Approaches for Evaluating Stock Status in Data-Limited Fisheries

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Introduction

Sustainable fisheries management relies heavily on accurate stock assessments to inform decisions such as setting catch limits, implementing conservation measures, and ensuring the long-term health of marine ecosystems. Traditional stock assessment methods often require extensive data, which is not always available, particularly for small-scale, artisanal, or newly developed fisheries. Unlike well-monitored fisheries, where robust datasets enable precise evaluations, data-limited fisheries require innovative methodologies to determine the status of fish stocks. Data-limited fisheries face several challenges, including:

- Lack of historical data: Many small-scale and artisanal fisheries do not have long-term data records.
- Resource constraints: Limited financial and human resources to conduct comprehensive surveys.
- Ecological complexity: Variability in fish populations and environmental conditions complicates stock assessment.
- Technological limitations: Limited access to advanced technologies and methodologies.

Despite these inherent difficulties, various methods and approaches have emerged, specifically tailored to address the constraints of limited data. The lack of conventional datasets prompts a shift towards alternative strategies, necessitating a departure from traditional stock assessment norms. In response, the scientific community has devised a range of methodologies uniquely attuned to extracting valuable information from data-limited situations.

These approaches can be broadly categorized into two main themes. First, length-based assessments are a key component of data-limited fisheries management. Without comprehensive catch data, these assessments use available size-frequency distributions to infer population parameters and gauge the health of fish stocks.

This method leverages the valuable information within the size structure of the population, offering a nuanced perspective on the dynamics of these fisheries.

Secondly, approaches based on catch, production, effort, and biomass form the other major category of methodologies for data-limited fisheries. These multifaceted approaches utilize available data on catch, production, effort, and biomass, allowing scientists and resource managers to synthesize a comprehensive understanding of the fishery's status. By integrating diverse datasets, these methods strive to fill information gaps, providing a holistic view of the complex interplay between fishing activities and fish stock dynamics.

These innovative approaches offer a promising path for informed decision-making and sustainable resource management in the face of data constraints. By exploring length-based assessments and catch/production/effort/biomass-based approaches, researchers and practitioners can unlock valuable insights, paving the way for effective conservation and exploitation strategies in fisheries with limited data availability. Here are some common methods for assessing the stock status of data-limited fisheries:

Stock status plots

For the management of marine fisheries, it is essential to assess marine fish stocks. Measurement of the exploitation status of fish stocks is the key to their assessment. Well-developed fish stock assessment techniques are adopted by many countries to evaluate their marine fish stocks and these methods heavily depend on the ability to estimate the abundance or biomass of both the exploited and unexploited fish stocks. However, the efficacy and reliability of the stock assessment techniques are debatable, especially when it comes to applying the techniques uniformly over various types of fisheries practised around the world. The use of indicators gives a fair representation of the stock status of all countries and can be compared. One such set of indicators is Stock Status Plots (SSP).

Stock-status plots are bivariate graphs that summarise the status of the multispecies fisheries of a fished area or ecosystem over time (e.g., "developing," "fully exploited," "overexploited," etc.). These plots are extremely helpful for explaining, at a glance, the changing status of multispecies fisheries, even though they have limitations.

According to FAO (1984), the evolution of fishery over time can be described by the following phases – (i) pre-development, (ii) growth, (iii) full exploitation, (iv) over-exploitation, (v) collapse and (vi) recovery. The data behind generating the stock status plots are the time series of fish landings which can picturize the changes in abundance and species composition.

Fishing effort is another factor that is taken into consideration to capture the scenario of stock fluctuations under intense and moderate levels of fishing to study the stages of the development of fisheries (Csirke and Sharp, 1984) and plot the relationship between abundance, fishing effort and total catch at each stage.

Grainger and Garcia (1996) conceived the first version of the Stock Status Plots (SSP) by fitting time series of landings with polynomials, and classifying their slopes, i.e.:

1. Flat slope at a minimum: undeveloped;
2. Increasing slopes: developing fisheries;
3. Flat slope at a maximum: fully exploited;
4. Decreasing slopes: senescent fishery (collapsed).

This led to the graph reproduced here as Fig. 1, which formed the basis for inferences on the status of global fisheries. Grainger and Garcia's (1996) main finding was that catch increases were not possible in many cases, and that increased exploitation would result in lower catch rates. This highlighted the fact that even total landings may provide a false sense of security when the development phase is not taken into account.

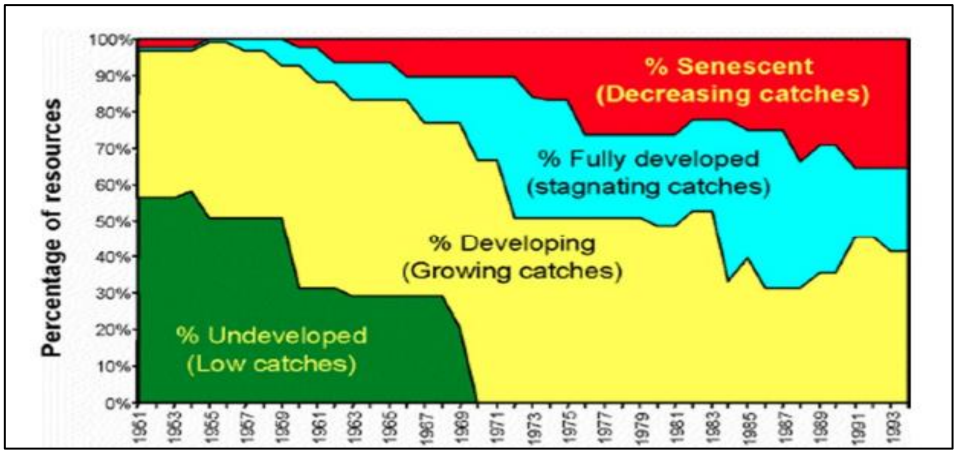

Fig. 1. Evolution of the state of world resources from 1950-1994, based exclusively on statistical trends for 200 major stocks (Grainger and Gracia, 1996).

{Source: https://www.seaaroundus.org/doc/Methods/StockStatusMethod/Method-SSP-new-June-08-2015.pdf}

Froese and Kesner-Reyes (2002), in their analysis of time series of catch data from ICES and FAO concerning the resilience of species towards fishing, simplified the approach of Grainger and Garcia (1996) by omitting polynomials from their analyses and designating stock status relative to the historically maximum catch. They defined the fishing status of over 900 stocks as undeveloped, developing, fully exploited, over fished, or collapsed. The designations they used are presented in Table 1.

Table 1. Criteria used to assign development stages to fisheries (Froese and Kesner-Reyes (2002)

Status of Fishery	Criteria
Undeveloped	Year before maximum catch and catch is less than 10% of maximum value
Developing	Year before maximum catch and catch is 10 - 50% of maximum value
Fully exploited	Catch larger than 50% of maximum value
Over fished	Year after maximum catch and catch is 10 - 50% of maximum value
Collapsed/Closed	Year after maximum catch and catch is less than 10% of maximum value

The typical transition of a fishery from undeveloped through fully exploited, to collapsed or closed is shown in Fig. 2. The benefit of this method for interpreting trends in fisheries was that it did not require fitting polynomial curves to the time series of catches of each stock.

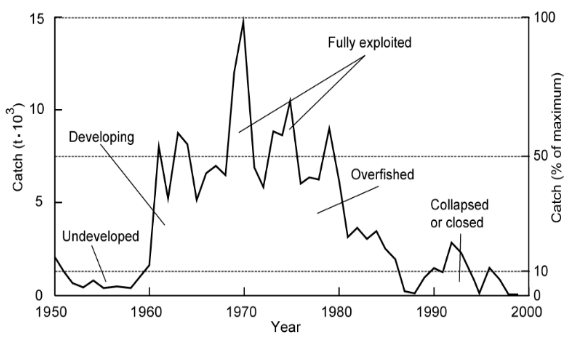

Fig. 2. Typical transition of a fishery as illustrated by a time series of catch data transiting from *undeveloped* through *fully exploited*, to *collapsed*, (or *closed*).

{Source: https://www.seaaroundus.org/doc/Methods/StockStatusMethod/Method-SSP-new-June-08-2015.pdf}

More recently, Pauly *et al.* (2008) created (and coined the name for) 'Stock Status Plots' for a UNEP compendium on Large Marine Ecosystems (LMEs; Sherman and Hempel 2008). They modified the definitions of Froese and Kesner-Reyes (2002) slightly, such as to produce graphs of the percentage of stocks by status and percentage caught by stock status over time (Table 2). One of the main modifications was the combination of the previous categories 'undeveloped' and 'developing' into a single 'developing' category.

Pauly *et al.* (2008) presented stocks as time series of species, genus, or family for which:

1) The first and last reported landings are at least ten years apart;

2) There are at least five years of consecutive catches; and

3) The catch in a particular area (LME) is at least 1,000 tonnes.

Higher taxonomic groupings and pooled groups were excluded. Two plots were created for each LME. The first was a plot of the number of stocks by status. To contrast the decline of (stock) biodiversity and bulk catch status, Pauly *et al.* (2008) also developed a second plot type, i.e., graphs of percentage catch by stock status over time. These plots, which they called status' plots, jointly with the 'stock-status' plots referring to stock numbers, tended to confirm that biodiversity is affected by fishing more strongly than bulk catch.

Table 2. Criteria used by Pauly *et al.* (2008) to interpret the status of a fishery resource

Status of Fishery	**Criteria**
Undeveloped	Year < max. landing AND landing <10% of max. value
Developing	Year < max. landing AND landing 10-50% of max. value
Fully exploited	Landing> 50% of max. value
Overexploited	Year > max. landing AND landing 10-50% of max. value
Collapsed	Year > max. landing AND landing <10% of max. value

One of the critical comments on the previous versions of the stock-status plots was that by definition the percentage of undeveloped or developed stocks was zero in the final year of the time series. To address this, counted stocks that have a peak in catch in the final year of the time series as 'developing.' Additionally, in cases where stocks have recovered (e.g., through management actions), the 'stock- status plots' do not take stock recovery into account. Norway provides an excellent example of this, e.g., with regards to Atlantic herring, whose catch increased to a maximum in 1966 and then plummeted to a minimum in 1979. Thereafter, the catch gradually increased through the 1980s and early 1990s as a result of management rebuilding actions and remained above 50% of the maximum catch through the 2000s. This recovery should not be reclassified as a 'developing' stock; rather an additional category, 'rebuilding' (initially labelled as 'recovering'), is defined when the stock drops to 'collapsed' status and then recovers.

To implement this, a 'post-maximum minimum' was defined as the minimum landings occurring after the maximum landings. This modification also addresses the former concern that, by definition, the percentage of developing stocks is zero in the final year of the time series. Because 'recovering' is a form of stock (re-)development (hence now called 'rebuilding'), it is displayed within the 'developing' category in the plots, and thus better demonstrates the amount of improvement in the status of stocks within a particular area (See Fig. 3, top).

The final criterion for determining the stocks' status by area is presented in Table 3. To better view the overall trend and remove anomalous peaks in the stock-catch status plots, one can use a three-year running average to smooth the curves.

Table 3. Criteria used by Kleisner and Pauly *et al.* (2011) and Kleisner *et al.* (2013) to interpret the status of a fishery resource. This requires the definition of a post-maximum-minimum (post-max. min.): the minimum landing after the maximum catch

Status of Fishery	**Criteria**
Rebuilding (Recovering)	Year of landing > year of post-max. min. landing AND post-max. min. landing <10% of max. landing AND landing is 10-50% of max landing
Developing	Year of landing < year of max. landing AND landing < or = 50% of max. landing OR year of max. landing =final year of landing
Exploited	Landing> 50% of max. value
Over exploited	Year of landing > year of max. landing AND landing is between 10-50% of max. landing
Collapsed	Year of landing > year of max. landing AND landing <10% of max. landing

The Sea Around Us' SSPs are created in four steps (Kleisner and Pauly 2011). The first step is the definition of a stock. We define a stock to be a taxon (either at species, genus or family level of taxonomic assignment) that occurs in the catch records for at least 5 consecutive years, over a minimum of a 10-year time span, and which has a total catch in a given area of at least 1000 tonnes over the time span. Secondly, assessment of the status of the stock is to be done for every year, relative to the peak catch. Thirdly, the graph of number of stocks by status is created by tallying the number of stocks in a particular state in a given year, and presenting these as percentages. Finally, the cumulative catch of stock by status in a given year is summed over all stocks and presented as a percentage in the catch by stock status graph, or stock-catch-status plot (SCSP). The combination of these two Figures represents the complete SSP (Fig. 3).

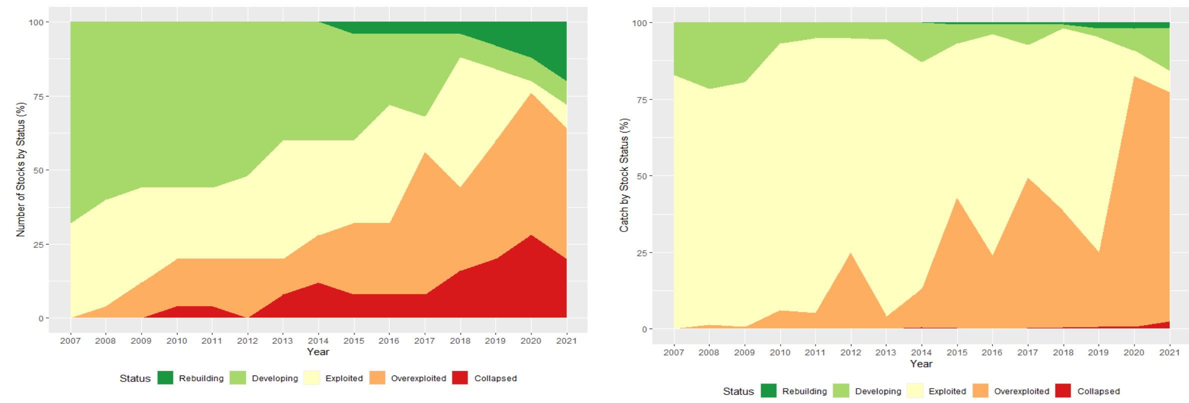

Fig. 3. Example of a Stock Status plot (as per criteria used by Kleisner and Pauly *et al.* (2011) and Kleisner *et al.* (2013)); rebuilding stocks in the upper right corners of the graphs (see text).

R Package: SSplots

Pauly *et al.* (2008) created (and coined the name) 'Stock Status Plots' for a UNEP compendium on Large Marine Ecosystems (LMEs, Sherman and Hempel 2008). Stock status plots are bivariate graphs summarizing the status (e.g., developing, fully exploited, overexploited, etc.), through time, of the multispecies fisheries of a fished area or ecosystem. This package contains two functions to generate stock status plots viz., SSplots_pauly() (as per the criteria proposed by Pauly *et al.*,2008) and SSplots_kleisner() (as per the criteria proposed by Kleisner and Pauly (2011) and Kleisner *et al.* (2013). The package is available https://cran.r-project.org/web/packages/SSplots/index.html

Usage

SSplots_pauly (data,lower.lt,upper.lt, tsplots)

Arguments

Data	dataset
lower.lt	lower limit
upper.lt	upper limit

library (SSplots)
data(SampleData)
SSplots_pauly(data=SampleData,lower.lt=10,upper.lt=50, tsplots=FALSE)

Note: tsplots=TRUE for generating the time series plots for each resource. In that case, it is advisable to set a working directory and the number of time series plots generated will be equal to the number of resources.

The second function available is SSplots_kleisner.

Usage

SSplots_kleisner(data,lower.lt,upper.lt, tsplots, MA)

Arguments

Data	Dataset
lower.lt	lower limit
upper.lt	upper limit
Tsplots	time series plot
MA	moving average

```
library (SSplots)
data (SampleData)
SSplots_kleisner(data=SampleData,lower.lt=10,upper.lt=50,tsplots=FALSE,MA=FALS)
```

Note 1: Here, post-maximum-minimum (post-max-min) indicates the minimum landings occurring after the maximum catch.

Note 2: tsplots=TRUE for generating the time series plots for each resource. In that case, it is advisable to set a working directory and the number of graphs generated will be equal to the number of resources.

Note 3: MA=TRUE for using the running average of order 3 (a three-year running average was used to smooth the curve).

CMSY and BSM Approach

Surplus production models, introduced by (Graham, 1935) are commonly used for assessing the state of fish stocks. These models view the population as one unit of biomass, with all individuals having the same growth and mortality rates. The surplus production models deal with the entire stock, the entire fishing effort and the total yield obtained from the stock. It is used to determine the optimum level of effort that is the effort that produces the maximum yield that can be sustained without affecting the long-term productivity of the stock, or the maximum sustainable yield (MSY).

Surplus production models assume that variation in population biomass results from increases due to growth and reproduction and decreases from natural and fishing mortality. Surplus production models use Catch-Per-Unit-Effort (CPUE) as input. The data, which represent a time series of years, are usually collected from the commercial fishery. The model is based on the assumption that the CPUE is proportional to the biomass of the fish in the sea.

Catch Maximum Sustainable Yield (CMSY) is a method for estimating maximum sustainable yield (*MSY*) and related fisheries reference points (*Bmsy*, *Fmsy*) from catch data and resilience, developed by Froese et al. (2015). It is an advanced implementation of the Catch-MSY method of Martell & Froese (2013).

Schaefer model is one of the most popular surplus production models which is given by the following equation:

$$B_{t+1} = B_t + rB_t(1 - \frac{B_t}{k}) - C_t, \quad C_t = qE_tB_t$$

where B_{t+1} is the exploited biomass in the subsequent year t+1, B_t is the current biomass, r is the intrinsic growth rate, k is the carrying capacity, C_t is the catch in the current year t, E_t is the fishing effort at time t and q is the catchability coefficient. Surplus production models use CPUE as an index of biomass (i.e., $CPUE_t = qB_t$).

The above equation has been modified to account for reduced recruitment at severely depleted stock sizes, a linear decline of surplus production, which is a function of recruitment, somatic growth, and natural mortality is incorporated if biomass falls below ¼ k (Froese *et al*., 2017).

$$B_{t+1} = B_t + 4\frac{B_t}{k}(1 - \frac{B_t}{k})rB_t - C_t, \quad if \ \frac{B_t}{k} < 0.25$$

The term 4*Bt/k* assumes a linear decline of recruitment below half of the biomass that is capable of producing MSY.

There are two possible cases when using a time series of catch to estimate the fisheries reference points:

> ***Case 1:** when a measure of fishing effort is available*
>
> ***Case 2:** when fishing effort is not available (data-poor situation)*

Case 1 is based on the delay difference model to describe nonlinear population dynamics. The State–space model allows the incorporation of random errors in both the biomass dynamics equations and the observations. Because biomass dynamics are nonlinear, the common Kalman filter is generally not applicable for parameter estimation. However, it is demonstrated by (Meyer and Millar, 1999) that the Bayesian approach can handle any form of nonlinear relationship in the state and observation equations as well as realistic distributional assumptions. Difficulties with posterior calculations are overcome by the Gibbs sampler in conjunction with the adaptive rejection Metropolis sampling algorithm (Millar and Meyer, 1999; Froese *et al.* 2017). This approach has been named (BSM-Bayesian Schaefer Model) and is fitted to catch and standardized fishing effort data.

CMSY estimates biomass, exploitation rate, MSY, and related fisheries reference points from catch data and the resilience of the species. A prior estimate for biomass (*B*) relative to carrying capacity (*k*) i.e. *B/k* has to be given. Next probable ranges for the maximum intrinsic rate of population increase (*r*) and carrying capacity (*k*) are given as inputs which then are filtered with a Monte Carlo approach to detect 'viable' *r-k* pairs. An R package named *R2jags* (Yu-Sung and Masanao, 2015) was used for sampling the probability distributions of the parameters with the Markov chain Monte Carlo method. This package provides wrapper functions to implement Bayesian analysis in JAGS (Plummer, 2003). The convergence of the MCMC model is assessed using Rubin and Gelman Rhat statistics, automatically running an MCMC model till it converges, and implementing parallel processing (using a *doparallel* package in R) of an MCMC model for multiple chains. The *r*-ranges for the species under assessment, the proxies for the resilience of the species as provided in FishBase (Froese *et al.*, 2000; Froese and Pauly, 2015) and then converted as given by Froese *et al.* (2017).

Both approaches were implemented using R studio (https://www.rstudio.com/). The inputs of the time series of catches and information on species resilience are required for running the code and generating the outputs. To run the code, the R-libraries required are *R2jags, coda, parallel, foreach, doParallel, gplots, mvtnorm, snpar, neuralnet,* and *conicfit.*

Data Description

Indian mackerel, *Rastrelliger kanagurta*, is an important pelagic fish resource of Andhra Pradesh. The resource is assumed to exist as a single stock along the coastline of Andhra Pradesh (A.P.). The coastline of Andhra Pradesh, which is 974 kilometres long is spread over nine coastal districts viz., Srikakulam, Vizianagaram, Visakhapatnam, East Godavari, West Godavari, Krishna, Guntur, Prakasam and Nellore (FRAD, 2018). Several gears have been found to harvest mackerel almost throughout the year. Like any other tropical pelagic fish, mackerel also exhibited seasonal and annual fluctuations in landings.

The mackerel landing was estimated from the commercial landings along the coast of A.P. using a scientifically planned sampling design based on a stratified multi-stage random sampling technique (Sukhatme, 1958; Srinath *et al*., 2005), where the stratification is done over space and time. A time series of catch and effort (in hours of operation) from 1997 to 2022 taken from the National Marine Fishery Resources Data Centre (NMFDC) of CMFRI, Kochi has been used for the analysis.

The annual landings of Indian mackerel in Andhra Pradesh ranged from a low of 7903t (2007) to a high of 55631t (2014) during the study period (Fig. 4).

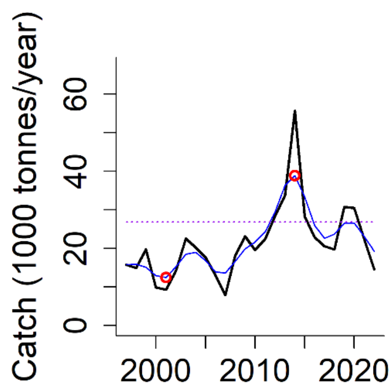

Fig. 4: Time series of Indian mackerel landings from 1997 to 2022 (The blue line is the three-year moving average, maximum and minimum landings are denoted with red dots)

The standardised fishing effort during the study period indicated an increasing trend with the maximum fishing effort exerted in 2022 (Fig. 5).

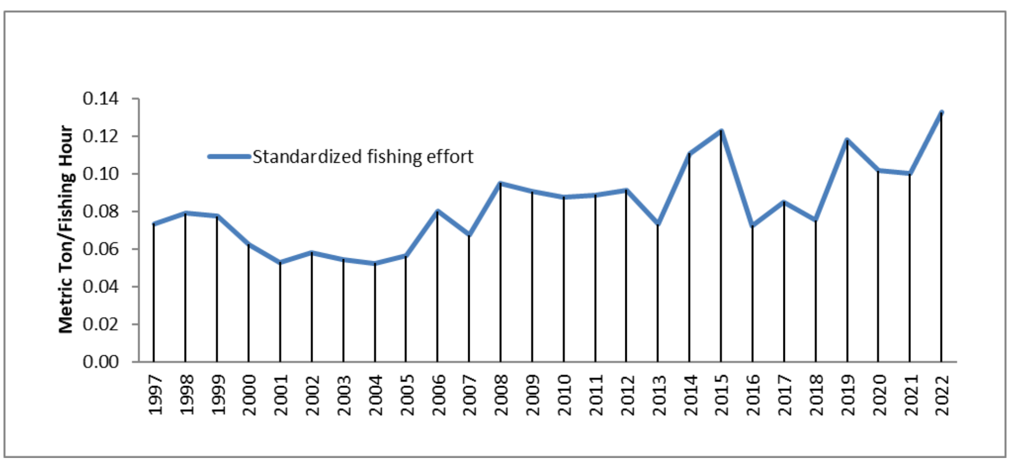

Fig. 5: Time series of standardised fishing effort during 1997-2022

FishBase (Froese *et al.*, 2000; Froese and Pauly, 2015) has provided the proxies for the resilience of various fish resources and used to set the prior *r*-ranges by converting as (0.6 – 1.5 for High; 0.2 – 0.8 for Medium; 0.05 – 0.5 for Low and 0.015 – 0.1 for Very low) given by Froese *et al.* (2017). Prior ranges for *q* are obtained as follows:

$$q_{low} = \frac{0.25 r_{pgm} CPUE_{mean}}{C_{mean}} \quad \text{and} \quad q_{low} = \frac{0.5 r_{high} CPUE_{mean}}{C_{mean}}$$

where q_{low} is the lower prior for the catchability coefficient for stocks with high recent biomass, r_{pgm} is the geometric mean of the prior range for *r*, $CPUE_{mean}$ is the mean of catch per unit effort over the last 5 or 10 years, and C_{mean} is the mean catch over the same period. where q_{high} is the upper prior for the catchability coefficient for stocks with high recent biomass, r_{high} is the upper prior range for *r*. Prior ranges for *r*, *k* and *q* are 0.2-0.9, 92.6 – 624 and 0.000111 - 0.003 respectively.

Once the prior values were given as inputs along with the landings data, the next step in the analysis is to search for viable *r*-*k* pairs (Fig. 6). The grey colour indicates the viable *r*-*k* pairs that fulfilled the CMSY conditions.

The most probable *r*-*k* pair is marked by the blue cross, with the indication of approximate 95% confidence limits. The black dots show the estimates of the BSM method, with the red cross indicating the 95% confidence limit.

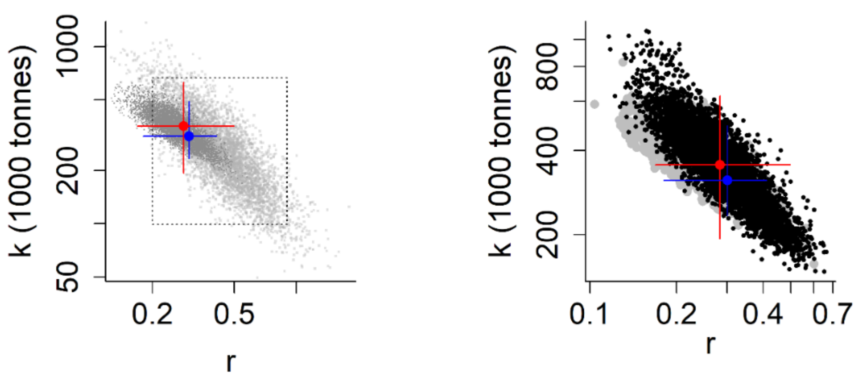

Fig. 6. Search for viable *r*-*k* pairs

Once the r-k pair was selected the relative biomass along with confidence limits was predicted by both the CMSY and BSM methods (Fig. 7). The bold curve (blue colour) in Fig. 4 is the relative biomass predicted by CMSY, with confidence limits (dotted curves). The normal curve (red colour) indicates the relative biomass predicted by BSM, and the dots indicate the CPUE data scaled by BSM and corrected for effort creep. The horizontal dashed line indicates biomass at MSY (Bmsy) and the dotted line indicates half of Bmsy.

The relative biomass plot indicated that in the starting years, the biomass in relation to carrying capacity was low. This result follows based on the prior estimates of B/k that we had given. The low relative biomass could be a reflectance of the lower yields from the fishery which was operating at lower fishing effort during the initial years of the study period. From 2005 onwards the fishing effort has been steadily increasing which has also resulted in higher landings since 2005. During this period the relative biomass was above MSY levels. The overfished status of Indian mackerel along the AP coast is further highlighted in the CMSY/BSM output showing catch relative to MSY over biomass relative to unexploited stock size (Fig. 8). The red line indicates BSM predictions for exploitation and relative stock size, with the dots showing predicted catch per predicted biomass as scaled by BSM, and the blue line indicates estimates by CMSY. The indentation of the parabolas below 0.25 k (half of Bmsy) results from the inclusion of a stock-recruitment model which assumes reduced recruitment at low stock sizes.

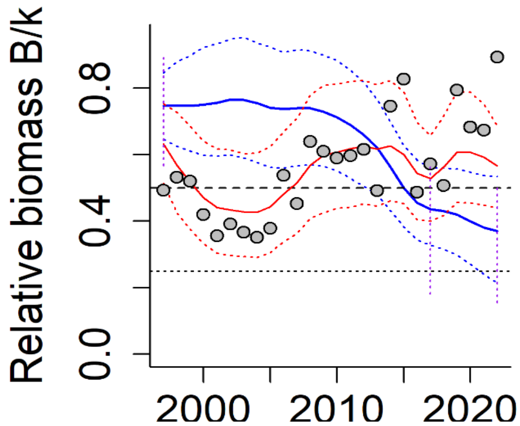

Fig. 7. Relative biomass

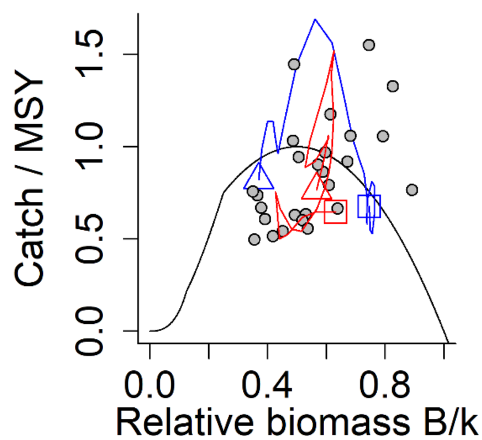

Fig. 8. The ratio of catch to MSY and relative biomass (*B/k*) over years

The points which are above the curve indicate overfishing and shrinking of biomass and the points below the curve indicate sustainable exploitation and growth of the stock. Here, the points are clustered around the equilibrium curve, thus giving confidence in the assessment.

The estimates of MSY and model parameters along with their confidence limits are shown in Table 4. It can be seen from the table that the estimate of MSY is very close to both approaches with smaller confidence in the case of BSM. As BSM takes into account CPUE, further management plans have been derived based on the BSM results. The landings of Indian mackerel since 2016 have fallen below the estimated MSY.

Table 4. Estimates of MSY and model parameters along with confidence limits

Parameters	**CMSY**	**BSM**
MSY	23500 (17900 – 29600)	25100 (19000 - 35500)
R	0.301 (0.18 - 0.411)	0.283 (0.169 - 0.498)
K	312000 (234000-490000)	355000 (193000-628000)
Relative biomass in last year (B_{2022}/k)	0.37 (0.214 - 0.534)	0.566 (0.439 – 0.686)
Exploitation F/(r/2) in last year	1.15 (0.618-2.78)	0.676 (0.412 – 1.11)
q	-	0.000418 (0.000228- 0.000805)
B_{msy}	-	178000 (96500- 314000)
Fishing mortality (F_{msy})	-	0.142 (0.0845 - 0.249)
F_{msy} in last year	-	0.096 (0.0488 - 0.194)

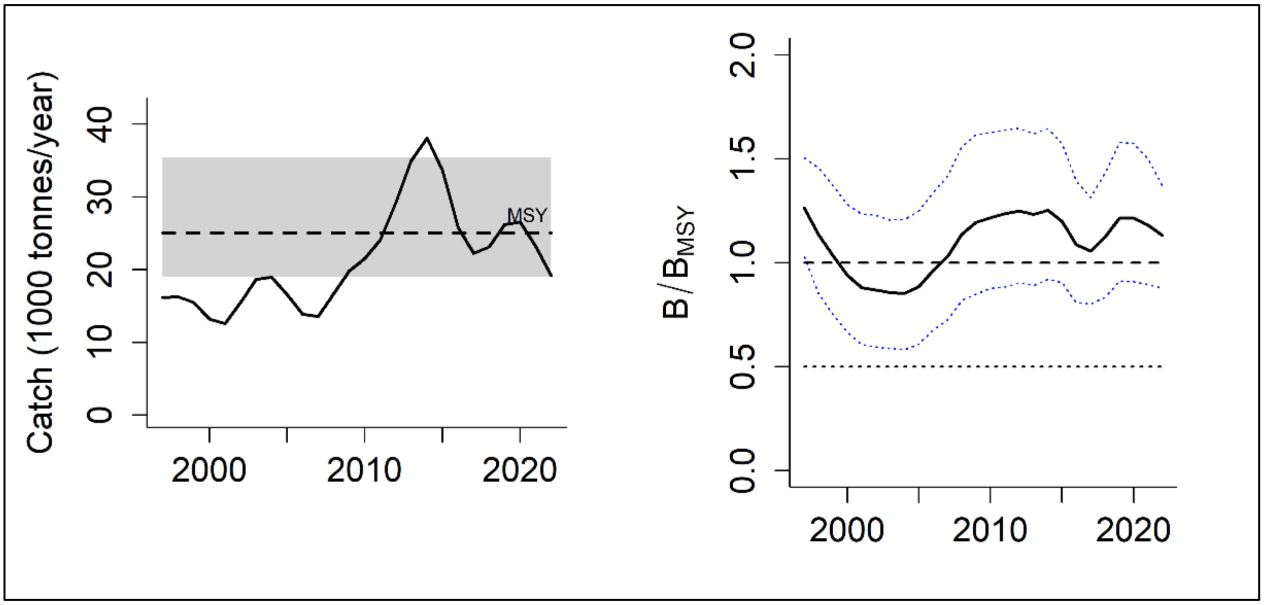

Fig. 9. Catch in comparison to MSY and (*B/ B_{msy}*) over the years

The plots of landings vs MSY and that of B/B_{msy} (Fig. 9) also indicate the over-fished status of Indian mackerel along the AP coast from 2012 to 2015. The horizontal dashed line in the first plot indicates MSY with a lower and upper confidence limit of MSY in grey colour. The bold curve in the second plot is the biomass predicted by BSM, with confidence limits (grey colour). The horizontal dashed line indicates B_{msy} and the dotted line indicates half of B_{msy}. The solid line is above the B_{msy} line indicating that current biomass is slightly more than biomass at MSY. Ideally, this ratio should be as high as possible. Levels near 1 indicate that the biomass of the stock of Indian mackerel along the AP coast is just at the threshold of being unhealthy.

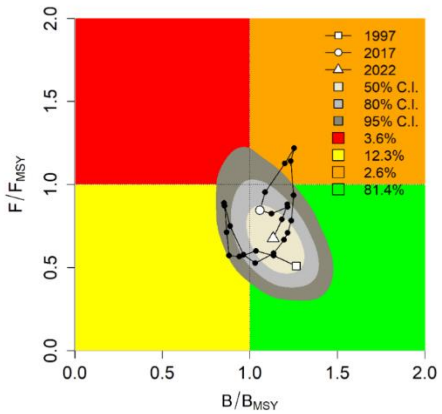

Fig. 10. Development of biomass and exploitation relative to B_{msy} (vertical dashed line) and F_{msy} (horizontal dashed line) for Indian mackerel along the AP coast

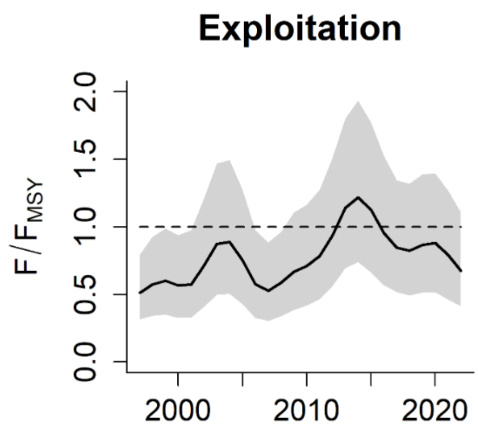

Fig. 11. F/F_{msy} over time for Indian mackerel along the AP coast

The plots of current fishing mortality (F) in relation to F at MSY (F_{msy}) (Fig. 10 and 11) indicated that the current fishing mortality is lower than fishing mortality at MSY. However, since current biomass is above the threshold of B_{msy} the stock can be thought to be reaching a sustainable level.

A common misconception of Bayesian analyses is that the priors determine the results. It is true that if grossly wrong priors are provided as input to both CMSY and BSM, the results will be wrong. But that is true for any model provided with wrong data. If instead reasonable priors are provided, as in Fig. 12, shows, the priors (light grey) inform the results, with posterior understanding (dark grey) of the stock has been improved compared to prior perceptions. The lower the prior-posterior variance ratio (PPVR), the more the posterior knowledge is improved relative to prior knowledge.

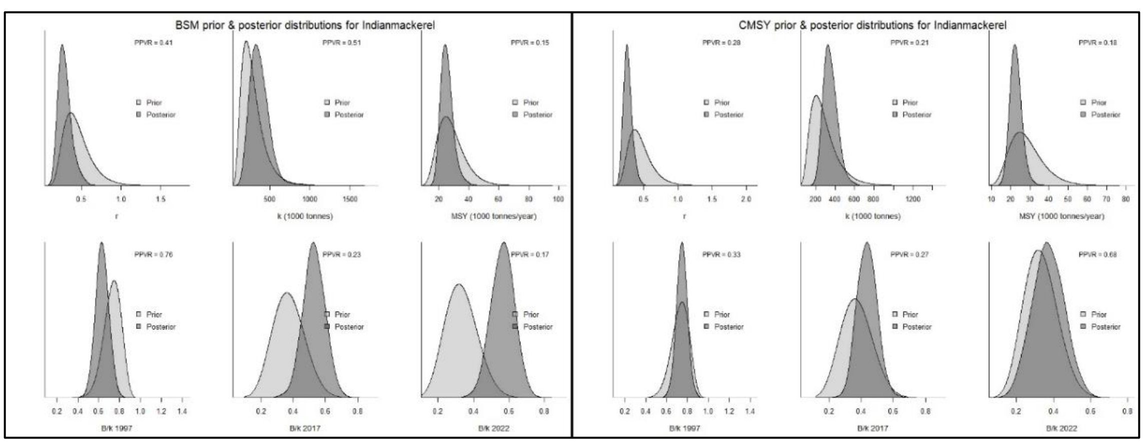

Fig. 12. Comparison of prior and posterior densities (same area under curves) for resilience or productivity (r), unexploited stock size (k), maximum sustainable yield (MSY), and relative stock size (B/k) at the beginning, the end, and an intermediate year of the available time series of catch data, for Indian mackerel in the AP coast.

The retrospective analysis, (a comparison of results if the last one, two, or three years of data are omitted from the analysis) for each set of years and a new graph (Fig. 13) is produced for comparing the predicted time series of exploitation (*F/Fmsy*) and relative stock size (*B/Bmsy*). In the example for Indian mackerel in the AP coast (Fig. 10), the results are not changed much by omitting years. If, however, the predictions for all years differ substantially from those without the last year, i.e. in the presence of a strong retrospective discrepancy, then it might be prudent to, e.g. not increase allowed catch until the data for the last year are confirmed.

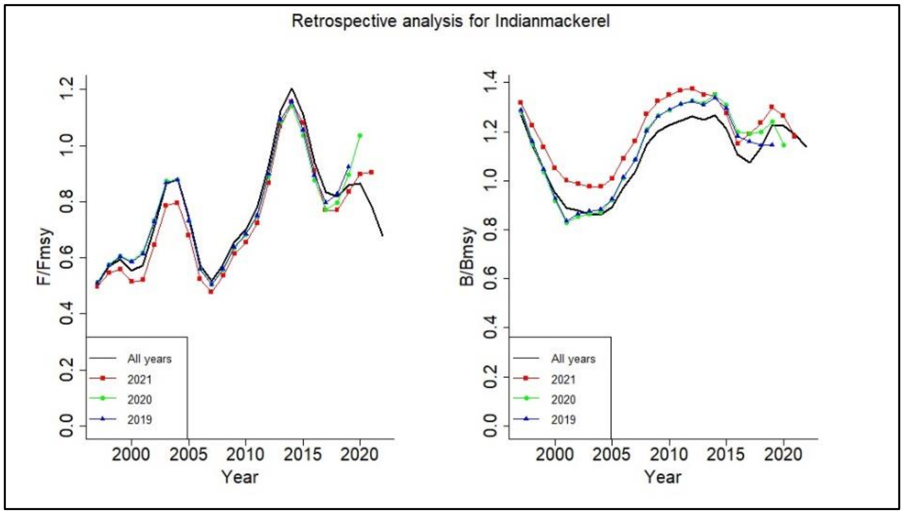

Fig. 13. Comparison of predictions for exploitation (F/Fmsy) and relative stock size (B/Bmsy) when the last 1-3 years are omitted from the analysis, here for Indian mackerel in the AP coast.

Length Based Indicators (LBIs)

Froese (2004) proposed three length-based indicators (LBIs) to assess the exploitation of fish stocks for managing recruitment and growth overfishing. Indicator 1 ('let them spawn') is the proportion of mature fish in the catch, with a target of letting 100% of mature fish spawn at least once before getting caught. Indicator 2 ('let them grow') is the proportion of fish in the catch at ±10% of the optimum length (L_{opt}) that maximizes yield and revenue with a target of 100% in the catch. Indicator 3 ('let the mega-spawners live') is the proportion of large, old fish (fish of optimum length + 10%), with a target of 0% in the catch. These LBIs use length-frequency data from a sampled fish stock or assemblage, which can be easily collected or already available for most inland fisheries (Froese, 2004). The LBIs combine life-history characteristics, such as length at first maturity (L_{mat}), to define target values.

Based on the indicators proposed by Froese (2004), P_{mat} (the proportion of fish larger than L_{mat} in the catch), P_{opt} (the proportion of fish at optimal harvest length of L_{opt}), and

P_{mega} (the proportion of fish larger than L_{opt} + 10%, or mega spawners) can be worked out using the following equations:

$$P_{mat} = \sum_{L_{mat}}^{L_{max}} P_L \,, \;.................. (1)$$

$$P_{opt} = \sum_{0.9\,L_{opt}}^{1.1L_{opt}} P_L, \;.............. (2)$$

$$P_{mega} = \sum_{1.1\,L_{opt}}^{L_{max}} P_L, \;............ (3)$$

where P_L is the proportion of catch in length class L; L_{mat} is the length at which 50% of the population matures; L_{max} is the maximum length, and L_{opt} is the length at which maximum yield is possible which can be derived following Beverton (1992), as $L_{opt} = L_\infty * [3/(3+M/K)]$. The major assumption here is that the length composition in catch is representative of the stock. Based on the indicator framework proposed by Froese (2004), values of L_{mat}, L_{opt}, P_{mega}, L_{max}, and L_∞ were superimposed on length-frequency distributions.

The Froese (2004) LBIs are not always sufficient to protect stocks from overfishing, especially for multi-gear fisheries, due to inadequate knowledge of gear size selectivity, which is important for sufficiently interpreting target values (Cope and Punt, 2009), so Cope and Punt (2009) proposed a new measure, P_{obj}, which is the sum of P_{mat} (equation 1), P_{opt} (equation 2), and P_{mega} (equation 3). Application of P_{obj} enhanced the recommendations of Froese (2004) by distinguishing fishery selection and informing whether the current SSB was at or above target SSB RP under a range of selectivity. A decision tree (Cope and Punt, 2009) describes fishery selectivity using P_{obj} and the ratio of L_{mat}/L_{opt}. Depending on selectivity, P_{mat} or P_{opt} are compared to an empirically established SSB RP to infer whether the population is fished above or below the SSB target or limit RP. If $P_{obj} < 1$, selectivity does not follow the Froese (2004) sustainability recommendation, whereas if $P_{obj} >1$, selectivity follows the Froese (2004) sustainability recommendation. Using the decision tree of Cope and Punt (2009), if $P_{obj} < 1$ and $P_{opt} + P_{mga} = 0$, the fishery selects small, immature fishes, and if $P_{opt} + P_{mga} = > 0$, the fishery selects small, optimal-sized or all but largest fishes. If P_{obj} = 1-2, the fishery selects mature fish. If $P_{obj} = 2$ and $P_{opt} < 1$, the fishery selects optimally sized fishes, and if $P_{opt} = 1$, the fishery selects optimally sized fishes. Cope and Punt (2009) also suggested trade-offs of indicators for the decision tree and suggested means for identifying the probability that SSB was below the target reference point (TRP) of 0.4 SSB_0 or the limit reference point (LRP) of 0.25 SSB_0, or both, using trigger values for P_{obj} at $L_{mat}/L_{opt} \leq 0.75$ or $L_{mat}/L_{opt} = 0.9$. A practical application of these indicators can be found in Suresh *et al.* (2023).

Growth-Type-Groups Length-Based-Spawning-Potential-Ratio (GTG-LBSPR)

The Growth-Type-Groups Length-Based-Spawning-Potential-Ratio (GTG-LBSPR) approach assumes that selectivity is size-dependent, rather than age-dependent, as in the selectivity of the LBSPR model (Hordyk *et al*., 2016), which is centred on the impact of fishing on spawning biomass per recruit. In the absence of fishing, a population can reach its full unexploited spawning potential (100%), whereas fishing reduces the unexploited spawning potential by removing spawners. This model uses von Bertalanffy growth parameters (L_∞ = asymptotic length and K = growth coefficient), M/K ratio, length at 50% and 95% maturity (L_{mat} and L_{mat95}), length at 50% and 95% selectivity (SL_{50} and SL_{95}), and F/M ratio. The model assumes that the fishery is at equilibrium, selection is logistic, and the length-frequency represents a steady-state exploited population (Hordyk *et al.,* 2015a). The GTG-LBSPR assumes that the length composition of the catch results from overall fishing mortality, which necessitates that length composition data are from the predominant fleet or multiple fleets treated as one aggregate fleet (Hordyk *et al*., 2015a). Length frequency data collected from all sampling stations and landing centres were pooled as a composite annual length frequency of catches to satisfy the assumption. The model uses maximum likelihood to estimate length at 50% and 95% selectivity (SL50 and SL95) and relative fishing mortality (F/M) that reduce the difference between observed and predicted length frequency of the catch. The corresponding SPR is then calculated as an indicator of stock status (Hordyk *et al*., 2015a, b; Prince et al., 2015). The SPR defines the proportion of remaining reproductive potential of stock under any fishing pressure (Goodyear, 1993; Mace and Sissenwine, 1993; Walters and Martell, 2004), which is used to set target and limit RPs of SPR (Hordyk *et al*., 2015b). An unfished stock has SPR equal to 1 (100%), and SPR equals zero when all mature fish are harvested before spawning. Prince *et al*. (2015) considered an SPR of 40% or 0.4 as a proxy for MSY, and 20% or 0.2 was considered a minimum threshold, below which recruitment would be impaired (Walters and Martell, 2004; Prince *et al.,* 2015). The open source 'R' software, version 4.0.3 (R Core Team 2021) with the LBSPR package (version 0.1.6), was used to estimate selectivity, relative fishing mortality, and SPR, and to simulate the expected length composition and yield curves. Dependence of SPR, SSB/SSB_0, and relative yield on relative fishing mortality can provide easily understood fishery status indices and adjustments in exploitation needed to sustain harvest (Hordyk *et al*., 2020). Life-history parameters (L_∞, K, and M) are sources of uncertainty if data quality is poor (Brooks *et al*., 2010; Prince *et al*., 2015; Hordyk *et al*., 2015b; Maria *et al.,* 2022), so the uncertainty of the deterministic SPR was addressed using a stochastic approach to re-estimate SPR. The stochastic SPR considers a more extensive range of L_∞ and M/K than a single bootstrapped deterministic estimate.

Summary

Although there are several methods which are commonly used by numerous research and governance bodies of various countries to assess their marine fish stocks, their effectiveness relies heavily on estimating the abundance or biomass of both exploited and unexploited fish stocks. Nevertheless, the reliability and effectiveness of these stock assessment techniques are always subject to debate, particularly regarding their uniform application across diverse types of fisheries practiced worldwide. A summary of some of the methods along with the data requirements, major outputs and reference for details and model assumptions are given in Table 1.

Table 1. List of selected methods along with data requirements, major outputs and key references[#] (adapted from Jayasankar *et al*., 2024)

Sl No.	Methods/Models	Input data requirements	Major model outputs	Key references for details and model assumptions
1.	Stock Status Plots	Time-series of catch	Status of the stocks over years	Pauly *et al.* (2008); Kleisner and Pauly (2011); Kleisner *et al.* (2013); Pauly *et al.* (2008); Varghese and Jayasankar (2023); Varghese *et al.* (2023)
2.	Biomass dynamics models / Surplus production models	Time-series of catch and Index of abundance	Estimates of carrying capacity (K); Population growth rate (r); Maximum Sustainable Yield (MSY); Predicted biomass (B); Biomass at MSY (BMSY); Fishing mortality (F); Fishing mortality at MSY (FMSY)	Graham (1935); Schaefer (1954, 1957); Ricker (1975); Fletcher (1978); Gulland (1983), Fox (1970); Pella and Tomlinson (1969); Shepherd (1982); Ludwig and Hilborn (1983), Freon *et al.* (1990), Punt (1994); Restrepo and Legault

				(1998); Sathianandan *et al.* (2021)
3.	CMSY	Time-series of catch and species resilience	Estimates of carrying capacity (k); r; MSY; Relative biomass (B/k); BMSY; F; FMSY; F/ FMSY; B/ BMSY	Froese *et al.* (2018); Palomares and Froese (2017); Froese *et al.* (2021); Varghese *el al.*(2020); Suresh *et al.* (2021)
4.	BSM	Time-series of catch and Index of abundance	k; r; Catchability (q); MSY; B/k; Biomass BMSY; F; FMSY; F/ FMSY; B/ BMSY	Froese *et al.* (2018); Palomares and Froese (2017); Froese *et al.* (2021); Varghese *et al.* (2020); Suresh *et al.* (2021)
5.	AMSY	A time series of CPUE (or index of biomass), prior ranges for r and relative stock size (Bt/k)	Maximum sustainable value (MSYq) of relative catch Cq; relative carrying capacity (kq), or the CPUE, if there were no fishing; F/ FMSY; B/ BMSY	Froese *et al.* (2020)
6.	LBIs	Length-frequency data over years; L_{mat}, L_{opt}, L_{max}, and L_{∞}	P_{mat}; P_{mega}; P_{opt}; P_{obi}; decision tree based on these measures	Froese (2004); Cope and Punt (2009); Suresh *et al.* (2023)
7.	LBSPR	Case1: Asymptotic length (L∞); instantaneous growth rate (K); M/K ratio (natural mortality divided by von Bertalanffy K coefficient);	Case1: Simulated length composition based on the inputs provided	Hordyk *et al.* (2015a, b and c); Hordyk *et al.* (2016); Suresh *et al.* (2021)

		Length at 50% maturity (Lmat50); Length at 95% maturity (Lmat95); Length at 50% selectivity (SL50); Length at 95% selectivity (SL95); F/M ratio or SPR; Bin Width; Bin Maximum; Bin Minimum Case2: Length-frequency data; M/K ratio; Lmat50; Lmat95	Case2: Estimated Spawning Potential Ratio (SPR)	
8.	LBB	Length-frequency data over years; L∞; Lc (Length where 50% of the individuals are retained by the gear-Length at first capture) and Lmat50, if available	Z/K; M/K; F/K; Lc; Lc_opt (Optimum Length at First Capture); Lmean; Lopt; F/M; B/B0	Froese *et al.* (2018)
9.	JABBA	Time-series of catch, CPUE (or Index of abundance) and standard error of CPUE (if available); priors for r, K and B/K	Estimates of carrying capacity (K); r; MSY; predicted biomass (B); BMSY; F; FMSY, Projection of the reference points under defined scenarios	Winker *et al.* (2018)
10.	Sraplus	Case 1: "Catch-only" SIR model Time-series of catch	Case 1: Catch/ Maximum Sustainable Yield (MSY); Biomass at MSY (BMSY); Fishing	Ovando *et al.* (2021)

		Case 2: Time-series of catch, Fisheries Management Index (fmi) and Swept Area Ratio (sar)	mortality (F); Fishing mortality at MSY (FMSY); F/ FMSY; B/ BMSY; Rate of depletion Case 2: Catch/ Maximum Sustainable Yield (MSY); Biomass at MSY (BMSY); Fishing mortality (F); Fishing mortality at MSY (FMSY); F/ FMSY; B/ BMSY; Rate of depletion	

#Only selected few methods/tools/models available for fish stock assessment are listed

Conclusion

In conclusion, the methods for assessing data-limited fisheries emphasize the need for context-specific considerations, acknowledging the inherent uncertainty compared to assessments with comprehensive data. Despite this uncertainty, tailoring approaches to each fishery's unique conditions enhances the relevance of insights. The key lies in combining multiple assessment methods and involving stakeholders. This collaborative approach not only mitigates data limitations but also fosters a more comprehensive understanding and commitment to sustainable practices. In navigating the complexities of data-limited fisheries, a balanced and tailored strategy ensures informed decisions that account for ecological, social, and economic factors.

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