Bangladesh Marine Fish Stock Assessment Summary Report 2023

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Sustainable Coastal and Marine Fisheries Project
Department of Fisheries, Bangladesh
Ministry of Fisheries and Livestock

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Executive Summary

In Bangladesh Marine Fish Stock Assessment Summary Report 2023, results are reported for two types of stock assessment:

- Catch-effort using a state-space production model (JABBA)
- Length frequency data analysis using a catch curve (fishblicc)

The Catch-effort data analysis relies on time series of total catch from the stock and catch per unit effort (CPUE) time series that has been standardised to remove the effect of changes in vessel fishing power. Due to various uncertainties including a short available time series, results are uncertain and this is reflected in the risk assessment for each stock.

The following stocks that could be assessed using this method include species groups:

Stock	Current Catch(t) (mean 2016-2020)	Recommended TAC(t)[a]	Status
Finfish (all excluding Hilsa & Bombay Duck)	321113	270000	High risk
Shrimp	46323	38000	High risk
Hilsa Shad	498358	600000	Medium risk
Bombay Duck	68342	75000	Medium risk
Pomfret	10841	25000	Low risk
Croakers	36926	35000	Medium risk

[a]The recommended total allowable catch (TAC) is estimated taking account of uncertainty and can be considered a maximum safe catch based on the JABBA stock assessment. The working group chose the 20th percentile of the credibility interval from the JABBA model estimates for species groups except Pomfret which used the 50th percentile (median). This reflected the confidence the group had in the estimates. This TAC can be considered a proxy for the MSY estimate.

Length frequency data analysis is restricted to single-species assessments. Unlike the catch-effort analysis, this assessment does not require a continuous time series, but assumes the population is in a stationary state. A preliminary rapid assessment of all available length frequency data suggested that of the 112 species examined, 35% of stocks had a greater than 50% probability of being below the SPR40% (“at risk of overfishing”) and 23% had a greater than 50% probability of being below the SPR20% (“at high risk of being overfished”).

The following species were examined in detail, providing fuller estimates of status:

Stock	SPR (CI 80%)[1]	$F/F_{0.1}$ (CI 80%)[2]	Status
Bombay Duck	0.355 (0.258-0.484)	0.717 (0.480-0.994)	Medium risk
Hilsa Shad	0.244 (0.160-0.365)	1.693 (0.931-2.853)	High risk
Savalai Hairtail	0.678 (0.396-0.902)	0.359 (0.088-1.027)	Medium risk
Coromandel Ilisha	0.685 (0.270-0.917)	0.234 (0.045-1.597)	Medium risk
Silver Pomfret	0.753 (0.448-0.930)	0.173 (0.040-0.595)	Low risk

Results may change once more recent data across all fisheries becomes available. Currently, the catch-effort time series data are short which limits the ability of these methods to provide reliable

[1] The Spawning Potential Ratio (SPR) compares the number of large mature fish in the catches with what might be expected if the population is healthy. Values at or above 0.4 are generally considered safe, values below 0.2 at very risk of recruitment failure.

[2] $F/F_{0.1}$ is used here as an MSY proxy for fishing mortality. Values above 1.0 are considered to be “overfishing”.

assessments. The estimates based on length data are primarily dependent on data collected from 2012-2018 from the artisanal fishery. More recent data and data from the commercial trawl fishery were not available.

These indicators suggest that most finfish species are probably not overfished, but shrimp may be. Fishing may be depleting some finfish species relative to others dependent on their vulnerability and action is probably required to prevent the fishery from reducing the diversity of the catches as less productive species are removed.

An improved assessment of hilsa shad is recommended. The length frequency and catch-effort data appear to give conflicting results on the status of hilsa shad. The reason for this is not known and requires more research.

Introduction

The main goal of the stock assessment is to develop an overarching risk assessment for Bangladesh multispecies fisheries and provide scientific advice consistent with government policy. The advice will be limited by the information available, and while new data are improving understanding of the fish stocks, fisheries and their status, there remain many gaps. This stock assessment makes use of industrial catch effort data, the scientific research vessel survey data and artisanal monitoring data based on a project that ran 2012-2018. Artisanal data are the main limitation as they form the largest fisheries and dominate catches, as well as being of great socio-economic importance.

Two types of data are currently available, which for the current assessments have been analysed separately:

1. Catch and effort data span the period 2010-2020, with total catches being reported through FAO statistics back to 1950s. The research vessel survey also provides relative abundance information but for a very short period. There are research vessel surveys going back to 1984 but they were not conducted in a consistent manner, so interpretation of data from before 2016 is difficult.
2. Length frequency data have been collected for the artisanal fishery 2012-2018 and from the research surveys. Unfortunately, no length frequency data are available for the industrial trawl fishery, although data collection has been initiated. In general, these data are insufficient to treat as a continuous time series.

This preliminary report provides information on the approach used to analyse the data, current results and plans to improve the analyses. The results from the final stock assessments will be used to inform the Fishery Management Plans.

Data Review

Total Catch Data

For purposes of stock assessment, these data need to be complete. For Bangladesh, these data are sparse and this results in mostly species groups being assessed using catch and effort data. The most complete series of total catch data was obtained from the Yearbook of Fisheries Statistics of Bangladesh and the FAO statistics. The accuracy of these data is not known and given the lack of consistent time series data, it is not clear how they have been estimated. Nevertheless, these data are the most complete time series for these fisheries unless other sources can be found. How the data have been gathered and estimated over the years needs documentation.

Catch-Effort and Relative Abundance Data

Unlike the total catch data, these data need not be complete, but less data leads to poor results. Missing data or limited data extent will lead to greater uncertainty, resulting in vague scientific advice. In Bangladesh, the time series of available catch and effort data is very short, with missing periods. Much of the catch data are not reported to species level. The research vessel survey data are important, but still the survey time series is short, has gaps and significant observation error because the deployed nets are not particularly efficient in capturing many species.

Length Frequency Data

Considerable length frequency data exist from the artisanal fishery and the research vessel survey. These data are species-specific, but there is no consistent monitoring time series. There are probably much more data which were unavailable for these analyses. It is likely considerable length data have been collected in the past for academic purposes and by various projects. An initiative to collect species and length data from the industrial trawl fishery has just started, so hopefully will come available in 2024.

Length frequency data have been collected for well over 100 species that are caught in Bangladesh fisheries. Combined across years, these form sufficient samples to estimate mortality. The main issue is that the gear selectivities are unlikely to be flat-topped, which is an assumption for most methods. For example, gill nets are the predominant gear in the artisanal fishery and it is likely this is more selective to mid-size of fish, and therefore is dome-shaped rather than flat. The ecosystem is also heavily affected by seasonality associated with a river delta and monsoon which results in changes in fish size caught through the year. These and similar issues still need to be addressed to obtain reliable analyses of the available length frequency data.

Catch and Effort Data Analysis

The JABBA Model

Given total catch and indices of abundance, it's possible to fit surplus production (biomass dynamics) models. JABBA ("Just Another Bayesian Biomass Assessment") is a state-space production model that allows the model to account both for process and observation errors, which provides better indication of uncertainties. JABBA is implemented in R and generates reproducible stock status estimates and diagnostics. JABBA runs quickly and by default generates many useful plots and diagnostic tools for stock assessments.

The state space model allows for process (random growth in biomass) and observation error (error associated with catch and abundance indices). The model used here is the Schaefer version (M=2), which is reasonably precautionary in its MSY reference point and with data being limited, offers the best chance for a successful model fit. JABBA allows forecasting with different TACs, although adaptations to allow alternative projections could be implemented.

The model is fit using MCMC with multiple CPUE indices as appropriate, so the industrial CPUE, artisanal CPUE and the research vessel survey biomass estimates can all be included in the assessment where available. The main limitation of the model is the requirement for total catch. The only complete series were obtained from the FAO reported annual landings (FAO Stat). Other estimates (excepting for pomfret) were unavailable at this time.

Data were sufficient for attempted four assessments: for the species groups "shrimp" and "marine finfish" (excluding hilsa), and for the species hilsa and bombay duck for which there are separated catches recorded. The breakdown of catch into species is problematic in Bangladesh and severely limits what models can be fitted and their reliability. Improving this situation should be a major focus in improving stock assessment data in future, while improved models are required to make better use of these historical data.

Log-CPUE from the artisanal and industrial fisheries was standardised using the covariates available based on gear type, vessel and engine size, indicators of net size, and fishing time and location. Standardisation corrected for changes in CPUE that could be explained by changes in fishing power and selectivity rather than abundance. In all cases, the main year effect parameter estimates were used to estimate an expected log-CPUE for use in the JABBA model. For the research vessel survey, an annual swept-area biomass estimate was used as the index. The biomass estimate was much lower than the catch in all cases, so it was treated as a relative index.

Finfish

An assessment was applied to all finfish excluding hilsa. A full time series of catch data could be proposed for use in this type of model based on statistics reported to FAO. The model is entirely empirical, so no justified prior on the parameter *r* in particular was available and trials suggested a precautionary value of 0.4 was reasonable as an average across species being caught. Otherwise, artisanal, industrial and vessel survey abundance indices were all used. However, the assessment including all indices in a single fit was rejected as the standardised CPUE indices from the industrial and artisanal data were incompatible. Further work is required to look for a consistent approach to combine information from the various scenarios. Therefore, it was proposed to consider two scenarios using the same catch series, but separate the industrial and artisanal CPUE into different fits to try to provide a range of results.

Catches (Figure 1) and hence fishing mortality (Figure 3) show a continuous upward trend since the 1950s. The relatively flat artisanal CPUE is reasonably well-fitted, whereas the industrial CPUE is less well-fitted. The survey had too few points to make any difference. The data were primarily informative on the unexploited stock size (K) and had little effect on other parameters although the posterior for the intrinsic rate of increase (r) parameter showed a slight shift to a higher value (Figure 2).

The catch and effort data from the artisanal fishery, industrial fishery and research surveys indicate that it is likely that the overall status of finfish in Bangladesh is probably not overfished, although precautionary advice would still suggest a small decrease in catch to protect the stocks. Although the worst case using the industrial fishery indicates overfishing (Figure 4), the model fits poorly and is dependent on a decreasing trend in CPUE which is not fit well and not apparent in other indices. However, results are not exact and significant risk of overfishing remains. The MSY estimate is highly uncertain, but peak catches (2008/9) were at the point where the probability MSY has been exceeded is around 50-80% (Figure 5), implying that there is little room to expand catches on the inshore stocks. The uncertainty in the results is because the time series of data are very short and there is insufficient information to test whether this model is appropriate.

Current data limitations are the main problem for this assessment. The model requires a complete catch time series, which needs to be brought up to date. This should be a priority for the new collection programme.

Note that this stock assessment has convergence issues with the MCMC. Results are not necessarily consistent between runs and the limited diagnostics for JABBA are helpful in this regard. This issue will need further evaluation, but further work is not recommended until extended time series from the new data collection are included in the assessment.

Notwithstanding the issues identified above, it is recommended that the two selected models form the basis for testing and selecting an updated harvest control rule to applied to the joint artisanal/industrial fishery for the purpose of limiting overall fishing activity.

The maximum sustainable yield of all finfish combined cannot be estimated with precision, but risks of catches exceeding MSY have been estimated. Recent catches in the region of 350000t have a significant probability (>27%) of being unsustainable (Table 1), and maintaining lower catches will reduce this risk. In particular, the industrial abundance index shows a decline (Figure 1), suggesting the component of the stock harvested by the industrial vessels may be at greater risk of overfishing.

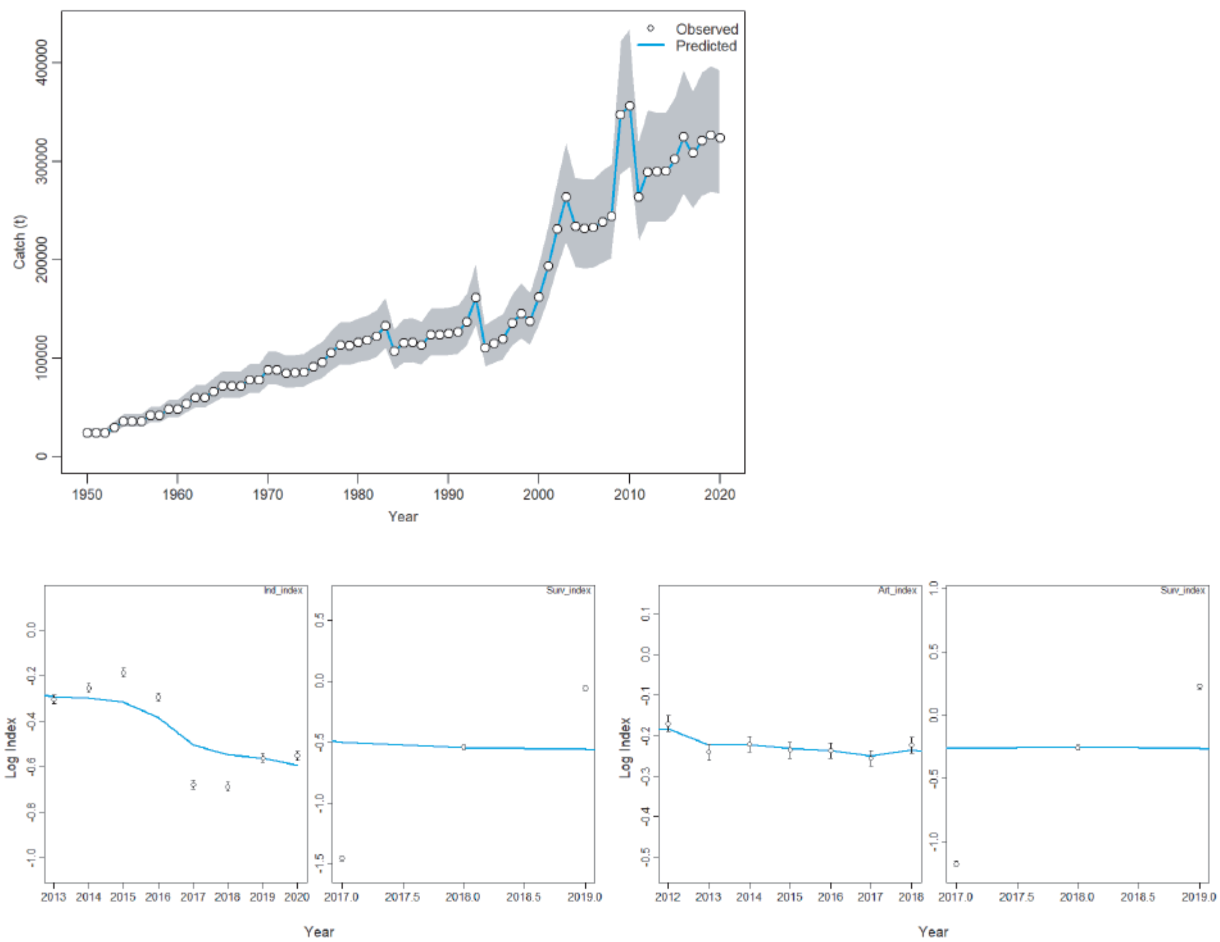


Figure 1 Fitted finfish total catch (top) and CPUE (bottom) for industrial (Ind_index) and artisanal (Art_index) in the separate models, and research vessel survey (Surv_index) log abundance indices in the tested models.

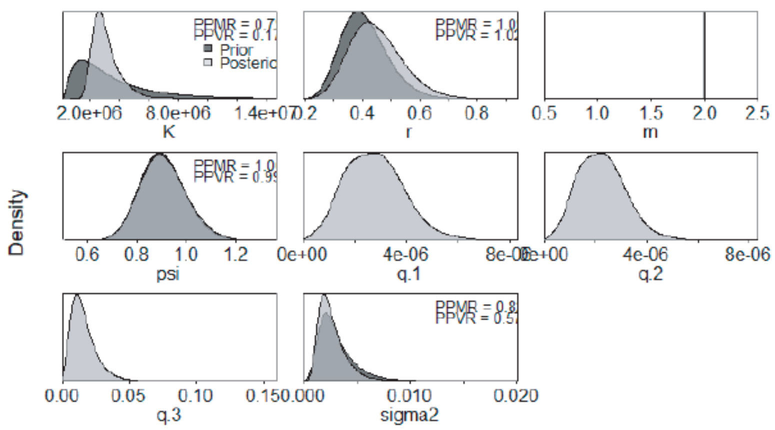


Figure 2 Finfish prior (dark grey) and posterior probability (light grey) densities for the model parameters. Differences between the probability densities indicated the influence of the data.

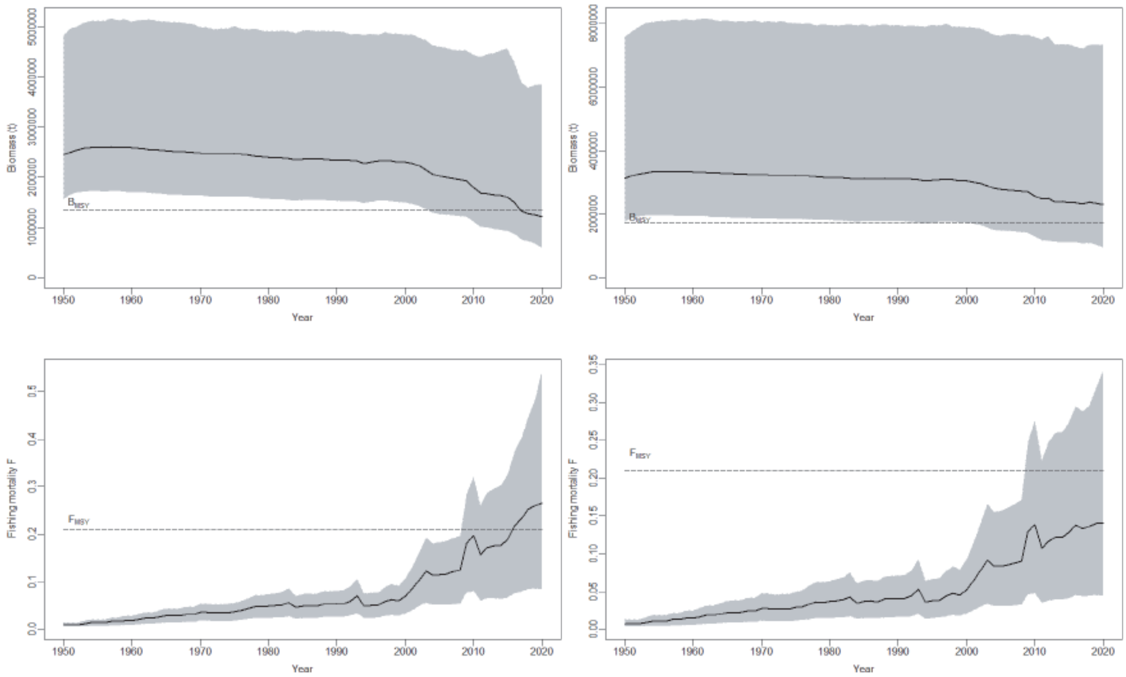


Figure 3 Estimates of finfish biomass (top) and fishing mortality (bottom) relative to the MSY levels for the industrial (left) and artisanal (right) index scenarios. For the Schaefer model, MSY is 50% unexploited stock size (K).

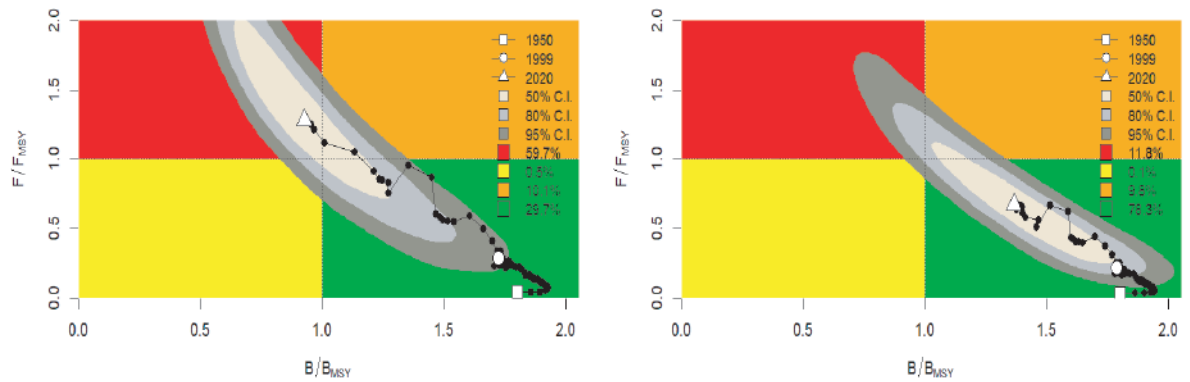


Figure 4 Finfish "Kobe" plot showing past stock status trajectory mean and credible intervals for the industrial (left) and artisanal (right) models. While the stock is not likely to be heavily overfished, the probability of the overall populations of finfish being in an overfishing / overfished state is significant.

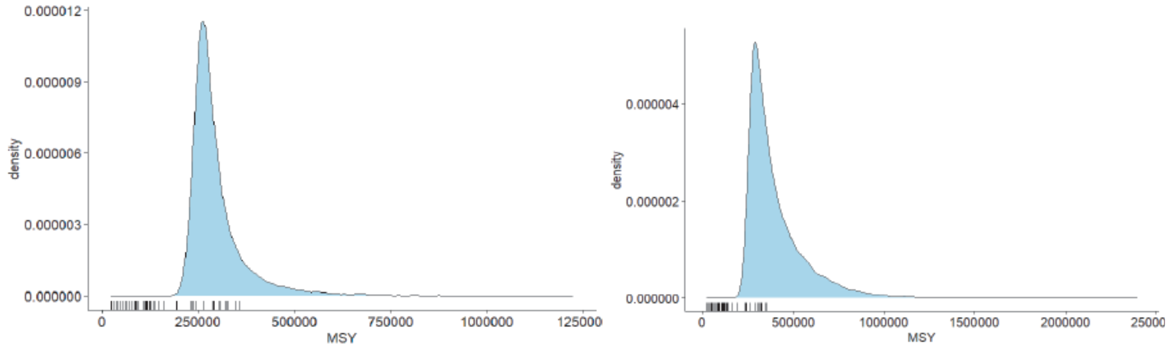


Figure 5 Probability density for the finfish MSY estimate for the industrial (left) and artisanal (right) index models. Reported catches are shown on the x axis as rug lines.

Table 1 Probability that the finfish catch (TAC) would be greater than the MSY under the industrial and artisanal index models.

TAC	Industrial Index	Artisanal Index
250,000	0.110	0.020
270,000	0.239	0.062
290,000	0.341	0.122
310,000	0.407	0.182
330,000	0.447	0.233
350,000	0.472	0.275
370,000	0.491	0.312
390,000	0.504	0.341
410,000	0.514	0.367
430,000	0.522	0.390
450,000	0.527	0.408

Shrimp

An assessment was applied to all shrimp using the full time series of catch data from FAO statistics. It should be noted that, as for finfish, different species of shrimp may be exploited at different levels which the model does not address. The model is entirely empirical, so no justified prior on the parameter *r* in particular was available and trials suggested a precautionary value of 0.5 was reasonable as an average across species being caught. Otherwise, industrial and vessel survey abundance indices were used. Data from the artisanal fishery was limited and did not form a simple consistent index.

Catches (Figure 6) and hence fishing mortality (Figure 8) show a continuous upward trend 1985 -2010, but thereafter has declined somewhat. Both abundance indices show a clear decline in recent years which the model was able to fit. Note however, the first few years of the industrial index is not well-fitted. In common with other assessments, the data were primarily informative on the unexploited stock size (K) and had little effect on other parameters as they showed no departure from their priors (Figure 7).

The catch and effort data from the industrial fishery and research surveys indicate that it is likely that the overall status of shrimp in Bangladesh is overfished (Figure 9). The MSY estimate is around 40000t which has most likely been exceeded (Figure 10; Table 2), implying that catches will need to be reduced below this level to allow recovery. There is still considerable uncertainty in the results primarily because the time series of data are very short.

Overall, indicators are that shrimp is fully overexploited in Bangladesh because catches have peaked and declined and recent abundance indicators show a downward trend. Note that the downward trend in survey indices was reversed in 2022, beyond the scope of the current model. It is therefore quite possible different results will result from analyses as data accumulates, a further indication of significant uncertainty.

The scientific advice is to reduce catches sufficiently to see an increasing trend in the industrial trawl standardised CPUE. The assessment suggests that this would require maintaining catches below 38000t. Further advice might be available on individual species, particularly on tiger shrimp if a reliable catch time series can be developed.

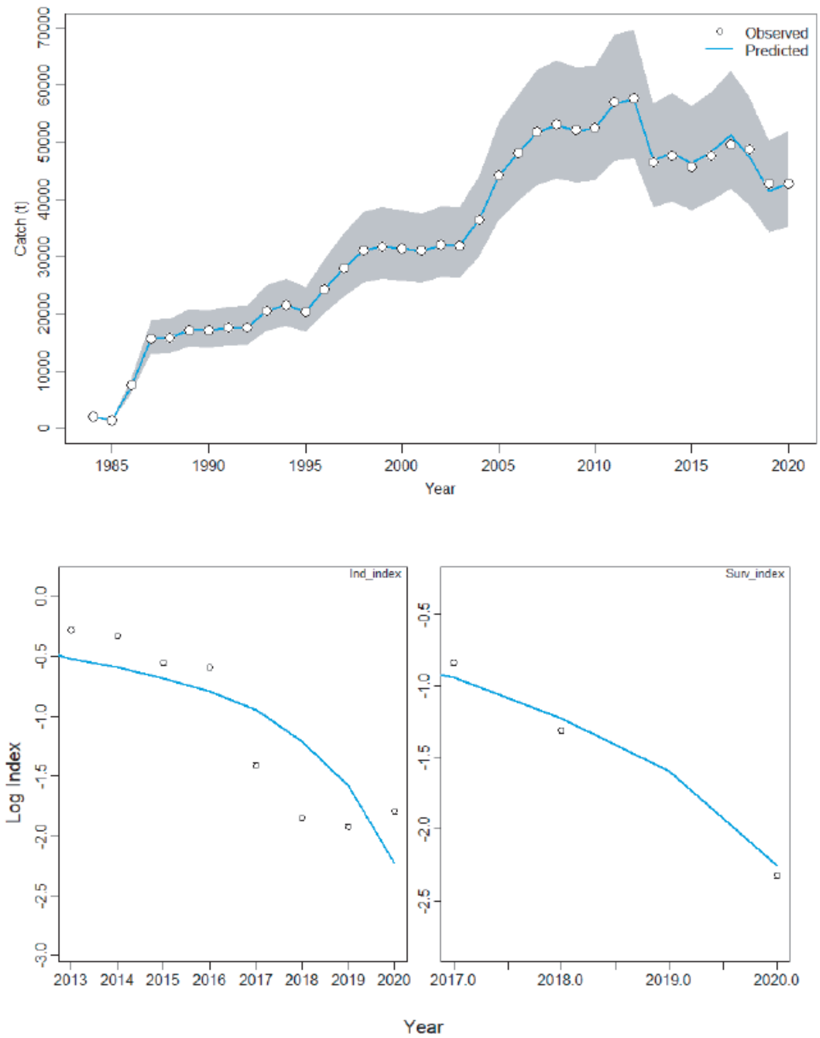


Figure 6 Shrimp fitted total catch (top) and CPUE (bottom) for industrial (Ind_index) and research vessel survey (Surv_index) log abundance indices.

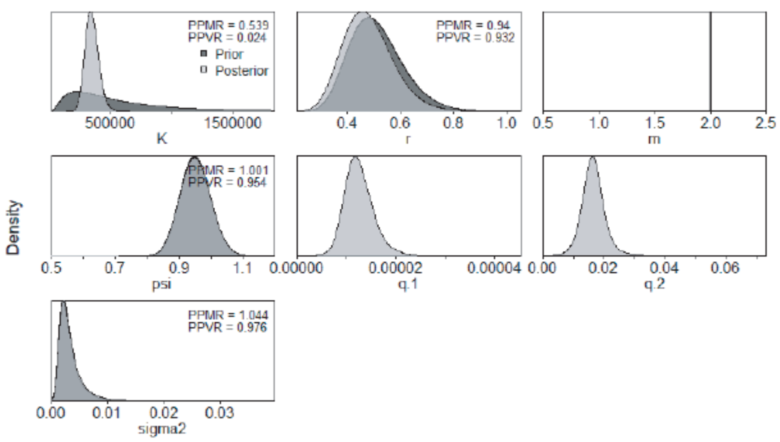


Figure 7 *Shrimp prior and posterior probability densities for the model parameters.*

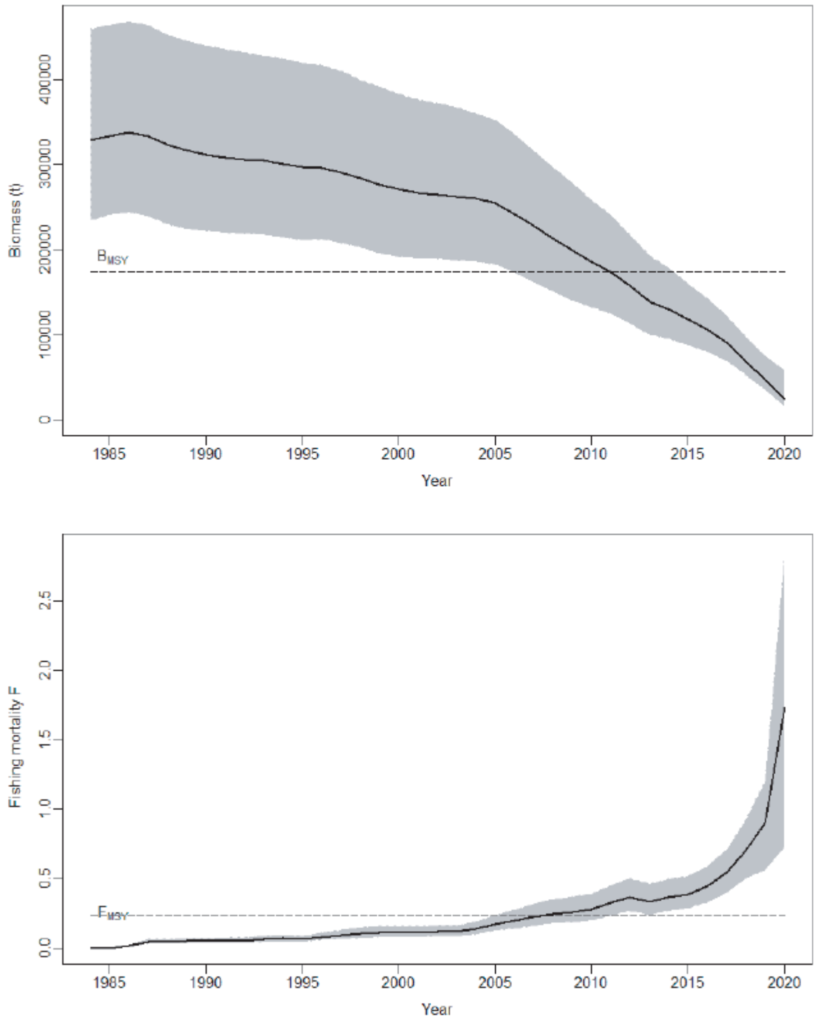


Figure 8 Estimates of biomass (top) and fishing mortality (bottom) relative to the MSY levels. For the Schaefer model, MSY is 50% unexploited stock size (K).

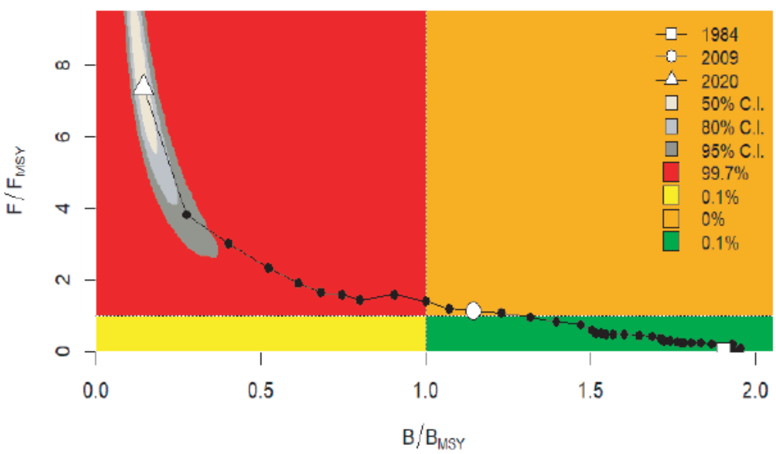


Figure 9 Shrimp "Kobe" plot showing past stock status trajectory mean and credible intervals for the current status. The shrimp stock is highly likely overfished.

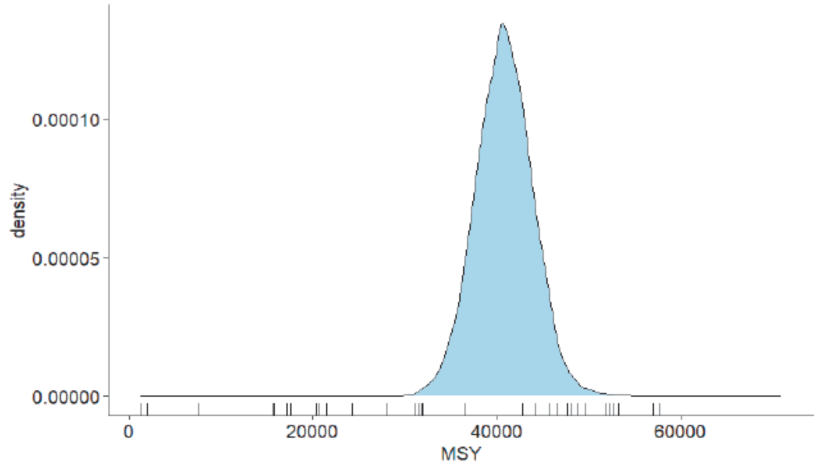


Figure 10 Probability density for the shrimp MSY estimate. Reported catches are shown on the x axis as rug lines.

Table 2 Probability that the shrimp catch (TAC) would be greater than the MSY under the different scenarios: the base model, a lower mean for the prior on the intrinsic rate of increase (r), and fitting the model without the industrial CPUE index.

TAC	Base	Low r	No Industrial index
30,000	0.000	0.022	0.000
31,000	0.001	0.048	0.001
32,000	0.004	0.100	0.002
33,000	0.008	0.186	0.005
34,000	0.017	0.306	0.010
35,000	0.034	0.455	0.020
36,000	0.063	0.608	0.040
37,000	0.110	0.742	0.076
38,000	0.179	0.841	0.128
39,000	0.275	0.909	0.201
40,000	0.395	0.948	0.293
41,000	0.525	0.972	0.396
42,000	0.657	0.985	0.499
43,000	0.770	0.992	0.588
44,000	0.855	0.995	0.664
45,000	0.917	0.997	0.721

Tenualosa ilisha (Hilsha Shad)

A relatively long time series of catch data were available for hilsa, combining the freshwater and marine catches. All catches of hilsa are assumed to be a single stock. A prior on the parameter *r* was based on previous assessments at around 0.6 reported in Fishbase. Otherwise, industrial and artisanal abundance indices only were used, as hilsa is not commonly caught in the research vessel survey.

Catches (Figure 11) and hence fishing mortality (Figure 13) show a continuous upward trend since 1985. Both abundance indices are flat over the short period they cover which the model was able to fit. In common with other assessments, the data were primarily informative on the unexploited stock size (K) and had little effect on other parameters as they showed no departure from their priors (Figure 12).

The catch and effort data are weakly information hilsa status. The stock appears stable and with little evidence of depletion, the model suggests large biomass which is not overfished (Figure 13). Given the little contrast in the data, it is not clear that this stock assessment is useful for scientific advice without further support.

In general, the model favours a very high biomass to explain the current data (Figure 13). The problem with this hypothesis, apart from the limited data in the model, is that hilsa are not widely caught in the survey. If the abundance was so high, we might expect higher survey catches. Because the fish aggregate, it is possible that the CPUE is hyper-stable and therefore not responding to depletion.

While these results are probably not very reliable, the catch and effort data from the industrial fishery and artisanal fishery do not indicate overfishing (Figure 14). The MSY estimate is around 500 - 1000 kt with only around 10% probability this may have been exceeded (Figure 15; Table 3). This result is in contrast to the analysis of the length frequency data which suggests the stock is fully to overexploited.

The uncertainty is primarily because the time series of data are very short and CPUE may not be very responsive to changes in stock size. Determination of the stock status of Bangladesh hilsa shad will improve over time as more data are gathered. In addition, it is likely that there are much more data and research material than used in this analysis that is currently unavailable to the working group. All these data and information need to be brought together to develop a consensus assessment or assessments that accurately reflect stock status and potential yield with full uncertainty and provide robust scientific advice under risk.

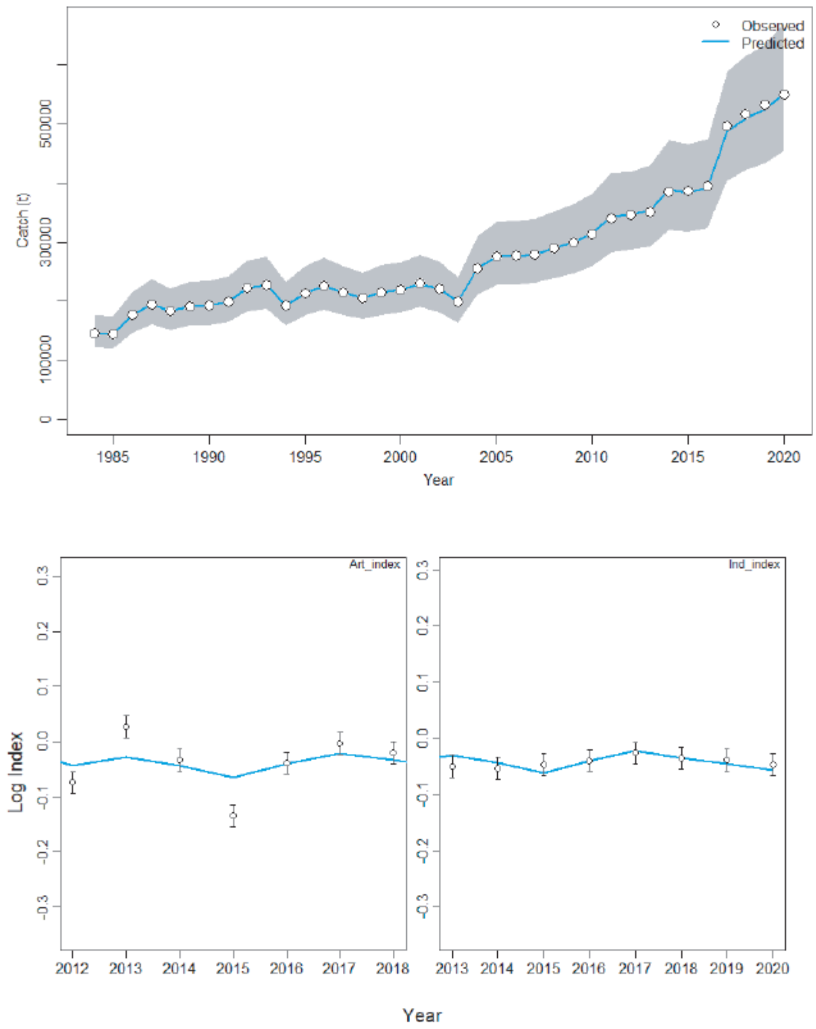


Figure 11 Fitted hilsa total catch (top) and CPUE (bottom) for artisanal (Art_index) and industrial (Ind_index) log abundance indices.

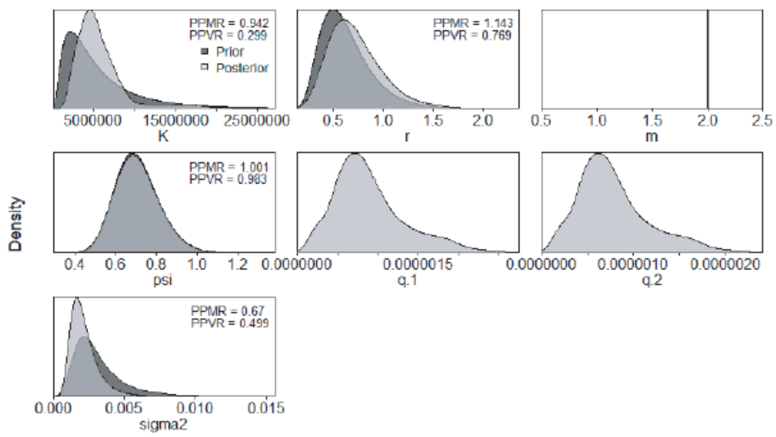
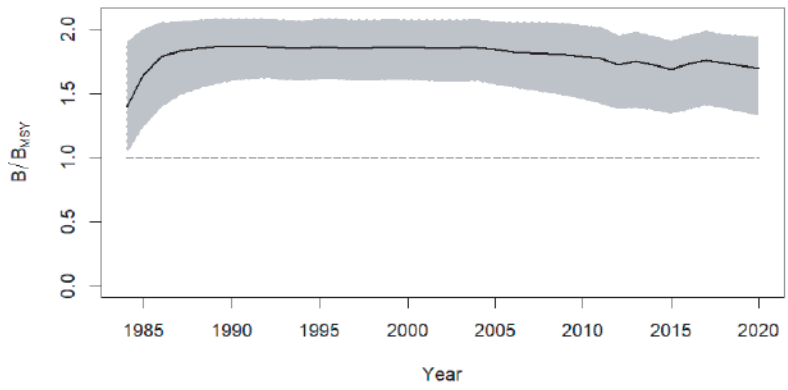


Figure 12 Hilsa prior and posterior probability densities for the model parameters.



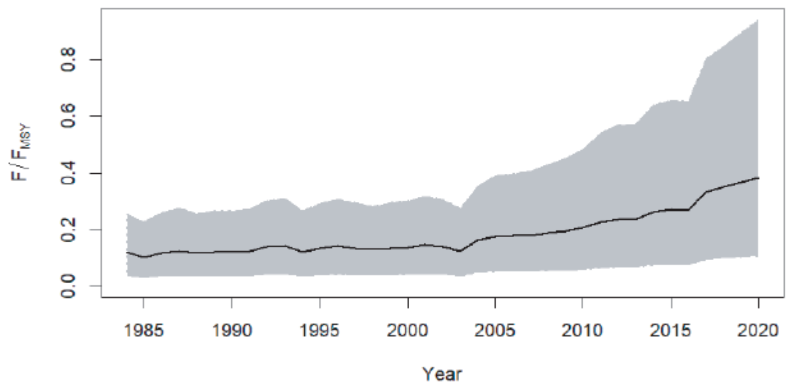


Figure 13 Hilsa estimates of biomass (top) and fishing mortality (bottom) relative to the MSY levels. For the Schaefer model, MSY is 50% unexploited stock size (K).

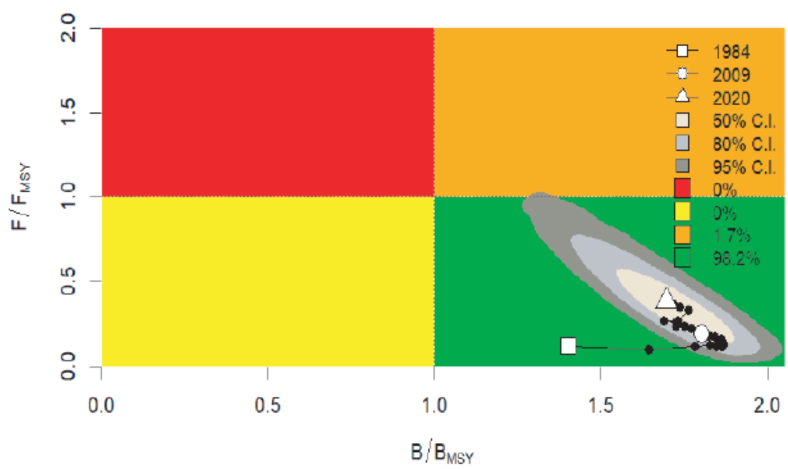


Figure 14 Hilsa "Kobe" plot showing past stock status trajectory mean and credible intervals for the current status. The stock is not likely overfished.

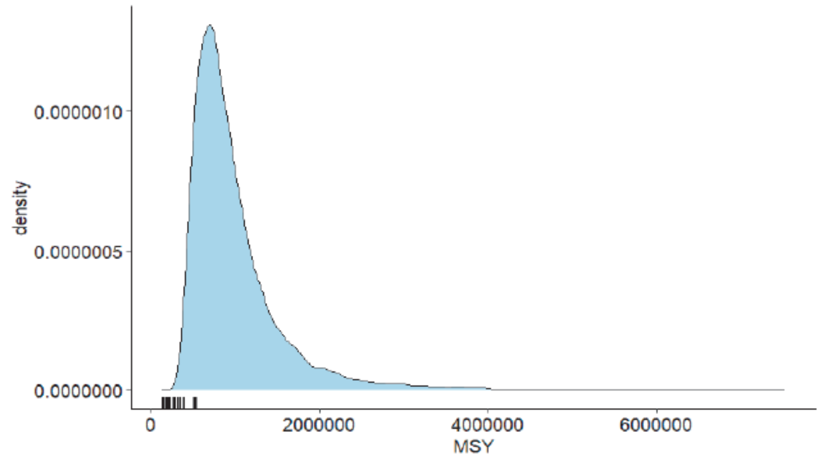


Figure 15 Probability density for the hilsa MSY estimate. Reported catches are shown on the x axis as rug lines.

Table 3 Probability that the hilsa catch (TAC) would be greater than MSY under the different scenarios.

TAC	Base	Low r	No Artisanal index	No Industrial index	Low initial state
510,000	0.101	0.017	0.004	0.014	0.006
540,000	0.136	0.022	0.006	0.017	0.008
570,000	0.173	0.026	0.008	0.020	0.011
600,000	0.212	0.031	0.010	0.023	0.014
630,000	0.252	0.035	0.012	0.026	0.017
660,000	0.291	0.039	0.015	0.029	0.020
690,000	0.329	0.043	0.017	0.031	0.023
720,000	0.366	0.047	0.020	0.034	0.026
750,000	0.402	0.050	0.022	0.036	0.029
780,000	0.435	0.054	0.025	0.039	0.032
810,000	0.468	0.057	0.027	0.041	0.035

Harpadon nehereus (Bombay Duck)

A relatively long time series of catch data were available for bombay duck, partly because the fish are an important commercial species, but also because they are easily identified in catches. A prior on the parameter *r* was based on precautionary estimate at around 0.77, the lower bound as reported in Fishbase. Values above 1.0 may make the biomass dynamics models unstable, and high *r*-values suggest a shorter time step may be required, making bombay duck a strong candidate for a seasonal model. Otherwise, industrial, artisanal and research survey abundance indices were used.

Catches (Figure 16) and hence fishing mortality (Figure 18) show a very shallow upward trend since 2008. Both abundance indices are flat over the short period they cover which the model was able to fit. In common with other assessments, the data were primarily informative on the unexploited stock size (K) and had little effect on other parameters as they showed no departure from their priors although the *r* marginal posterior showed a slight shift to a higher value (Figure 17).

The catch and effort data are uninformative on bombay duck status. The stock appears stable and with little evidence of depletion, the model therefore suggests a large biomass which is not overfished and which is stable throughout the period data are available (Figure 18). Given the little contrast in the data, it is not clear that this stock assessment is useful for scientific advice without further support.

Overall, the available catch and effort data from the artisanal, industrial fisheries and the research surveys do not indicate overfishing (Figure 19). However, results are not exact and significant risk of overfishing remains. Determination of the stock status of Bangladesh bombay duck will improve over time as more data are gathered. According to the model MSY is likely between 70 – 100 kt and there is a 15% probability MSY has been exceeded (Figure 20; Table 4).

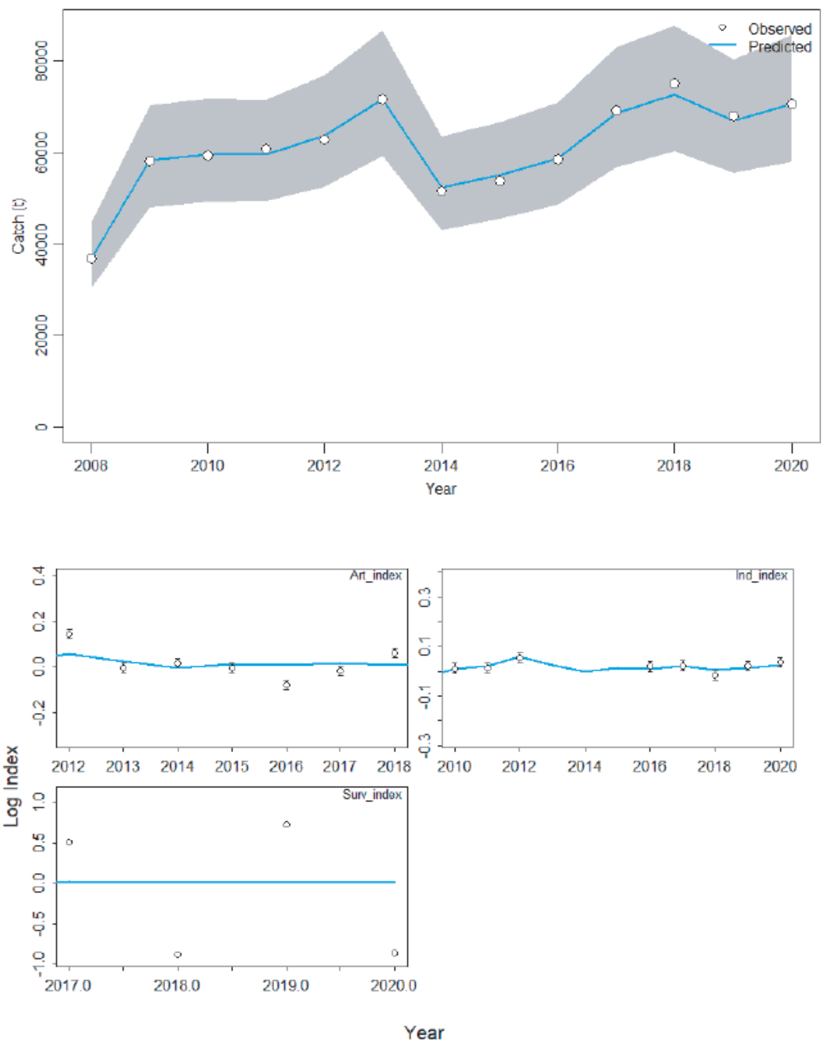


Figure 16 Bombay duck fitted total catch (top) and CPUE (bottom) for artisanal (Art_index), industrial (Ind_index) and survey (Surv_index) log abundance indices.

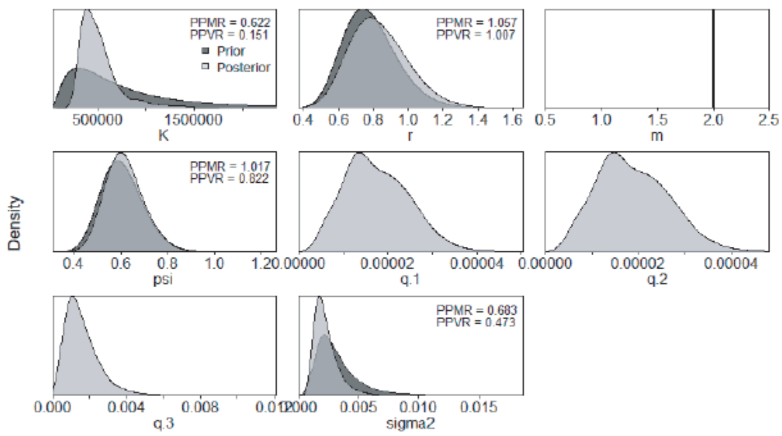
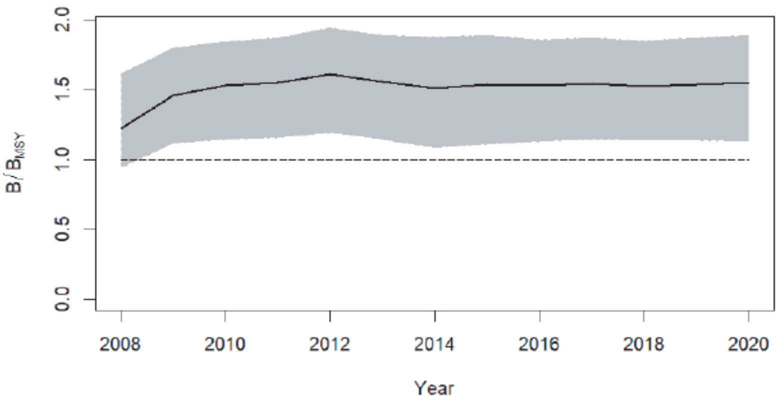


Figure 17 Bombay duck prior and posterior probability densities for the model parameters.



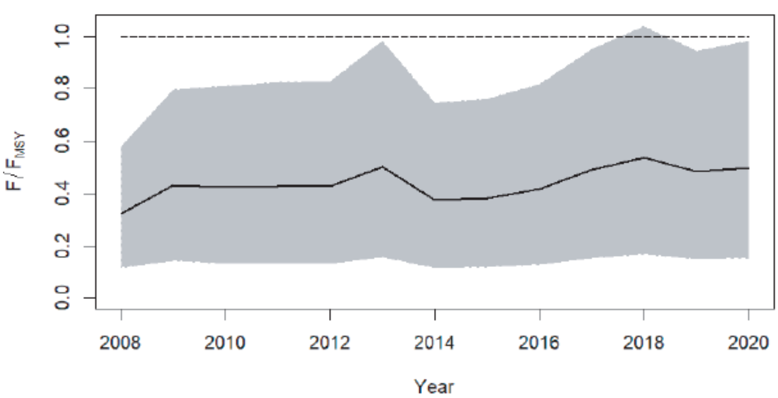


Figure 18 Estimates of bombay duck biomass (top) and fishing mortality (bottom) relative to the MSY levels. For the Schaefer model, MSY is 50% unexploited stock size (K).

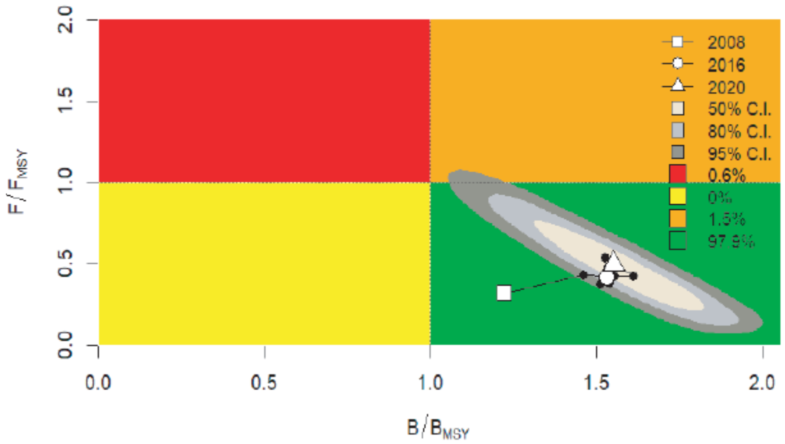


Figure 19 Bombay duck "Kobe" plot showing past stock status trajectory mean and credible intervals for the current status. While the stock is not likely to be overfished, the probability of the overall populations of finfish being in an overfishing / overfished state is still significant.

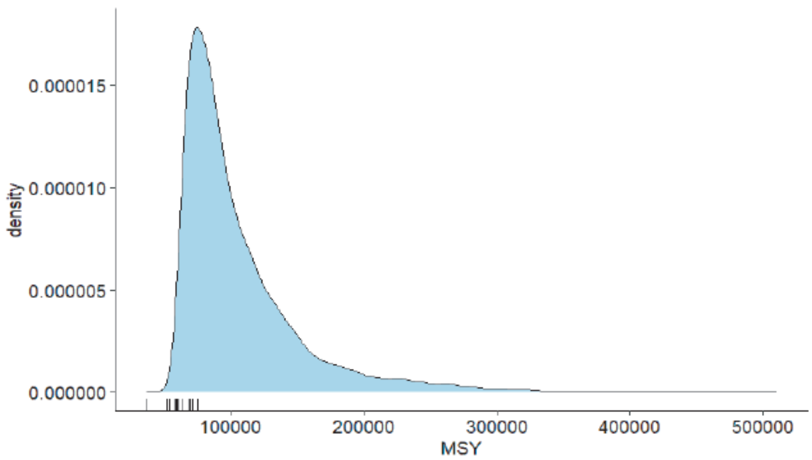


Figure 20 Probability density for the bombay duck MSY estimate. Reported catches are shown on the x axis as rug lines.

Table 4 Probability that the bombay duck catch (TAC) would be greater than MSY under the different constant catch scenarios.

TAC	Base	Low r	No Artisanal index	No Industrial index
60,000	0.00980	0.07760	0.00800	0.19835
70,000	0.14000	0.45785	0.11205	0.44110
80,000	0.32215	0.74100	0.24690	0.57345
90,000	0.47780	0.86845	0.37070	0.65610
100,000	0.59025	0.92845	0.46950	0.71630
110,000	0.67515	0.96370	0.55270	0.76505
120,000	0.74255	0.98040	0.62320	0.80365
130,000	0.79320	0.98980	0.67840	0.83445

Pomfret

While the data time series for pomfret (a group of Silver pomfret and Chinese pomfret) is relatively short, the data shows a decline and subsequent increase in the industrial trawl abundance index coinciding with changes in catches that the model interprets as a depletion and recovery event. This allows the model to estimate parameters more reliably.

The production model fitted the catch and standardised industrial CPUE abundance index well (Figure 21). The artisanal index showed a similar declined, but it is not aligned in time with the catches and the fit was less good. Nevertheless, the industrial CPUE decline and recovery matching the catch suggests that this is the most reliable catch-effort stock assessment out of those examined.

The results suggest the stock declined to an overfished state in 2015 but have since recovered rapidly (Figure 23; Figure 24). Of most interest is the long-term sustainable catch which needs to be maintained less than the MSY. With careful monitoring, catches around 25000t may be safe (Table 5) as long as further adjustments are made in future as information improves.

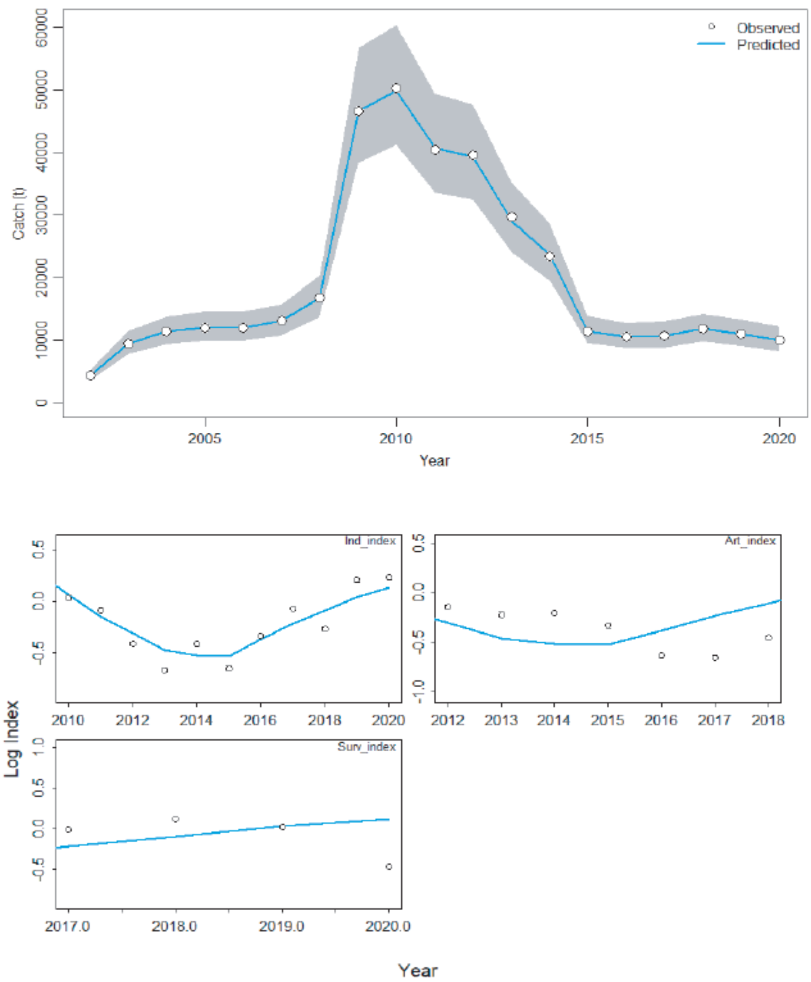


Figure 21 Pomfret fitted total catch (top) and CPUE (bottom) for industrial (Ind_index), artisanal (Art_index), and survey (Surv_index) log abundance indices.

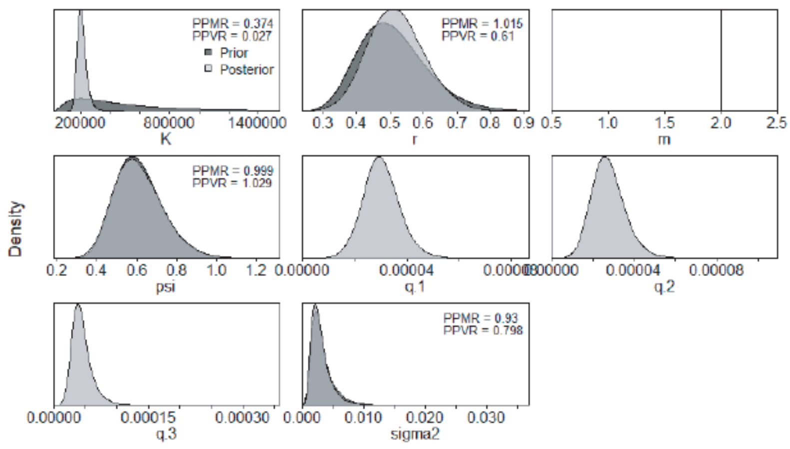


Figure 22 Pomfret prior and posterior probability densities for the model parameters.

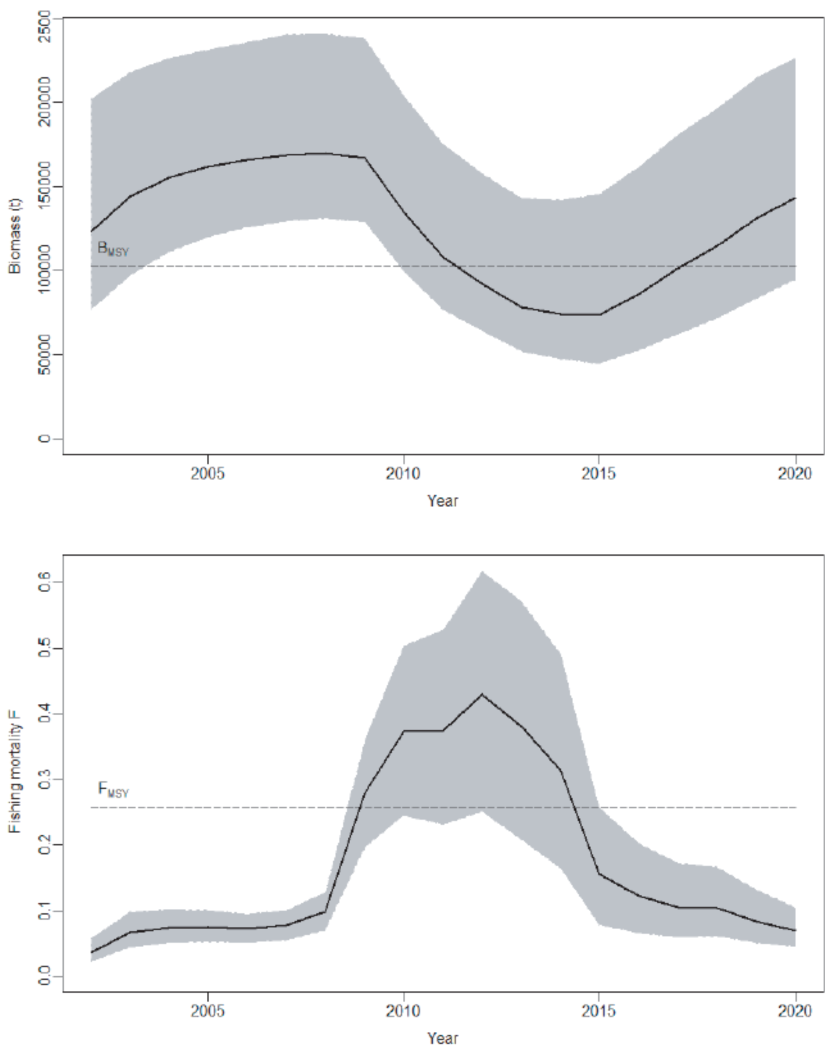


Figure 23 Pomfret estimates of biomass (top) and fishing mortality (bottom) relative to the MSY levels. For the Schaefer model, MSY is 50% unexploited stock size (K).

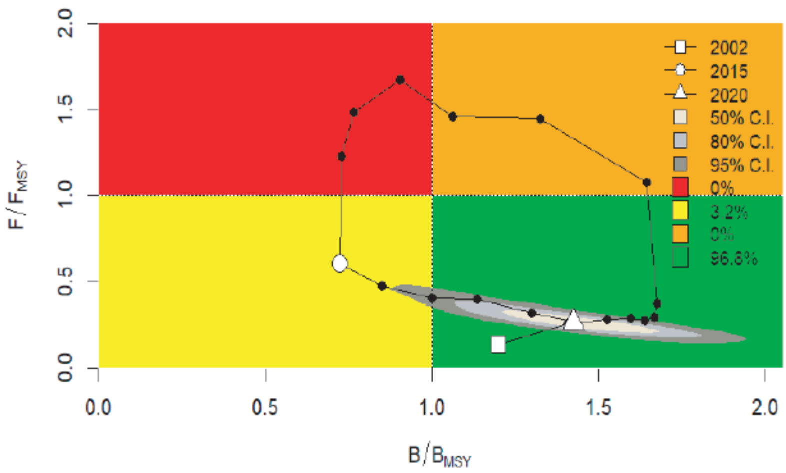


Figure 24 Pomfret "Kobe" plot showing past stock status trajectory mean and credible intervals for the current status. While the stock is not likely to be overfished, the probability of the overall populations of finfish being in an overfishing / overfished state is low.

Table 5 Total pomfret catches and the probability of exceeding the MSY value for the different scenarios.

TAC	BASE	LOW INITIAL STATE	NO ARTISANAL INDEX	NO INDUSTRIAL INDEX
20000	0.003	0.001	0.001	0.168
21000	0.008	0.003	0.002	0.294
22000	0.025	0.013	0.009	0.453
23000	0.066	0.041	0.026	0.605
24000	0.147	0.103	0.068	0.721
25000	0.276	0.220	0.150	0.803
26000	0.436	0.382	0.280	0.850
27000	0.602	0.559	0.441	0.877
28000	0.746	0.710	0.604	0.893
29000	0.844	0.822	0.732	0.902
30000	0.906	0.892	0.831	0.909

Sciaenidae (Croakers / Jewfish)

There is a short time series of catch data 2010-2020 which is relatively flat, but shows some changes in catch. In addition, industrial CPUE, artisanal CPUE and survey data exist for this species group over the same time period.

The model fitted the data well (Figure 25), but there was little support for the estimates except stock size and results depend on assumed priors (Figure 26). There is little evidence of overfishing (Figure 27), but this evidence is very weak and anecdotal reports have suggested the availability of croakers is decreasing so caution is advised. However, the model does provide some guidance on sustainable catches based on the past reported catches. This suggests catches at or below 35000t (Figure 29; Table 6) are likely sustainable as long as monitoring continues.

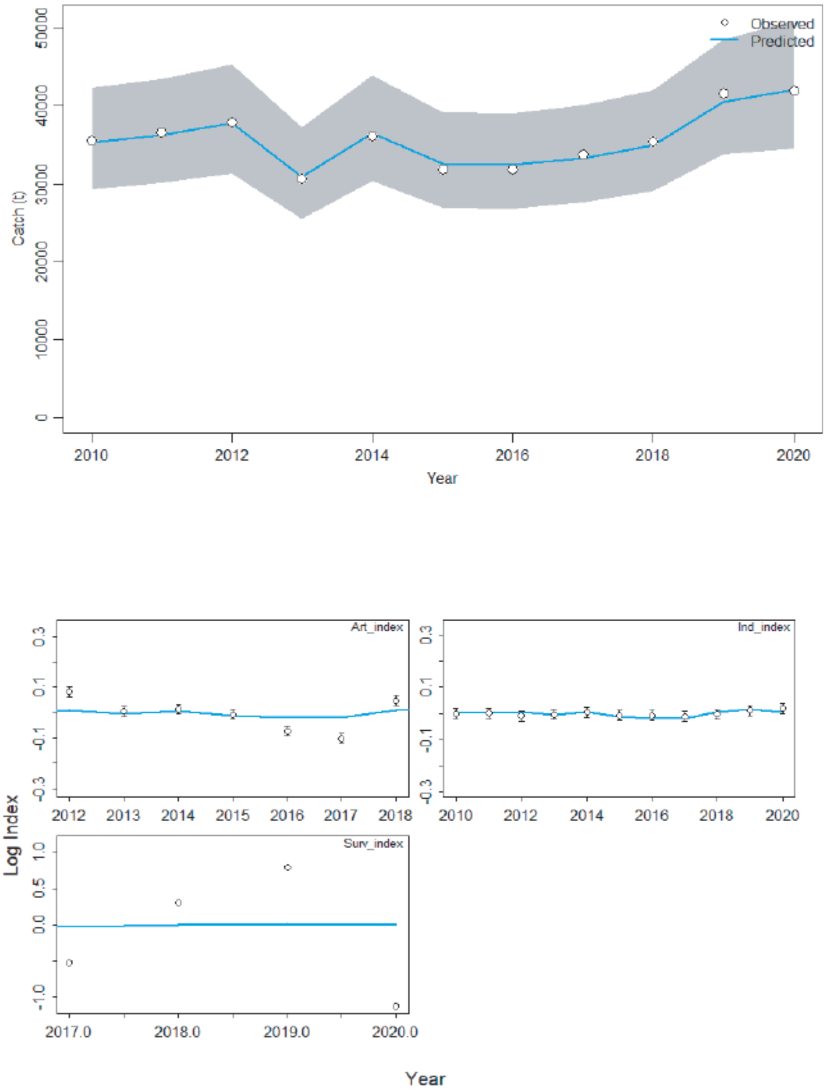


Figure 25 Croaker fitted total catch (top) and CPUE (bottom) for artisanal (Art_index), industrial (Ind_index) and survey (Surv_index) log abundance indices.

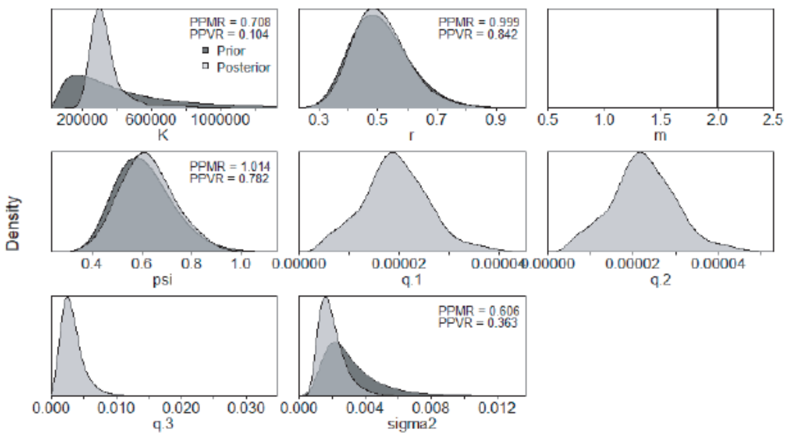


Figure 25 Croaker prior and posterior probability densities for the model parameters.

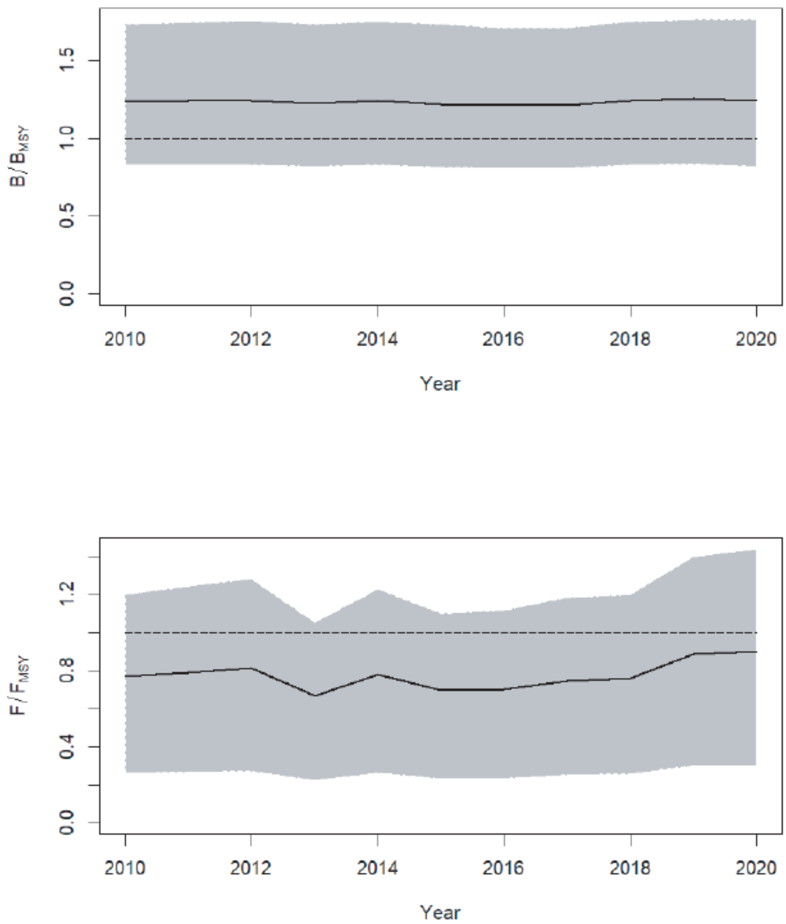


Figure 27 Croaker estimates of biomass (top) and fishing mortality (bottom) relative to the MSY levels. For the Schaefer model, MSY is 50% unexploited stock size (K).

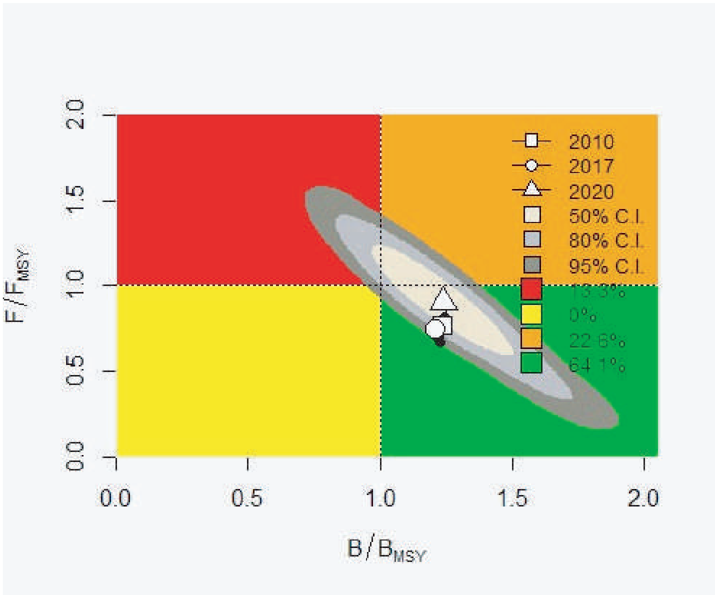


Figure 28 Croaker "Kobe" plot showing past stock status trajectory mean and credible intervals for the current status.

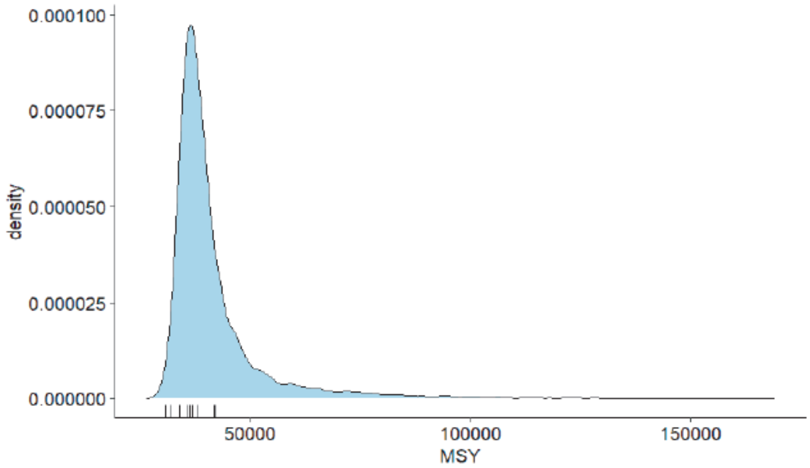


Figure 29 Probability density for the croaker MSY estimate. Reported catches are shown on the x axis as rug lines.

Table 6 Total croaker catches and the probability of exceeding the MSY value for the tested scenarios: the base model, a lower mean for the intrinsic rate of increase (r) prior and excluding each main abundance index in turn.

TAC	Base	Low r	No Artisanal Index	No Industrial Index
25000	0.000	0.000	0.000	0.005
27500	0.000	0.000	0.000	0.034
30000	0.005	0.002	0.003	0.147
32500	0.045	0.031	0.035	0.368
35000	0.201	0.194	0.165	0.597
37500	0.444	0.494	0.377	0.746
40000	0.635	0.737	0.554	0.829
42500	0.744	0.871	0.673	0.878
45000	0.809	0.939	0.752	0.910

Length-based Catch Curve (fishblicc) Method

The fishblicc Model

A fuller description of the model is provided in Annex I: Length-based Catch Curve Model. The model estimates mortality from different sources and their combined effect on the population. This requires that data be organised into homogeneous selectivity groups, usually based on gear. In addition, relative catch of each of these groups is also required. This has been assumed to be in proportion to the sample sizes within each group, an assumption which depends on the sampling design. The scientific survey was assumed to have a fishing mortality of zero because catches by the survey are negligible.

The length frequency is interpreted as a stable size structured population subject to growth and mortality processes. A Bayesian model is used to estimate the overall mortality from the combined length compositions of a number of gears. The assumptions (steady state and form of selectivity) can be tested by comparing data from several sampling periods and testing the difference between domed and flat-topped selectivity.

To complete this preliminary assessment, Fish base was used as the main source of information with minimum checks of the primary source (Froese and Pauly 2022). It is planned to continue to improve this input information through local studies and primary literature review.

Spawning Potential Ratio (SPR) and Management Advice

The outputs from the fitted *fishblicc* model can be used to estimate spawning potential ratio (SPR) reference points, which can then be used to evaluate the estimated mortalities. This approach is suitable for the data being collected, can be used immediately within the life of the project, and provides management advice appropriate for the fisheries. The method used here is based on the proposals of Hordyk et al. (2015) and Prince et al. (2015), but improves the estimation methodology and places the approach more firmly in a robust risk-based framework. In addition, the length frequency data were evaluated where appropriate for their sensitivity to different selectivity models and length-inverse natural mortality.

SPR is the ratio of the per-recruit spawning stock biomass between the unfished and fished state. The spawning stock biomass depends on the growth, the length-weight and the length-at-maturity functions. In the fished state, the spawning stock biomass will also depend on the level of fishing mortality and the selectivity function. The SPR is easy to calculate and can be linked to robust decision-making using simulation methods.

Standard reference points based on SPR are usually defined as fishing mortalities that produce a spawning potential ratio of between 20 and 40%. Limit reference points are generally set at SPR20% as this is considered reasonably precautionary. This is a point it is important for the fishery to avoid as below this point the probability of stock collapse becomes unacceptable.

Target reference points are usually set at a higher level, with 40% being considered reasonably precautionary for groundfish and 30% being possible for very highly productive species. However, highly productive species, such as small pelagics, often fluctuate due to environmental effects, making higher fishing mortality potentially risky unless there is close monitoring of the stock so that when low abundance is detected prompt action can be taken. Most stocks in Bangladesh marine waters, such as hilsa, the pomfrets, sardines and bombay duck are highly productive, but also are probably affected by freshwater outflow from the rivers and therefore potentially vulnerable to the fisheries exacerbating low abundance resulting from environmental effects that could, in turn, lead to stock collapse. It is therefore recommended that the preliminary target reference points are set at SPR40% for all species and this will be applied by default unless stated otherwise. This applies an international standard, but should be reviewed by decision-makers considering the acceptable risk.

Preliminary Multispecies Stock Assessment Results

The primary purpose of the multispecies assessment was to review the range of length frequency data and identify species that are good candidates for detailed analysis based on the available data, and data that will likely become available from the trawl sampling. 112 species were identified as having sufficient data for analysis.

Of the 112 species for which there were some data, the largest proportion came from the scientific survey and were not recorded in the artisanal fishery data. The scientific survey data by itself is not considered reliable for this analysis because it probably does not reflect commercial trawl selectivity.

For all these species, in most cases reliable assessment will require commercial trawl length frequency samples.

All data used was either from the scientific survey or collected during the period 2012-18 by the Bangladesh Marine Fisheries Capacity Building Project. Full information on the sampling protocol applied by this project has not yet been obtained and there remain some errors in the historical data which need correction.

Shrimp analysis has not yet been completed due to different measurements being taken. Some further morphometric analyses may be required to address this and make consistent data sets.

Multiple-selectivity models were fitted in each case data existed, with separate selectivity for gill net, bag net and the scientific survey (trawl). Where there were only survey data the selectivity was assumed to be flat-topped (logistic), whereas in all other cases dome-shaped selectivity function (double-sided normal) was fitted. The research survey has a negligible effect on mortality and the data therefore contained no information on fishery selectivity, so a selectivity function has to be assumed for these data.

The models were fitted by finding parameters maximising the posterior density for each species using the Stan optimiser in the fishblicc package. The standard errors were estimated form the inverted Hessian matrix, which is only provides an approximation.

Based on the length data and the maximum posterior density (mpd) estimates, the majority of species are at or above the target level (SPR40%[3]). This equates to around 35% of stocks (39 out of 112 species) at greater than 50% probability of being below the SPR40% and around 23% of stocks (26 out of 112 species) at greater than 50% probability of being below the SPR20%.

Clearly some SPR estimates are poor. Apart from the poor fits to observed frequencies which might be corrected in a multi-selectivity model, estimates at the extreme ends (SPR close to 100% or 0%) are unlikely to be correct, although they may still indicate general status. Quantitative SPR estimates could be improved by more careful justification for priors used. Estimates of overfishing risks will be improved by fitting using MCMC.

These results have yet to be fully reviewed by the Stock Assessment Working Group, but the current results do support the general conclusion that some species may be overexploited and others could sustain higher harvests. Managing this number of species will require balancing exploitation levels among species to meet ecological as well as socio-economic objectives.

[3] The target level has not yet been agreed. The SPR40% is precautionary.

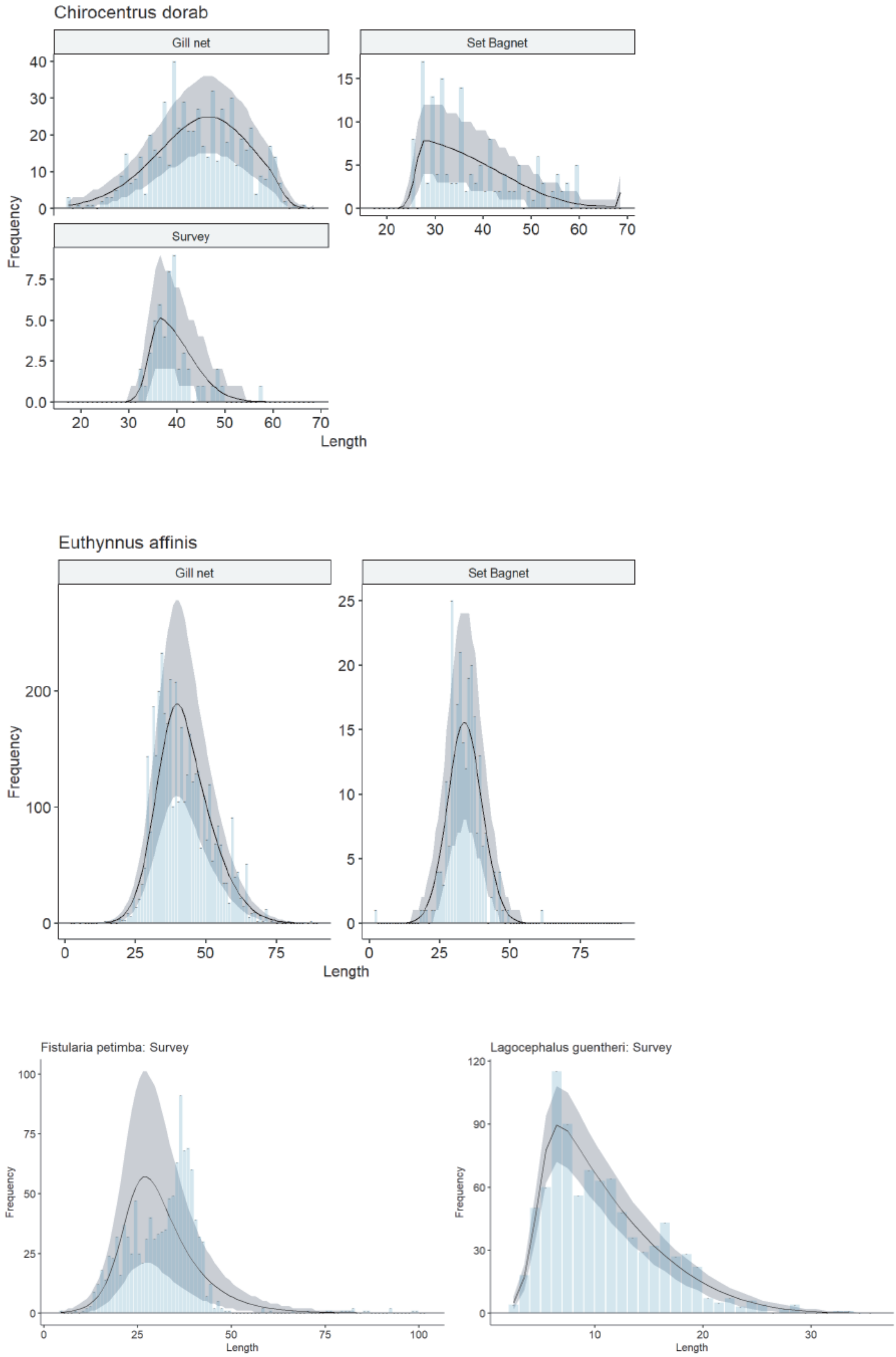


Figure 30 Example fits for 4 out of 112 catch curves fitted to length frequency data illustrating variation in model performance. Note that many sample sizes are small.

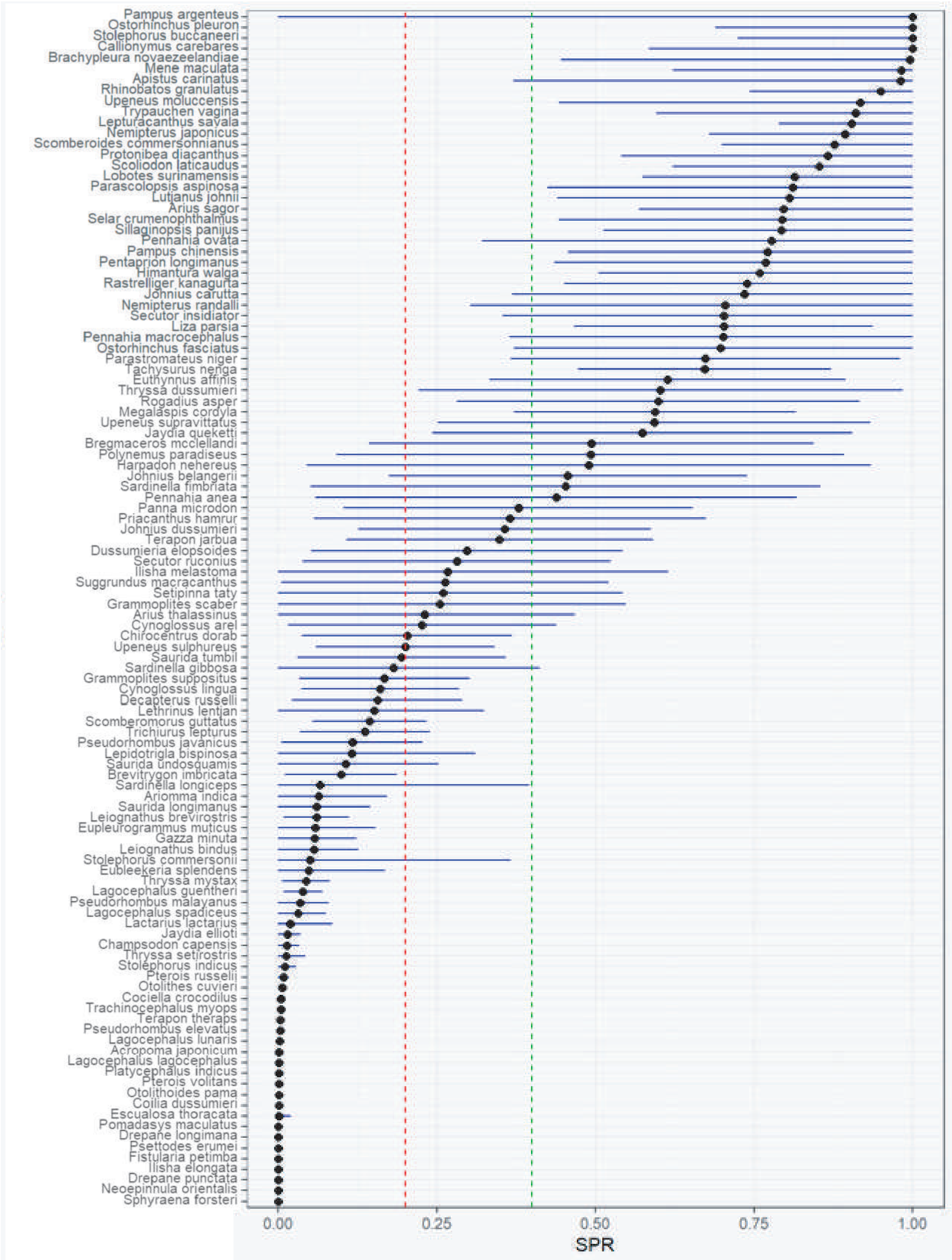


Figure 31 Spawning potential ratio (SPR) for 112 species examined. The blue dot represents the MPD estimate for each species and the horizontal blue lines are the 80% credible interval. The vertical dotted lines are the target (green: SPR 40%) and limit (red: SPR 20%) reference points.

Harpadon nehereus (Bombay Duck)

A significant amount of data had been collected for bombay duck from the artisanal fishery. The species is also caught in the scientific survey, but the length data from this source were found difficult to interpret and not included in the final model. Artisanal data were split into three gears: combined gill net, estuarine set bagnet and marine set bagnet. Catches were dominated by the marine set bagnet. Significant catches are also taken by the commercial trawl fishery for which there is no data. A final assessment would require length frequency data from all major sources of fishing mortality.

Two model fits were chosen to represent equally likely assumptions. The models assumed either natural mortality was constant or length-inverse (Lorenzen 2022). These models' results were combined in providing advice. The models fitted the data reasonably well (Figure 32) and therefore likely provide a useful basis for advice despite missing commercial trawl data. The gill net and marine set bagnet were estimated to have near identical selectivity (Figure 33).

Available evidence indicates that the Harpadon nehereus stock is not overfished (SPR > 20%). Based on combined model results (Figure 34; Table 7), there is around 1% probability that the stock is below the limit reference point (SPR<20%) but around 68% probability it is below a precautionary target (SPR<40%).

However, results also suggest that yield might be improved with the current fishing effort by raising the size at capture. For the current fishery, yield would be maximised by raising the marine set bagnet selectivity mode from 24.3 to 29.8. This increase might be achieved by an increase in mesh size or adjustment in fishing locations, although the impact on other species capture would need to be taken into account. Clearly, the estuarine catches need to be minimised on the same basis. While equally raising the size of capture by gillnets would be beneficial, gillnets are generally catching bombay duck as bycatch, so adjustment of catch size in this gear may be more difficult. Final advice will require data collected from the commercial trawl fishery.

Length frequencies for bombay duck are insensitive indicators of changes in fishing mortality (Figure 35) due to the estimated selectivity model which is heavily dome-shaped. This dampens the length-frequency data response to mortality effects because larger fish will be under-represented in the catches. Reliance on length frequency alone may result in relatively imprecise estimates of stock status, and so other data may be required to provide precise estimates of fishing mortality. Length frequency will still provide good information on changes in selectivity (e.g., mesh size), so can be used to monitor management performance for changes in selectivity.

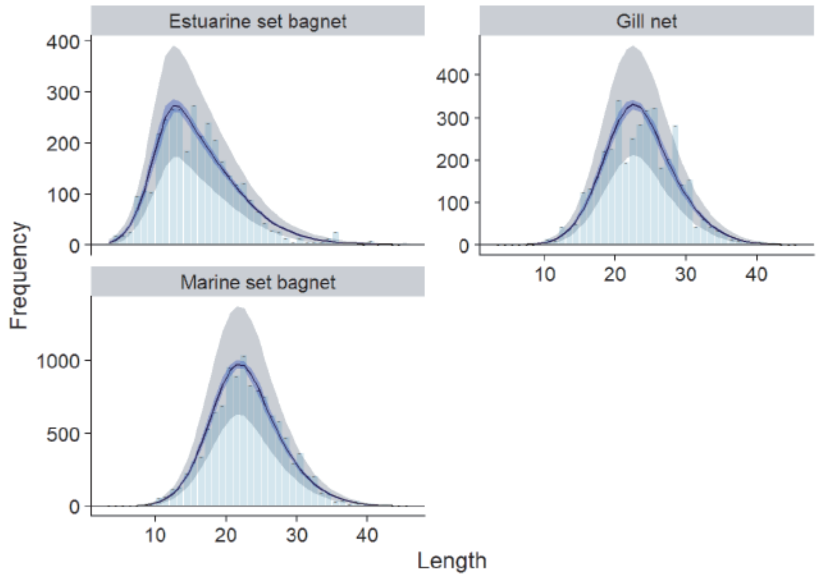


Figure 32 Observed (histogram) and expected (black line) length frequencies for each gear. The shaded blue and grey areas represent the 80% credible intervals for the expected value and the observations respectively.

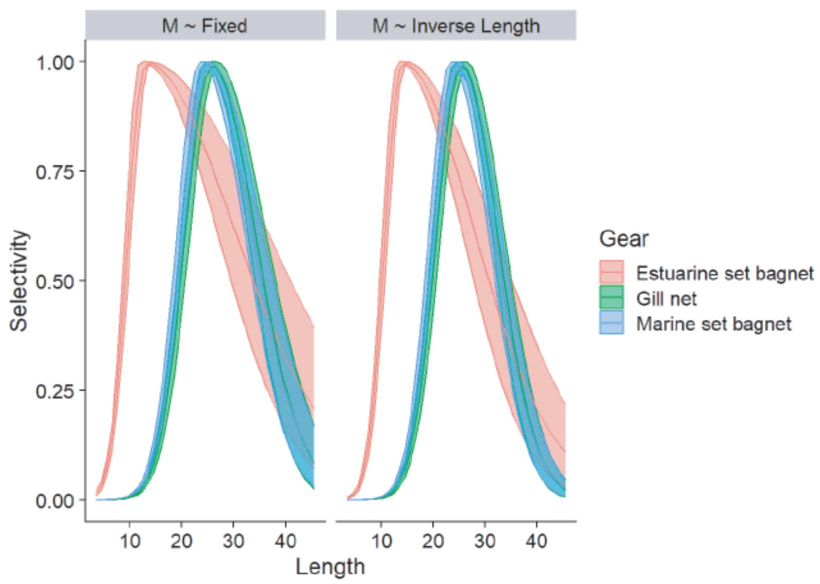


Figure 33 Estimated selectivity for the two base models.

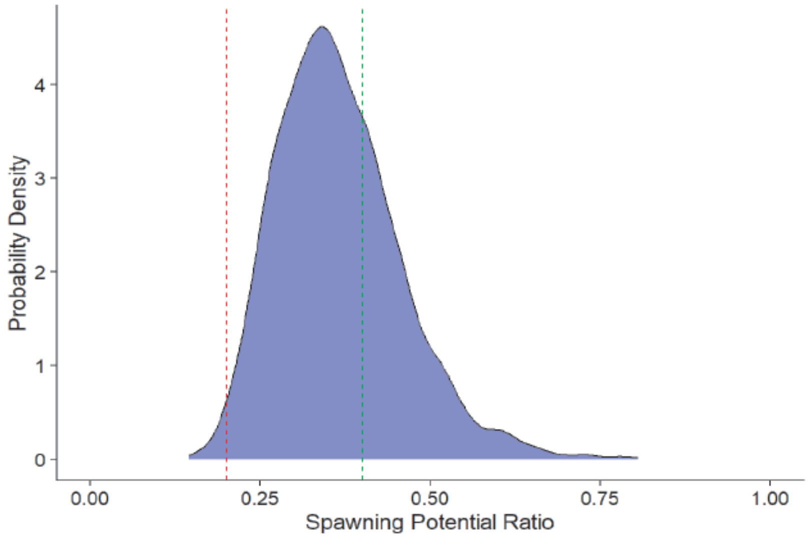


Figure 34 SPR probability density for the combined base models: the limit reference point (SPR20%) and target reference points (SPR40%) are shown as vertical red and green dotted lines respectively.

Table 7 Summary of SPR estimates and probabilities for Harpadon nehereus combined model fit

Mean (%)	SD	Pr< 20%	Pr< 30%	Pr< 40%
36.532	9.171	0.009	0.250	0.681

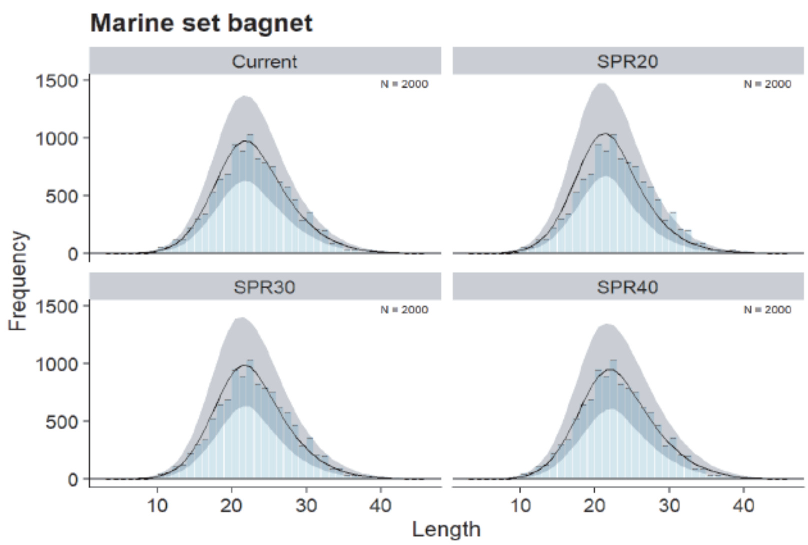


Figure 35 Expected length frequency (black line) with 80% data credible interval (grey shaded area). The current data are plotted as a histogram for reference.

Tenualosa ilisha (Hilsha Shad)

The previous Bangladesh Marine Fisheries Capacity Building Project collected the majority of their length frequency data on hilsa shad, as this is an important target species for the artisanal fishery. Evaluation of these data will make an important contribution to the design of a long-term sampling programme. The hilsa stock assessment is less likely to be sensitive to the absence of commercial trawl data because commercial trawl catches, while growing, are still small compared to the artisanal catch.

Although each gear makes a contribution to selectivity, it is not clear it is the only factor in determining selectivity. The majority of the samples (and hence it is assumed catches) were taken from the hilsa net. Examining length composition by sampling station suggested hilsa net catches could be split into two groups based on the grouped sampling location, and this led to an improved model fit with 5 separate selectivity models (Figure 36). Selectivity for each gear and the two locations are quite different (Figure 37). Therefore, the same net type may have different selectivity when used in different locations. Location may not be the only contribution to grouping selectivity, and it is recommended further work is conducted to define better groupings for these data.

The current array of results suggests that the stock is fully overexploited (Figure 39; Table 8). The SPR point estimate is 26% and there is a 27% probability that the stock is below the limit reference point (SPR20%). This indicates that the stock is at a much greater risk of overfishing than suggested by the catch-effort data analysis. These results appear robust to other considerations of selectivity function, and natural mortality, but still need further evaluation of selectivity models and data grouping. However, at this point it is not possible to determine which result is more reliable, and this suggests precaution should be applied in making decisions for this fishery.

An important uncertainty in modelling these data is the sampling design. Only a limited number of stations were visited, so it is unclear how representative the sampling is of the catches across the fishery in different locations and whether the overall sampling intensity is reasonably representative of the catch.

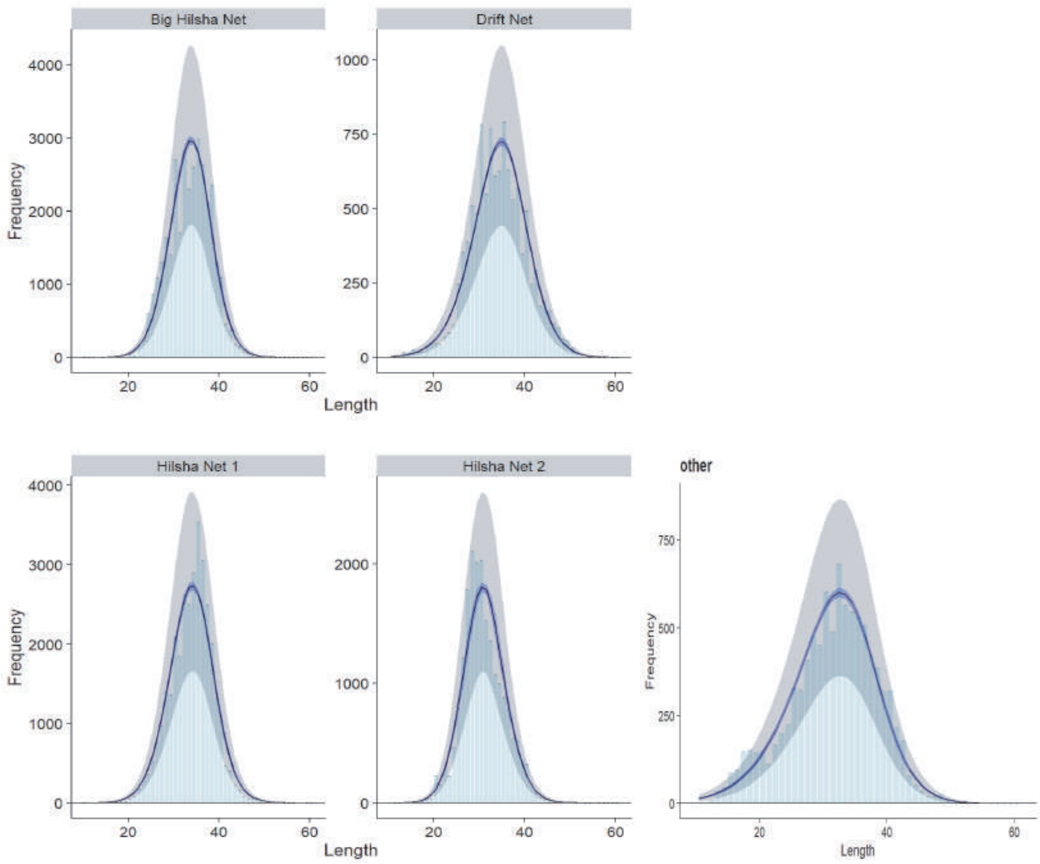


Figure 36 Observed (histograms) and expected (shaded curves) length frequency for 5 gears.

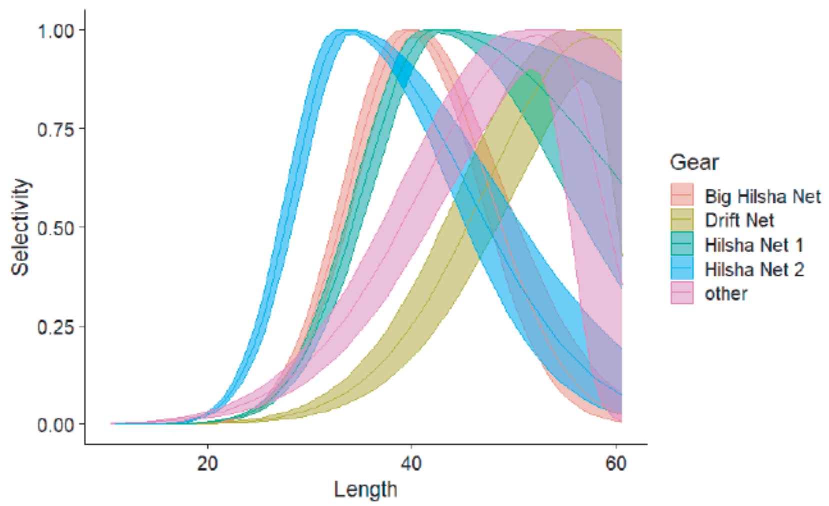


Figure 37 Estimated selectivity for the base model showing the five separate selectivities.

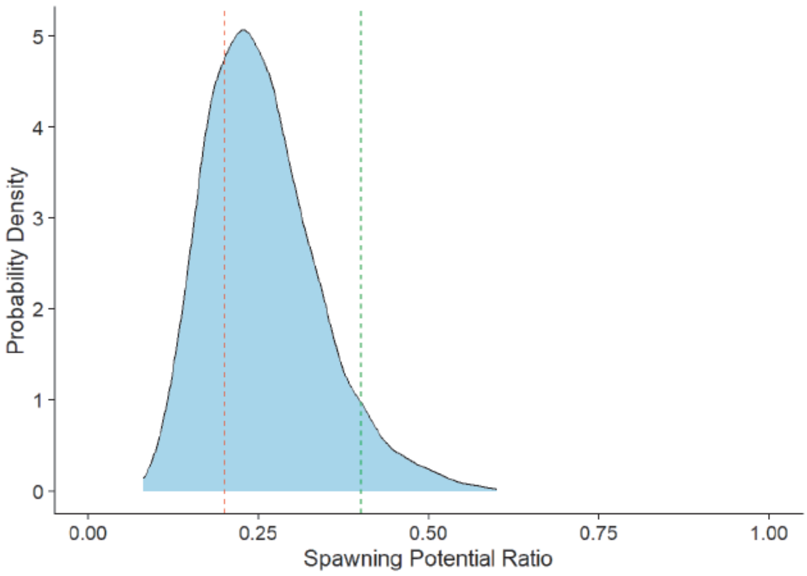


Figure 38 SPR probability density: the limit reference point (SPR20%) and target reference points (SPR40%) are shown as vertical red and green dotted lines respectively.

Table 8 Summary of SPR estimates and probabilities for Tenualosa ilisha combined model fit

Mean	SD	Pr< 20%	Pr< 30%	Pr< 40%
25.536	8.265	0.273	0.740	0.942

Lepturacanthus savala (Savalai Hairtail)

There were sufficient data to assess hairtail, but the model fitted the data poorly (Figure 39). As a result, SPR estimates are poor and unreliable. However, even with a better fitting model, it is unlikely that the qualitative results will change and therefore they are presented here. For quantitative estimates of fishing mortality, a better model fit will be required.

Two models were selected as equally likely to provide the best advice and were combined in results. The working group decided it was reasonable to assume both models were equally likely as both models fitted the data equally well, so the MCMC output can be combined into a single set for the calculation of probability densities. The models assumed either natural mortality was constant or length-inverse (Lorenzen 2022).

Based on combined model results, there is less than 1% probability that the stock is below the limit reference point (SPR<20%) and around 11% probability it is below a precautionary target (SPR<40%). In addition, SPR from all sensitivity runs considered by the working group varied from 73% to 92%.

Despite the poor model fit, the presence of large fish in the catches, well above the size at 50% maturity implies sufficient numbers of fish are reaching maturity to support recruitment (i.e., SPR > 40%). However, the model fit will need to be improved before quantitative results could be used, for example, in a harvest control rule.

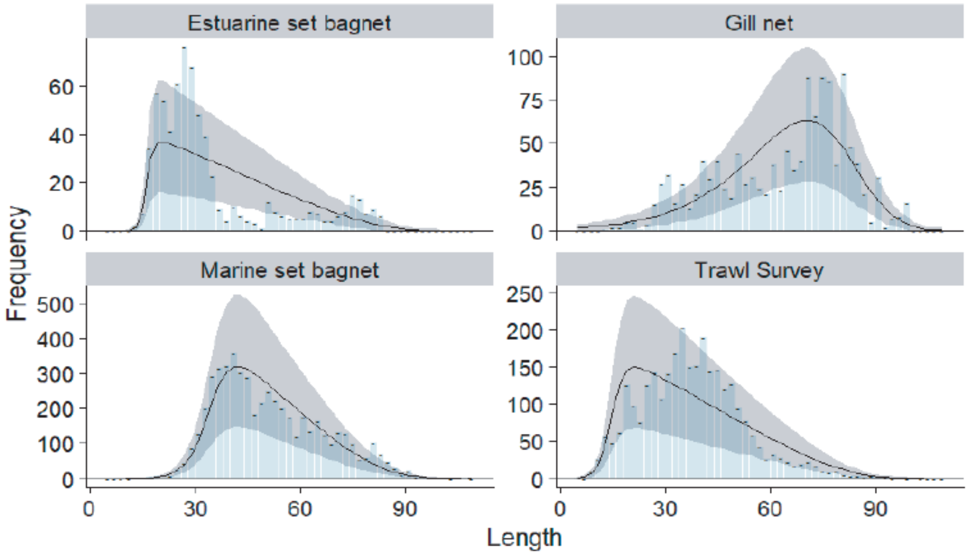


Figure 39 Observed (histograms) and expected (shaded curves).

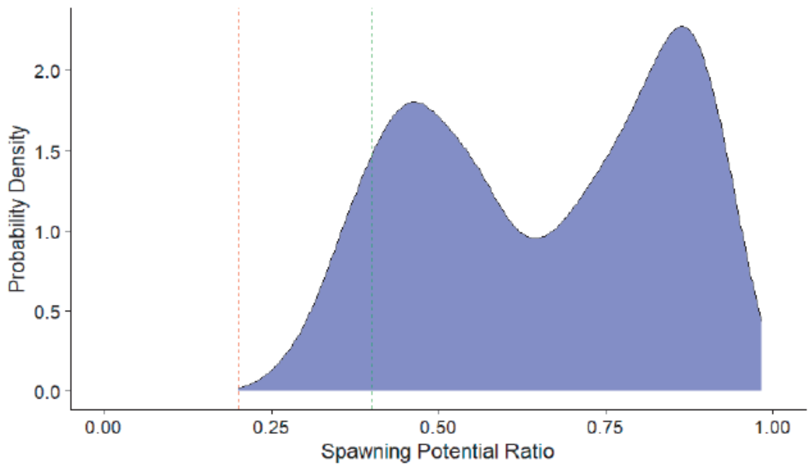


Figure 40 SPR probability density for the combined models

Table 9 Summary of SPR estimates and probabilities for Lepturacanthus savala combined model fit

Mean	SD	Pr< 20%	Pr< 30%	Pr< 40%
65.820	19.477	0.000	0.011	0.105

Ilisha filigera (Coromandel ilisha)

Length data were sampled from gillnets, set bagnets and the scientific trawl survey sufficient for stock assessment. Except for a small sample caught in stake nets and a few outliers of the smallest (<5cm) and largest (>45cm) fish, all data were retained. The outliers were suspected as being recording errors. The gillnet, set bagnet and trawl survey were treated as separate gears, with the trawl survey not contributing to fishing mortality (catch = 0).

The model fitted the data reasonably well (Figure 41), with gillnet selectivity being modelled as a logistic (i.e., flat-topped), while the set bagnet and trawl survey were best fit with a double-sided normal (i.e., domed). A flat-top selectivity fitted better for the gillnet because the selectivity mode was estimated to be at or above the maximum size for the species, so the downward slope of the selectivity was redundant. Among the alternative sensitivities examined, the run with the set bagnet also having a logistic (flat-top) selectivity estimated the lowest SPR. These two models were thought to bracket the uncertainty in the assessment, although it should be noted that the latter model fitted the data less well (Figure 41).

The results suggest that it is unlikely that the stock is overfished (Table 8; Figure 42). Even including the poorer fitting model as a precautionary worst-case scenario, the probability that the stock is below the limit reference point is around 3%, while there is a 25% probability that it is less than the target (SPR40%). On this basis, the stock is probably not fully exploited, although it should be noted that data will be required from the commercial trawl fishery to confirm this.

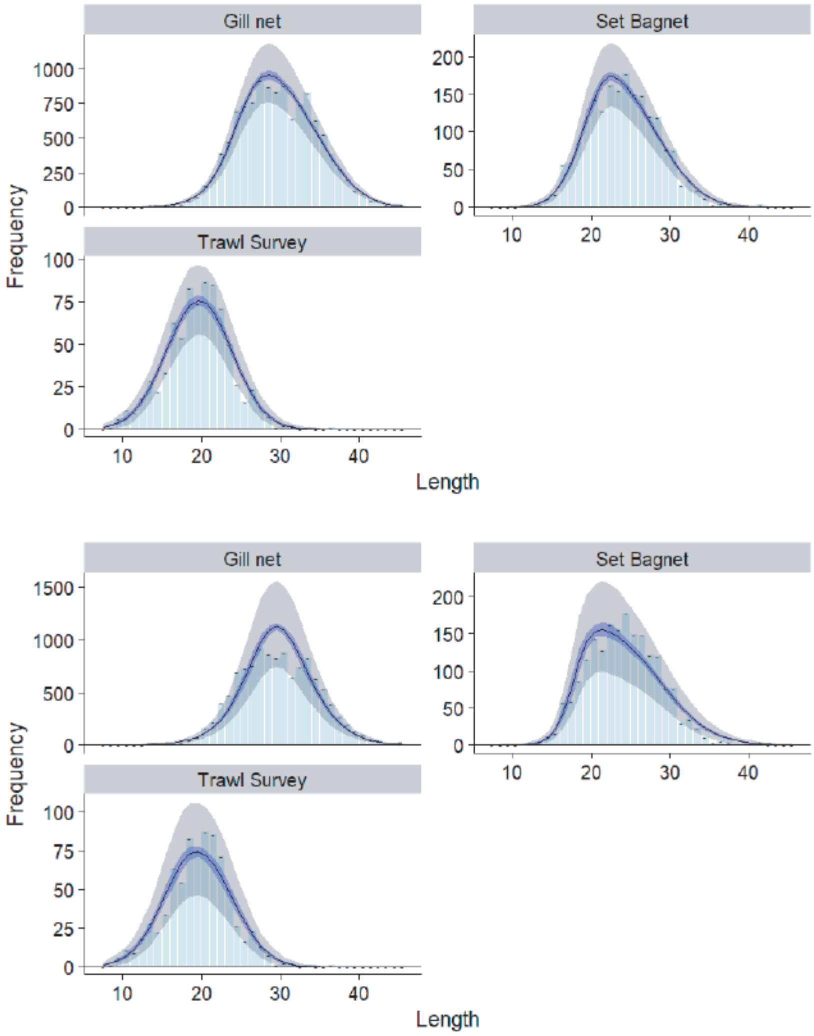


Figure 41 Observed (histograms) and expected (shaded curves) length frequency for the 3 gears for the base model (top) and the selected sensitivity where the set bagnet has a logistic selectivity (bottom). The grey shaded area represents the 95% credible interval for the data, including observation error.

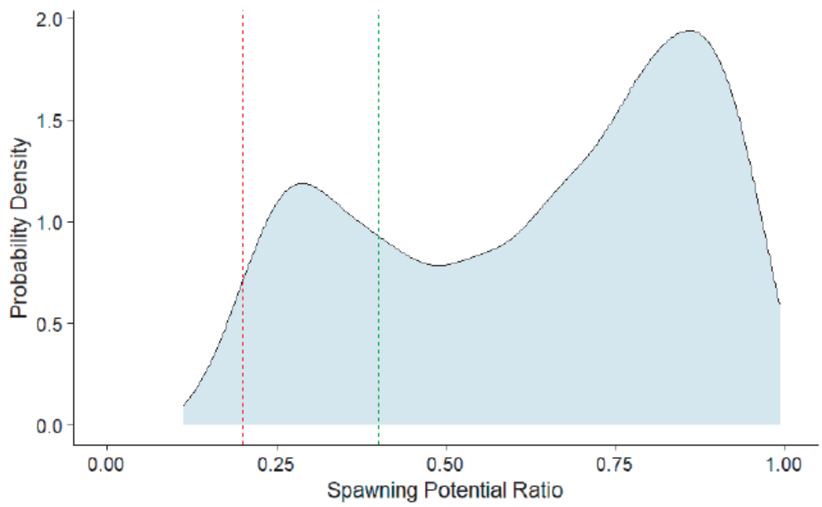


Figure 42 SPR probability density for the combined models.

Table 10 Summary of SPR estimates and probabilities for Ilisha filigera combined model fit.

Mean	SD	Pr< 20%	Pr< 30%	Pr< 40%
62.997	24.160	0.025	0.138	0.245

Pampus argenteus (Silver Pomfret)

Silver pomfret length frequency data were available from the artisanal fishery sampling and the scientific survey. Silver pomfret is caught in the commercial trawl as well as the artisanal fishery. Therefore, these results are preliminary until trawl data are available. The lengths above 40cm are too high for the species in Bangladesh waters. Therefore, the relatively few observations of larger fish were removed, on the basis these are unreliable and over-influential on the results.

Two models were chosen to bracket the uncertainty with higher and lower natural mortality priors. In general, natural mortality is an important parameter for which there is little information in length frequency data and therefore estimates depend upon the input priors. However, there was considerable uncertainty associated with the best model fit, and this should be re-examined when more recent data become available.

Both models fitted the data reasonably well (Figure 43), although there is some evidence of gillnet and bagnet being a mixture of underlying selectivities (i.e., more than one mode). In general, the assumed lower natural mortality fitted the data slightly better.

Both models gave similar average SPR estimates with the higher natural mortality estimating SPR around 63% and the lower natural mortality around 80%, although the higher natural mortality SPR estimate was more variable. In either, results did not indicate the stock was overfished during 2012-18, although the model assuming lower natural mortality showed greater uncertainty in the form of a much wider range of possible SPR (Table 11; Figure 44).

The SPR estimate is the average for the period 2012-2018, excepting the trawl survey data which comes from the 2016-2022 period. During this period the stock is supposed to have declined due to increased catches (see JABBA model fit for Pomfret (a group of Pampus argenteusand P. chinensis). This has not been detected in the length data. However, the catch-effort stock assessment was primarily driven by the industrial fishery, and the artisanal fishery showed little change in catch rates. The length frequency data came primarily from the artisanal fishery and no length frequencies are yet available from the industrial fishery. It is likely that spatial and other separation of the two fisheries has led to these differences and may explain the very rapid recovery of the pomfret stock from the apparent overfishing event. It may also point to a more complex stock structure between the industrial and artisanal fisheries than it is possible currently to assess. This observation is still consistent with a low-risk conclusion.

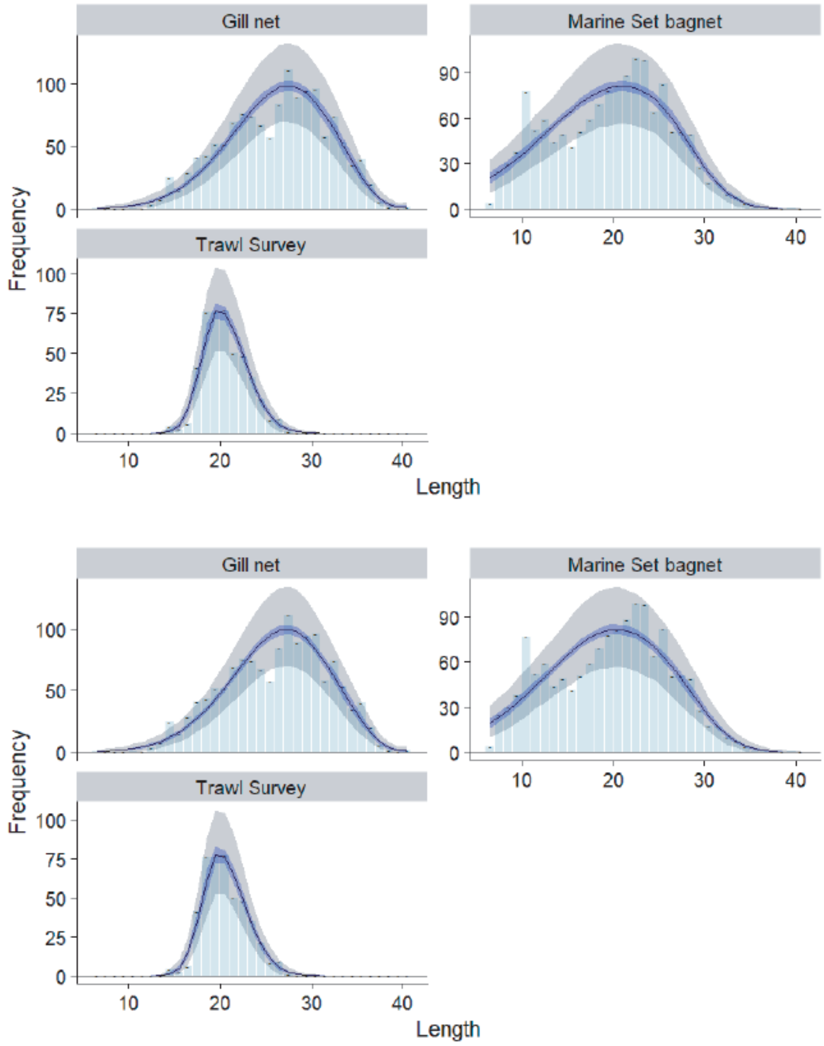


Figure 43 Observed (histograms) and expected (shaded curves) length frequency for the 3 gears for the low natural mortality (top) and higher natural mortality (bottom). The grey shaded area represents the 95% credible interval for the data, including observation error.

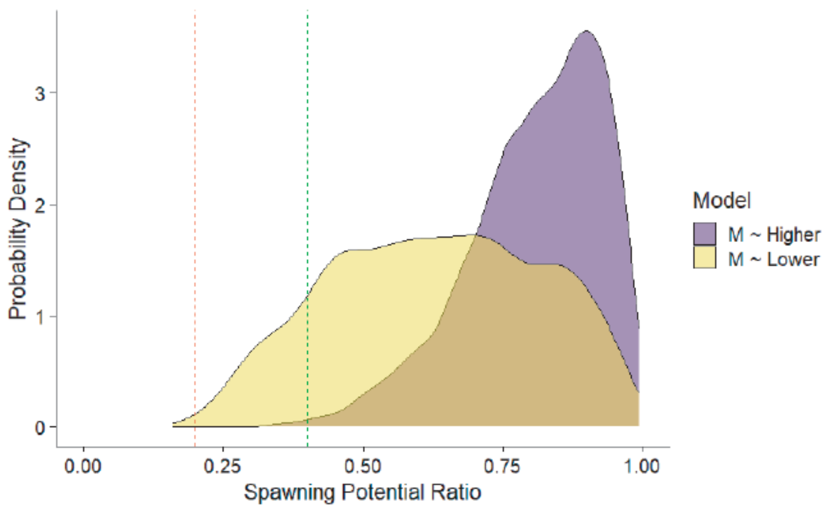


Figure 44 SPR probability density for the two tested models.

Table 11 Summary of SPR estimates and probabilities for Pampus argenteus combined model fit.

Mean	SD	Pr< 20%	Pr< 30%	Pr< 40%
71.941	18.118	0.001	0.018	0.066

Conclusion

Preliminary indicators suggest that most finfish species are probably not overfished, but shrimp may be. Furthermore, fishing may be depleting some finfish species relative to others dependent on their vulnerability and action may be required to prevent the fishery reducing the diversity of value of the catches as less productive species are removed.

This conclusion is preliminary and much more work is necessary to ensure reliable results. Bangladesh has considerable data and will continue to collect more data from recent initiatives. It is important to make sure that these data are fully used for better scientific advice. Compared to the cost of data collection, such analyses are inexpensive and therefore they should be completed to make sure as much value from the data collection is obtained as possible.

Further Work

More work over the coming months will be required by the scientific staff to complete the stock assessments:

- Continue the data correction of the artisanal data set and prepare a final documented version of the data.
- For the catch and effort data, develop a method to use the partial species-specific data, both in terms of estimating total catches and in CPUE estimates. This would likely require a hierarchical model.
- Complete development of more selectivity models for the length-based catch curve, with better use of dependencies among gears and species where possible.
- Work on preparing shrimp length frequency data and obtaining morphometric models as appropriate.
- Link length frequency data analysis to the JABBA model using priors, if possible, on the current exploitation levels.
- Develop seasonal stock assessment model for some species where data allow.

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Annex I: Length-based Catch Curve Model

Because *fishblicc* is a new length-based catch curve model, a more detailed description is provided below. It can be downloaded as an R package from: www.github.com/PaulAHMedley/fishblicc. Unlike standard length-converted catch curve models, it does not convert from length to age and then apply an age-based catch curve, but calculates the mortality across each length bin. In this sense, it is exactly analogous to an age-based model, but applied to fish length. The R package fits the Bayesian form of the model.

The model is built from the piece-wise mortality over each length interval using transition times based on the growth model. Unlike other models fitted to length frequency data, the model can account for changes in mortality over length as well as growth variability between individuals. The equations are derived from the case where mean length follows the von Bertalanffy growth model, variation in length-at-age is gamma distributed and total mortality is fixed within each length bin. With constant recruitment and deterministic mortality, the model derives the exact numbers of fish in each length bin.

In common with most length-based modelling, growth is assumed to be well approximated by the von Bertalanffy growth function:

$$L_t = L_\infty (1 - e^{-k(t - t_0)})$$

Growth uncertainty can be included in this model by considering variation in growth among fish, so the growth parameter L_∞ is treated as a random variable, each fish having its own maximum size. The obvious choice for the probability distribution for this parameter is the gamma distribution. The gamma distribution for the individual fish asymptotic length is given as:

$$G(L_\infty \mid \alpha, \beta) = 1/\Gamma(\alpha)\ \beta^\alpha\ L_\infty^{\alpha-1} e^{-\beta L_\infty}$$

The Gamma distribution has a fixed coefficient of variation: CV = $1/\sqrt{\alpha}$, and the CV for length at age is usually found to be between 5%-30%, so $\alpha=[9,400]$ and $\beta=\alpha/\overline{L_\infty}$ where in this case $\overline{L_\infty}$ is the mean asymptotic length for the species, and usually what is estimated.

The transition time for an individual fish across a length bin i in time units of k is:

$$t_i \mathrm{k} = (a_{i+1} - a_i)\ \mathrm{k} = \log\left(\frac{L_\infty - L_i}{L_\infty - L_{i+1}}\right)$$

Given its asymptotic length L_∞ and a fixed mortality rate ($Z_k = Z/K$), the probability for survival for an individual fish passing through a length bin i is:

$$e^{-Z_i t_i} = NA \qquad L_\infty \le L_i$$

$$e^{-Z_i t_i} = 0 \qquad L_i < L_\infty \le L_{i+1}$$

$$e^{-Z_i t_i} = \left(\frac{L_\infty - L_i}{L_\infty - L_{i+1}}\right)^{-Z_{ik}} \qquad L_{i+1} < L_\infty$$

If the mortality can be defined for sequential length intervals each with a fixed mortality, the survival for a particular fish starting at length L_0 to length L_n can be defined as the product of surviving each interval between:

$$s_n = \left(\frac{L_\infty - L_0}{L_\infty - L_1}\right)^{-Z_{k1}} \left(\frac{L_\infty - L_1}{L_\infty - L_2}\right)^{-Z_{k2}} \dots \left(\frac{L_\infty - L_{n-2}}{L_\infty - L_{n-1}}\right)^{-Z_{kn-1}} \left(\frac{L_\infty - L_{n-1}}{L_\infty - L_n}\right)^{-Z_{kn}}$$

This simplifies to:

$$\mathrm{s_n} = (L_\infty - L_0)^{-Z_{k1}} (L_\infty - L_1)^{Z_{k1}-Z_{k2}} (L_\infty - L_2)^{Z_{k2}-Z_{k3}} \dots (L_\infty - L_{n-1})^{Z_{kn-1}-Z_{kn}} (L_\infty - L_n)^{Z_{kn}}$$

$$= (L_\infty - L_0)^{-Z_{k1}} (L_\infty - L_n)^{Z_{kn}} \prod_{i=1}^{n-1} (L_\infty - L_i)^{Z_{ki} - Z_{ki+1}}$$

The probability that a fish will arrive at length interval n with lower bound L_n is given by:

$$S_n = \int_{L_n}^{\infty} \frac{\beta^\alpha}{\Gamma(\alpha)} L_\infty{}^{\alpha-1} e^{-\beta L_\infty} (L_\infty - L_0)^{-Z_1} (L_\infty - L_n)^{Z_n} \prod_{i+1}^{n-1} (L_\infty - L_i)^{Z_i - Z_{i+1}} dL_\infty$$

Note this also accounts for the probability that a fish's L_∞ is less than L_n, when it will never reach that length interval. The integral does not have an analytical solution, so numerical integration (Gauss-Laguerre quadrature) is used.

Assuming constant recruitment, the numbers of fish (N_n) and catch (C_n) within each interval can be estimated by integrating over the time interval:

$$N_n = \left(\frac{S_n - S_{n+1}}{Z_{kn}}\right)$$

$$C_n = \frac{F_{kn}}{Z_{kn}} (S_n - S_{n+1})$$

The mortality at length can be derived from any length-based function of natural and fishing mortalities. For example, fishing mortality can be determined using a double-sided normal function:

$$F_{ki} = F_k e^{-S_s (L_i - S_{mx})^2}$$

where L_i is the mid-point length for the length bin i, S_{mx} is the selectivity mode and S_s are two independent parameters for steepness each side of S_{mx}. For the flat-topped selectivity, the right-hand side S_s is set to zero.

Any selectivity function might be proposed. Currently, only two functions are used: the logistic model for flat-topped selectivity and double-sided normal for dome-shaped selectivity.
The parameters are described in

Table 12. "Fixed" parameters have not been fitted in the model because there is no information on these in the length frequency, but are used generate the spawning potential ratio (SPR). Priors for each parameter are set using a standard procedure (Table 13).

Table 12 fishblicc model parameters

Parameter	Description
Mk	Natural mortality in time units of growth rate parameter k (Mk = M/k).
Fk	Fishing mortality in time units of growth rate parameter k (Fk = F/k).
Linf	Mean asymptotic length at infinite age.
Galpha	Gamma probability distribution parameter for the variation in length at age (inverse of CV).
Sm	A vector of parameters for the various selectivity functions. Parameters consist of a location parameter (either the 50% selectivity for the logistic model, or mode for the normal models) and 1 or 2 slope parameters.
NB_phi	Negative binomial over-dispersion parameter, so (mean^2)/NB_phi is the additional variance over the standard Poisson variance.
Fixed Parameters	
b	Exponent of the length-weight relationship.
Lm	Length at 50% maturity for the maturity logistic function.
Ls	Steepness of the maturity logistic function.

Table 13 fishblicc parameter priors and their information source.

Parameter	Prior Function	Information Source
Mk	Lognormal	The default approach was to use an informative prior (lognormal standard deviation = 0.1) with the mean based on the life history invariant estimate (Prince et al. 2015). A typical estimate for this parameter would be 1.5 for groundfish. Values much higher or lower than this might be considered suspect.
Fk	Lognormal	Uninformative prior, with mean equal to Mk mean and standard deviation = 2 (i.e., 200% CV).
Linf	Normal	Either based on available estimates of L_∞, or a little below the maximum length, with standard deviation = 5cm or 10cm, dependent on L_∞.
Galpha	Lognormal	The mean growth coefficient of variation is set at 10%, with a lognormal standard deviation of 0.25.
Sm	Lognormal	The location prior mean is set at the observed mode of the length frequency or to the left of the mode for the logistic model. For the slope parameters, a standard uninformative lognormal with mean -5.0 and standard deviation 2.0.
NB_phi	Lognormal	A standard uninformative lognormal with mean -4.605 and standard deviation 0.5. The mean for this parameter sets the variance overdispersion compared to the Poisson distribution as $\mu^2/100$. This prior is lightly informative, and encourages the model to explain observations rather than attribute differences to observation error.
b	Fixed	The length-weight exponential parameter: either estimated or assumed to be 3.0. It is used for the SPR calculation, and may be used to provide a mean prior for Mk.
Lm	Fixed	Length at 50% maturity is either estimated or assumed to be 60% of the Linf mean.
Ls	Fixed	The slope for the maturity ogive is either estimated or can be safely assumed to be 0.5. It is used in the SPR calculations.

The model is fitted in Stan (mc-stan.org). However, it is not necessary to know Stan as the model is encapsulated in the *fishblicc* package, but the *fishblicc* package must be installed with Rtools, so that the package can be compiled on the local machine.

The software is still undergoing testing and improvement. It can be downloaded and installed using:

` remotes::install_github("PaulAHMedley/fishblicc") `[4]

The main functions are "blicc_dat()" that creates the data list from length frequency data and prior information (primarily suitable *Linf* prior parameters), "blicc_fit()" that fits the model using MCMC in Stan and produces a StanFit object and "blicc_ref_pts()" that processes the model parameters to estimate SPR reference points.

In most cases examined so far, results are sensitive to natural mortality assumptions or whether the selectivity is dome-shaped or not. In general, it is expected that a higher natural mortality or a more

[4] The `remotes` package can be installed from CRAN.

dome-shaped selectivity will lead to more optimistic results. It will be necessary to adopt an appropriate and precautionary method to deal with this uncertainty.

Although the model ideally should be fitted using MCMC to properly assess the uncertainty, this can be slow. Therefore, the maximum posterior density estimate is estimated for this preliminary investigation.

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