C_t. k is carrying capacity, and r is intrinsic population growth rate. When biomass fell below 1/4 k and stock sizes were severely depleted, the following equation was used:

$$B_{t+1} = B_t + 4\frac{B_t}{k}r(1 - {}^{B_t}/_{k})B_t - C_t | \frac{B_t}{k} < 0.25 \quad (2)$$

The resilience value for sardines was "high". Therefore, the prior range for r of 0.6–1.5 (Table 1) was used for sardines as the input prior [24]. Three assumptions were used to determine the prior range of k: firstly, the size of the unexploited stock (k) is greater than the time series' largest catch. Secondly, the productivity of the stock determines the maximum sustainable catch stated as a fraction of the available biomass (*Fmsy*). Thirdly, the maximum catch will make up a higher percentage of k in considerably depleted stocks as opposed to moderately depleted ones. The probabilistic biomass ranges (Table 2) automatically estimate the relative biomass at the beginning and end of the time series data based on the anticipated level of depletion.

Table 1. Prior ranges for the parameter r used in Monte Carlo method (CMSY) study.

Resilience	Very Low	Low	Medium	High
Prior r range	0.015–0.1	0.05–0.5	0.2–0.8	0.6–1.5

Table 2. Prior B/K (relative biomass ranges) using Monte Carlo method (CMSY).

Very Strong Depletion	Strong Depletion	Medium Depletion	Low Depletion	Nearly Unexploited
0.01–0.2	0.01–0.4	0.2–0.6	0.4–0.8	0.75–1.0

The carrying capacity ranges were calculated using the species' maximum catch and resilience in Equations (3) and (4):

$$k_{low} = \frac{\max(Catch)}{r_{high}}; k_{high} = \frac{4\max(Catch)}{r_{low}} \quad (3)$$

$$k_{low} = \frac{2\max(Catch)}{r_{high}}; k_{high} = \frac{12\max(Catch)}{r_{low}} \quad (4)$$

where the lower and upper bounds of k are denoted by k_{low} and k_{high}. At the end of the given time series dataset, Equation (3) accounts for the stocks with low prior biomass, whereas Equation (4) is used for the stocks with high prior biomass. In addition, the data were smoothed using a three-year moving average to lessen the impact of severe captures [15].

The equation below connects the *CPUE* (abundance index) to the stock biomass (B) through the catchability coefficient (q):

$$CPUE_t = qB_t \quad (5)$$

When r and k are calculated, $MSY = rk/4$, $F_{MSY} = 0.5r$, and $B_{MSY} = 0.5k$ are the estimated parameters for CMSY and BSM [21,25]. Table 3 shows the input values (Relative biomass, r, k and q ranges) for CMSY.

Table 3. Relative biomass (B), r, k, q ranges as priors in the CMSY and BSM used in this analysis.

Resource	Prior Initial Relative Biomass	Prior Intermediate Relative Biomass	Prior Final Relative Biomass	Prior Range for r	Prior Range of q	Prior Range for k
Sardine fishery	0.2–0.6	0.5–0.9 (in year 2015)	0.2–0.6	0.6–1.5	3.45×10^{-6} 1.09×10^{-5}	89.9–270

2.3. Surplus Production Models (SPMs) and ASPIC

Two non-equilibrium SPMs were run using the ASPIC computer package to evaluate the BRPs [16]. The logistic population growth model is represented by following Equation (6) [21], and the Gompertz growth model is represented by Equation (7) [20]:

$$\frac{dB}{dt} = rB(k - B) \tag{6}$$

$$\frac{dB}{dt} = rB(lnk - lnB) \tag{7}$$

In the calculation above, the description of the parameters are the same as the previous equations. Equation (6) as a continuous function is different from Equation (1) which is a discrete function.

An initial proportion (IP) value is a necessary input for the ASPIC. The ratio between the initial capture and the maximum catch from the data set was used to determine the IP value, which ranged from 0 to 1. While IP = one denotes the heavily exploited status of the stock in the first year of the data series, IP= zero denotes the time when the data series started with the virgin status of the stock. Since the catch in the first year was 40% of the maximum catch, this investigation, therefore, determined that IP was 0.4. Both Schaefer and Fox SPMs were executed in ASPIC. Bootstrap trials were used to calculate the confidence intervals. Since the ASPIC cannot calculate the value of r, it was manually calculated using the formula $r = 2 \times F_{MSY}$.

3. Results

3.1. Stock Status and BRPs for Sardine Fishery Derived from CMSY and BSM

The derived *MSY* of sardine fishery from the CMSY and BSM were 37,900 (29,500–51,100) t and 38,200 (33,400–43,700) t, respectively (Table 4). The values of *MSY* from both methods were very close to the catch from the latest year (38,051 t/year in 2020). The fishing mortality F (0.587) was higher than F_{MSY} (0.553), and last year's biomass (52,000 t) was lower than the B_{MSY} (69,100 t), indicating that this fishery in the BoB is overfished (Figure 3). In addition, the results of exploitation (F/F_{MSY} = 1.06 > 1.0) and B/B_{MSY} = 0.75 (<1.0) further support the overfished (Table 5) status of sardine stock in the study area (Figure 4).

Table 4. The estimated *k*, *r* and *MSY* values and their 95% confidence intervals for the sardine fishery in the Bay of Bengal, Bangladesh coast.

Method Name	*k* (*t*)	*r* (/*yr*)	*MSY* (*t*)
CMSY	138,000 (97,100–196,000)	1.11 (0.774–1.58)	37,900 (29,500–51,100)
BSM	138,000 (102,000–188,000)	1.11 (0.806–1.52)	38,200 (33,400–43,700)

Table 5. Estimated results for the management of sardine fishery based on Bayesian Schaefer model (BSM) analysis.

Resource	F (/*yr*)	F_{MSY} (/*yr*)	B (*t*)	B_{MSY} (*t*)	F/F_{MSY}	B/B_{MSY}	Assessment
Sardine fishery	0.587	0.553	52,000	69,100	1.06	0.752	overfished

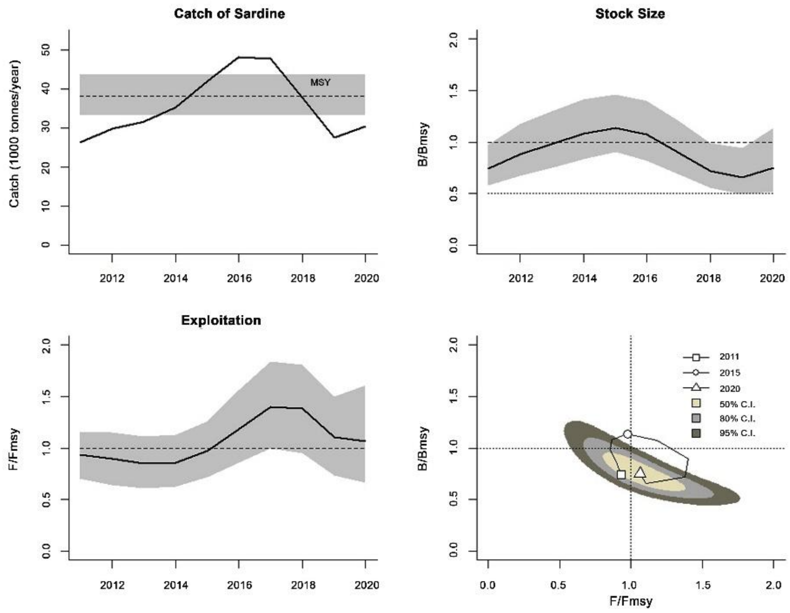

Figure 3. Schematic plots based on BSM analysis for the sardine fishery in the BoB, Bangladesh coast. The shaded areas are the 95% confidence intervals.

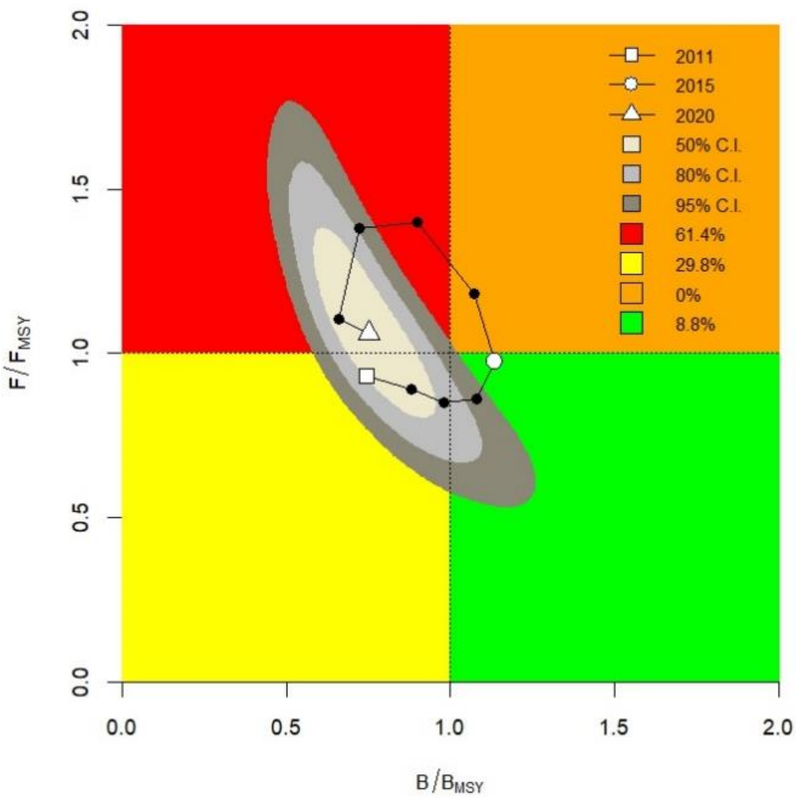

Figure 4. Kobe plot showing the simultaneous movement of exploitation (F/F_{MSY}) and relative biomass (B/B_{MSY}) using BSM for sardine fishery in the BoB, Bangladesh coast.

3.2. Stock Status and BRPs for Sardine Fishery Resource Derived from ASPIC

The population parameters estimated by the ASPIC are presented in Table 6. The estimated value of B/B_{MSY} = 0.92 (<1) and F/F_{MSY} = 1.07 (>1), obtained from the logistic model, indicating the overfished condition of the sardine fishery in the study area. However, the estimated values from the Fox model were B/B_{MSY} = 1.27 (>1) and F/F_{MSY} = 0.73 (<1). The Fox model's estimated k, MSY, B, B_{MSY}, and B/B_{MSY} values were greater than those from the logistic model, demonstrating the Fox model's conservatism. The logistic and Fox models derived using the ASPIC software demonstrated the inconsistent pattern of B/B_{MSY} and F/F_{MSY} (Figure 5). Furthermore, for the logistic and Fox models, the estimated values of k were 376,900 t and 686,700 t, and r = 0.41 and 0.33 year^{-1}, respectively. The logistic model's estimated values of F_{MSY} and B_{MSY} were, respectively, 0.205 and 188,500 t, while they were 0.163 and 252,600 t for the Fox model. The derived MSY values of sardines from logistic and Fox models were 38,650 t and 41,280 (Table 6) which is close to the last year's catch (38,051 t/year in 2020).

Table 6. Estimated results derived from ASPIC for the sardine resources using catch and effort data and 0.4 *IP* value.

Models	*IP*	*k*	*q*	*r*	*MSY*	*B*	B_{MSY}	*F*	F_{MSY}	B/B_{MSY}	F/F_{MSY}
Logistic	0.400	376,900	1.67×10^{-6}	0.41	38,650	173,590	188,500	0.22	0.205	0.92	1.07
Fox	0.400	686,700	9.13×10^{-7}	0.33	41,280	321,560	252,600	0.12	0.163	1.27	0.73

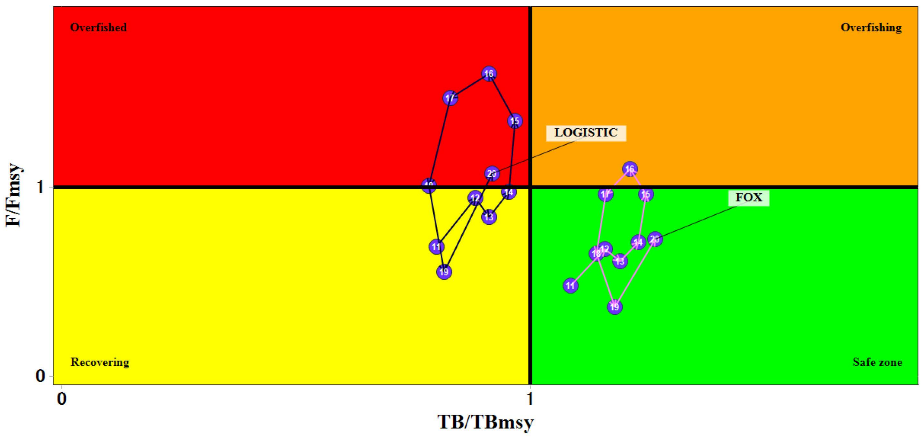

Figure 5. The Kobe plot for sardine fishery in the BoB, Bangladesh coast was obtained using the ASPIC software (logistic and Fox) for the ratios F/F_{MSY} (fishing mortality to F_{MSY}), and B/B_{MSY} (biomass to B_{MSY}).

4. Discussion

Scientific fish stock assessment is important for the rational exploitation of fisheries' resources. Most conventional stock assessment models need much data, which restricts their application to species with limited data [26]. For the assessment of fish stocks, MSY is a popular BRP [27], and B/B_{MSY} is utilized as a framework to ascertain the status of fisheries [8,17]. Besides the ASPIC software, the recent approaches of CMSY and BSM, which primarily rely on time series of catches and supplementary qualitative data to estimate biomass and related data on the stocks under consideration, are already well-established for assessing data-poor stocks [15,16,28]. In this contribution, the commercial sardine fisheries resource in the coastal water of Bangladesh was assessed using the data-limited stock assessment methodologies, CMSY and ASPIC.

4.1. Estimated Population Parameters of Sardine Fishery

The catchability coefficient (q), commonly known as the fishing gear efficiency, is the proportion of fishing mortality to fishing effort. When catch and effort statistics are important inputs for assessing fish stocks, the q value is crucial [15]. The BSM-derived q value (4.21×10^{-6}) was higher than that of the other models. An important indicator for understanding a fishery is the intrinsic growth rate (r) [29,30]. It is stated that population size can increase by 10% over time when r is 0.1 [31]. ASPIC estimated r values of 0.41 and 0.33/year for logistic and Fox models, and 1.11/year for CMSY and BSM models. Due to of the high correlation between r and k parameters, ASPIC estimated high k values of 676900t and 686700t while CMSY and BSM estimated low k value of 138000t. Luckily, $MSY = rk/4$ is of the most interest to us which is close for both of the approaches.

4.2. MSY, Exploitation and Stock Status of Sardine Fishery

Finding a reliable method for estimating the maximum sustainable yield (MSY) and essential BRPs for fishery management is crucial, especially when data are scarce [32]. The MSY as the target reference point (TRP) and related BRPs were taken into consideration to assume the stock status [17,32]. The lower observed catch and higher MSY value indicated the underexploited state. On the other hand, a fish stock's overexploitation state was indicated by a greater observed catch and lower MSY [31]. The MSY value of sardine stock produced from all the models ranged from 37,900 to 41,280 t (Tables 4 and 6). This was close to the catch from the latest year (38,051 t), indicating sardines' fully exploited status in the BoB, Bangladesh waters. When the observed catch is extremely close to or equal to the MSY value, the stock is said to be fully exploited and no further growth in capture is anticipated [4]. To protect the sustainability of fisheries, the MSY value is advised as the TAC (total allowable catch) [33,34].

In addition, the estimated values of B/B_{MSY} (<1.0) from the BSM and logistic models were 0.75 and 0.92, respectively (Tables 5 and 6), indicating the overfished status of sardine fishery. However, the estimated value from the Fox model was 1.27 (>1.0). The calculated values of F/F_{MSY} (>1.0) from BSM and logistic models comply with the overfished status. Furthermore, all models' (except the Fox model) produced fishing mortality (F) was higher than the F_{MSY}, and last year's biomass was lower than the B_{MSY}, also supporting the overfished status of sardine fishery in the coastal water of Bangladesh. Since BSM/CMSY/logistic models and Fox model assume different population growth functions, and we do not have independent information to know which one is correct, caution is required in making decisions.

In the current study area, there is little published information on BRPs to compare the various parameters of these fishery resources (Table 7). Reference [35] reported the slightly overfished and severely depleted status of the *sardinella* sp. in the BoB, which is consistent with the current study's findings. A similar finding was reported by [8] using the LBB (length-based Bayesian biomass) method. However, [8,35] found the not overfished condition of the rainbow sardine *(Dussumieria* sp.) in the northeastern Bay of Bengal. The sardinellas are the main target of intense sardine fishery. Very little is performed to exploit rainbow sardines; they are probably only caught accidentally. Several bycatch species in this fishery are of great concern, in addition to the sardinellas' declining numbers [35]. This also strongly complies with the overfished status of sardines stock in the coastal water of Bangladesh estimated by the present study. In addition, the overexploitation status for the oil sardine was reported in the northern Bay of Bengal, India [36]. Similar findings were reported by [37] for *Sardinella gibbosa*, and *Sardinella fimbriata* in the north west Bay of Bengal, India, which also comply with the present study's findings.

In addition, the continuous increase in the fishing effort (Figure 2) from 2011 to 2016 has increased sardine production more than two times. As a result, the stock has reached an overexploitation level. To control the overexploitation, fishing efforts were maintained at almost the same level from 2017 to 2020 (Figure 2). The result of this was that, after a certain decline (due to the impact of previous overfishing), the production seems to be starting to regain, which strongly comply with the present study findings. Therefore, for the sustainable management and protection of this resource, the existing effort should be controlled.

Table 7. Comparison of the present findings to the previous study in sardine fishery resource assessment in the Bay of Bengal.

Group or Scientific Name	Study Area	Assessment Result	Comparison with This Study	References
Sardinellas (*Sardinella* sp.)	Bay of Bengal, Bangladesh	Slightly overfished, Severely depleted	Consistent	[35]
Rainbow sardines (*Dussumieria* sp.)	Bay of Bengal, Bangladesh	Not over-fished	Inconsistent	[35]
Sardine (*Sardinella* sp.)	Northeastern Bay of Bengal, Bangladesh	over-fished	Consistent	[8]
Sardine (*Dussumieria* sp.)	Northeastern Bay of Bengal, Bangladesh	Not overexploited	Inconsistent	[8]
Oilsardine	Northern Bay of Bengal, India	Overexploited	Consistent	[36]
Sardinella gibbosa *Sardinella fimbriata*	North West, Bay of Bengal, India	Overfished	Consistent	[37]

4.3. Suitability of the Data Limited Methods for the Sustainable Fisheries Management

The fishery reference points of the sardine fishery from the BoB were evaluated in this study using ASPIC (a Stock Production Model Incorporating Covariates software suite), CMSY, and BSM methods. SPMs are thought to occasionally provide BRPs that are better than age-based models and can be used wherever [16]. Additionally, BRPs from multispecies data can be appropriately assessed using the ASPIC software with SPMs. To run the ASPIC program, an IP value must be carefully selected for fitting these models [16]. On the other hand, for the CMSY and BSM approaches, r and k were the essential prior information that could be acquired from the resilience data obtained from the FishBase [38]. When employed for less-captured fisheries or for very low resilience, the *MSY*, computed by CMSY and BSM, exhibits certain inefficiencies; medium to high resilience fisheries are the best fits [15]. The high resilience value for sardine suggests that the CMSY approach is the most useful for evaluating BRPs and stock status. In addition, the effectiveness of the CMSY approach was individually tested by the FAO [4], which found the better performance of this method at estimating fisheries stock status over short time series of data. Therefore, the CMSY method may be recommended as a possible substitute to estimate the stock status of the sardine population and other fisheries with the limited data in the BoB.

The fishery reference points derived from the CMSY, BSM, and logistic models showed that sardines are being overfished in the study area, which looks more reasonable with the present real scenarios of this resource in the BoB. However, the Fox-model-derived findings are partially consistent with those results. Hence, considering the outcomes of the present study, further studies focusing on sardine fishery, and analyzing the data by means of other models, are strongly recommended.

5. Conclusions

The current study assessed the biological reference points (BRPs) and stock status of the exploited sardine fishery resource on the BoB. CMSY-, BSM-, and logistic- (ASPIC) model-derived fishery reference points showed that sardines are being overfished in the study area. Even though fish are a renewable resource, overfishing reduces fish biomass and results in the ruin of the fishery. To ensure the sustainability of an overfished fishery, it is essential to undertake continuous monitoring of the stock assessment. Hence, the current study strongly suggests the adoption of management strategies, and the development of specific policies, in order to reduce the existing fishing pressure and keep the catch at the *MSY* level. In addition, a detailed study on the biology and life history of sardine fishery, along with the protection and conservation of the nursery and breeding grounds, is recommended. These results will aid in developing this fishery resource in the BoB, Bangladesh coastal water, and in formulating management strategies and conservation policies to ensure the sustainability of this commercially important resource.

Author Contributions: R.S.: conceptualization, methodology, data collection, analysis and interpretation, drafting, reviewing, and editing of the manuscript, Q.L.: conceptualization, study design, data analysis, data interpretation, editing, and reviewing, M.A.A.-M., P.P.B., M.M.S. and S.B.: visualization, data analysis, data interpretation, editing, and reviewing. All authors have read and agreed to the published version of the manuscript.

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