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Bayesian State-space Implementation of Schaefer Production Model for Assessment of Stock Status for Multi-gear Fishery

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SUMMARY

Knowing the status of marine fish stock is of utmost importance to develop management strategies for sustainable harvest of marine fishery resources. A widely accepted approach towards this is to derive sustainable harvest levels using time series data on fish catch and fishing effort based on fish stock assessment models like Schaefer's model that describe the biomass dynamics. In India, the marine fishery is of complex multi-species nature where in different species are caught by a number of fishing gears and each gear harvests a number of species making it difficult to obtain the fishing effort corresponding to each fish species. Since the capacity of the gears varies, the effort made to catch a resource cannot be considered as the sum of efforts expended by different fishing gears. Hence, it demands the importance of effort standardisation for making use in stock assessment models. This paper describes a methodology for the standardization of fishing efforts and assessing fish stock status using Bayesian state-space implementation of the Schaefer production model (BSM). A Monte Carlo based method namely Catch-Maximum Sustainable Yield (CMSY), has also been used for estimating fisheries reference points from landings and a proxy for biomass using resilience of the species. The procedure has been illustrated with data on Indian mackerel (*Rastrelliger Kanagurta*) collected from the coastal state of Andhra Pradesh, India during 1997-2018. Maximum Sustainable Yield (MSY) of Indian mackerel for Andhra Pradesh has been estimated. A comparison between both CMSY and BSM methods have been made and found that the estimates are in close agreements.

Keywords: capture fisheries, stock assessment, Schaefer model, Monte Carlo method, CMSY, BSM.

1. INTRODUCTION

Knowing the status of marine stock is of utmost importance to develop management strategies for sustainable harvest of marine resources. Stock assessment is the process of collecting, analysing and reporting fish population information to determine changes in the abundance of fishery stocks in response to fishing and, to the extent possible, predict future trends of stock abundance (Sparre and Venema, 1992). In fisheries where there are no fishery-independent measures of abundance, the commercial catch rate is commonly used as an abundance indicator (Vivekanandan, 2005).

Surplus production models, introduced by (Graham, 1935) are commonly used for assessing the state of fish stocks. These models view 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 commercial fishery. The model is based on the assumption that the CPUE is proportional to biomass of the fish in the sea.

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

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

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).

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

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

A major challenge in fitting such a production model is to find out CPUE, may be in terms of the units operated or in terms of hours of operation/actual fishing hours (AFH). As the fishing fleet is heterogeneous in most of the cases, it is partitioned into boat-gear categories in each of which the fishing units have similar characteristics and performance. When it comes to measure the combined effect of the fishing operations of the entire fleet to the exploitation of a fish stock, it becomes apparent that adding together effort exerted by different boat-gear categories is not always meaningful without first applying effort adjustment to increase its comparability (Stamatopoulos and Abdallah, 2015).

Stock assessment of individual species becomes difficult when a species is targeted by various gears and each gear may harvest more than the species targeted. Since the capacity of the gears vary and also each gear may contain multiple species, the effort made to catch a resource cannot be considered as the sum of duration/units of operation of all the gears. Hence, the problem of exploitation of the same stock by gears with different efficiencies has to be addressed. There are several techniques for dealing with such situations, the most commonly used one is the standardization of fishing effort. There is a lot of literature available on the standardization of the fishing effort. These methods deeply depend on characteristics of the gear being operated and the availability of the information.

Hilborn and Walters (1992) proposed the use of Generalized Linear Models (GLM) for standardization of fishing effort. Rochman *et al.* (2017) attempted to standardize CPUE to estimate relative abundance indices based on the Indonesian longline dataset time series using GLM with Tweedie distribution. Daniel *et al.* (2016) gave a method named multi-gear mean standardization (MGMS) which combining catch per unit effort data that standardizes catch per unit effort data across gear types. Setyadji *et al.* (2018) used GLM to standardize CPUE and to estimate relative abundance indices based on the Indonesian longline dataset. Six GLM models were considered viz., negative binomial, zero inflated Poisson, zero-inflated negative binomial, Poisson hurdle, and negative binomial hurdle models. AIC and BIC were used to select the best models among all those evaluated.

In the literature cited above, either CPUE or effort exerted to a catch particular fish or vessel/ gear characteristics available. A methodology for the standardization of fishing effort is to be required when one has to estimate the effort exerted to catch a particular species from the total effort hence it demands the importance of effort standardisation for making use in stock assessment models. Here, an attempt has been made to develop a methodology to standardize the fishing effort and further to arrive at MSY using Bayesian approach. A Monte Carlo method has also been used to obtain the MSY when a measure of fishing effort is not available. This is done by making use of the species resilience to derive a quantitative measure of productivity.

2. COMPUTATIONAL STEPS FOR EFFORT STANDARDIZATION

This method of standardization requires the species catch, total catch and total fishing effort. Let Y_{ijk} represents the catch of k^{th} species (k=1,2,...,s) from i^{th} (i=1,2,...,g) gear at the j^{th} (j=1,2,...,t) time point (say year) and corresponding effort is expressed as X_{ij}.

To calculate the component of standardized fishing effort for the species corresponding to each gear, the proportion of catch in the total catch by each gear for each year and a weighing factor for each gear is required. Following is the step-wise procedure of effort standardisation:

Step1: Calculate $P_{ijk} = \frac{Y_{ijk}}{Y_{ij.}}$, where $Y_{ij.} = \sum_{k=1}^{s} Y_{ijk}$

Step 2: Obtain the mean and variance of P_{ijk} for each gear and for each species

$$\overline{P_{i.k}} = \frac{1}{t}\sum_{j=1}^{t} P_{ijk} \text{ and } \sigma_{i.k}^2 = \frac{1}{t}\sum_{k=1}^{s}(P_{ijk} - \overline{P_{i.k}})^2$$

Step 3: Calculate weighting factor as

$$W_{i.k} = \frac{\overline{P_{i.k}}}{(\sigma_{i.k}^2 + 1)} \text{ and } W'_{i.k} = \frac{W_{i.k}}{\sum_{i=1}^{g} W_{i.k}}$$

The weighing factor is then adjusted for unit sum. The decomposition of fishing effort for the species is then obtained by multiplying the corresponding total fishing effort for the gear in the year with the proportion of the species for the year corresponding to the same gear and the weighing factor.

Step 4: Obtain the standardized gear-wise fishing effort as

$$E_{ijk} = W'_{i.k} \times P_{ijk} \times X_{ij}$$

Here, the sum of all the gear efforts would give a total effort. But, the efficiency of gears varies so also the capability to catch in an hour which demands scaling the fishing efforts into a single scale. Hence, it is better to express all gears in terms of a single gear (may be the least efficient or the most efficient) by deriving a suitable multiplication factor for each fishing gear.

Step 5: Calculate the catch per unit effort (gear-wise) as

$$CP_{ij} = \frac{Y_{ij.}}{X_{ij}} \text{ and } \overline{CP_{i.}} = \frac{CP_{ij}}{t}$$

The multiplication factor is $\overline{CP_{i''.}} = \frac{\overline{CP_{i.}}}{\overline{CP_{i'.}}}$, where $\overline{CP_{i'.}}$ is the least efficient or the most efficient gear

Step 6: Obtain the standardized fishing effort for k^{th} species at j^{th} time point as

$$\sum_{i=1}^{g} E_{ijk} \times \overline{CP_{i''.}}$$

3. ASSESSMENT OF MARINE STOCK: MONTE CARLO METHOD AND BAYESIAN APPROACH

After obtaining the standardized fishing effort, may be a proxy for CPUE, the stock assessment has been made using the following approaches:

Case 1: *when a measure of fishing effort is available*

Case 2: *when fishing effort is not available (data poor situation)*

Case1 is based on the delay difference model to describe nonlinear population dynamics. State–space model allows incorporation of random errors in both the biomass dynamics equations and the observations. Because the biomass dynamics are nonlinear, the common Kalman filter is generally not applicable for parameter estimation. However, it is demonstrated by (Miller and Meyer, 1998) 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, 1998; Froese *et al.* 2017). This approach has been named as BSM and fitted to catch and standardised fishing effort data.

CMSY estimates biomass, exploitation rate, MSY and related fisheries reference points from catch data and 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 MCMC model is assessed using Rubin and Gelman Rhat statistics, automatically running a MCMC model till it converges, and implementing parallel processing (using *doparallel* package in R) of a MCMC model for multiple chains. The *r*-ranges for the species under assessment, the proxies for 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).

Even though we have the standardised fishing effort, case 2 has been used to compare the estimate of MSY and the model parameters.

Both the approaches were implemented using R studio (https://www.rstudio.com/). The inputs of time series of catch and information on species resilience are required for running the code and generate the outputs. In order to run the code, the R-libraries required are *R2jags, coda, lattice, parallel, foreach, doParallel,* and *gplots*.

4. 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 kilometers 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.

Indian mackerel catches in A.P. have been reported from various gears viz., mechanized gillnet (MGN), non-mechanized gears (NM), outboard gillnet (OBGN), outboard ringseine (OBRS), outboard trawlnet (OBTN) and mechanized trawlnet including multiday trawlnet (MTN) and some minor gears.

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 and Srinath *et al.*, 2005), where the stratification is done over space and time. Time series of catch and effort (in hours of operation) from 1997 to 2018 taken from National Marine Fishery Resources Data Centre (NMFDC) of CMFRI, Kochi have been used for the analysis. Standardised fishing effort has been estimated using the proposed method.

5. RESULTS AND DISCUSSION

The annual landings of Indian mackerel in Andhra Pradesh ranged from a low of 6418t (2007) to a high of 55813t (2014) during the study period (Fig. 1a) with an average annual landing of 20551t (SD = 10216). Mackerel landings showed an increasing but variable trend from 1997 onwards, reaching the peak in 2014 and then showed a declining trend. Motorized ring seines (OBRS) landed the highest quantity of Indian mackerel along AP coast during the study period (Table 1). Besides, the summary of fishing effort exerted by major gears in terms of Actual Fishing Hours (in 1000 hrs) has also been given in Table 1. MTN is the gear which operated for a maximum of 3982 (SD = 1212) and OBTN with minimum of 148 (SD = 104).

Table 1. Average landing (in tonnes) and Actual Fishing Hours by each major gear

Gears	Mackerel Landing (t)	AFH ('000 hrs)
MTN	6428, n=22 (2827)	3982 (892)
MGN	1123, n=14 (1412)	438 (338)
NM	5100, n=22 (2711)	2565 (1212)
OBGN	4583, n=22 (2311)	2125 (475)
OBRS	10135, n=10 (6545)	184 (96)
OBTN	208, n=9 (456)	148 (104)

n=number of years with mackerel catch; Standard deviation in parenthesis

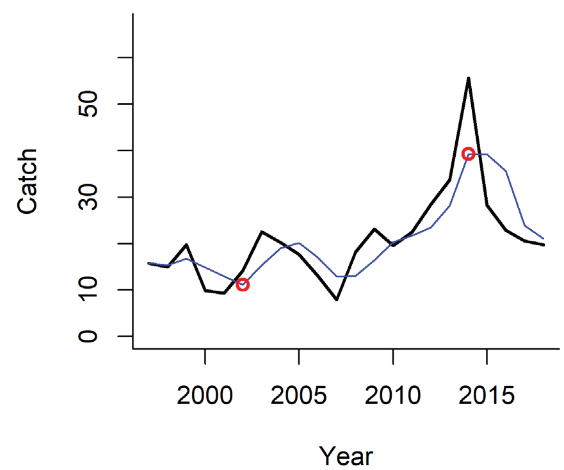

Fig. 1a. Time series of Indian mackerel landings during 1997-2018 (Blue line is the three year moving average, maximum and minimum landings are denoted with red dots)

The standardised fishing effort using the proposed method during the study period indicated an increasing trend with maximum fishing effort exerted in 2015 (Fig. 1b).

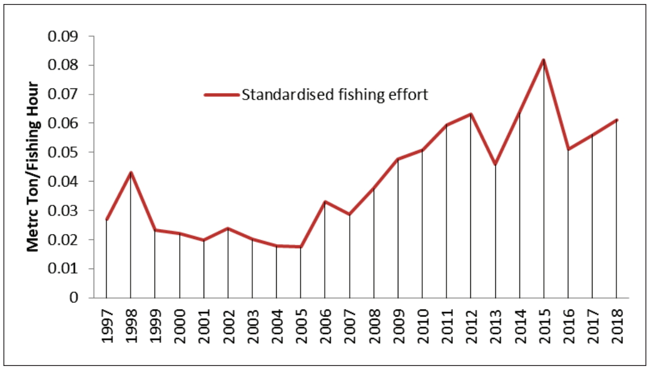

Fig. 1b. Time series of standardised fishing effort during 1997-2018

Since mackerel landings during the initial and final period of the time series are less, lower prior value for *B*/*k* was thought to be reasonable. Thus the prior ranges for *B*/*k* in the initial and final year were set to 0.2-0.6. Since mackerel landings during the intermediate period were high, the prior range for *B*/*k* was set to 0.5 - 0.9 for this period.

FishBase (Froese *et al.*, 2000; Froese and Pauly, 2015) has provided the proxies for 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:

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

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, 43.6-785 and 4.19e-07 - 1.78e-06 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.2). 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 indication of approximate 95% confidence limits. The black dots show the estimates of the BSM method, with the red cross indicating the 95% confidence limits.

Here, the resilience range of *r* = 0.2 to 0.9 seems to be meaningful as the points show convergence and fewer viable *r*-*k* combinations are found at the end of the *r* range. It also showed a close agreement with estimated *r*-*k* by both the approaches.

Once the *r*-*k* pair was selected the relative biomass along with confidence limits was predicted by both the CMSY and BSM method (Fig. 3). The bold curve (blue colour) in Fig.3 is the relative biomass predicted by CMSY, with confidence limits (dotted curves). The normal curve (red colour) indicates CPUE scaled by the catchability coefficient estimated by BSM. The horizontal dashed line indicates biomass at MSY (B_{msy}) and the dotted line indicates half of B_{msy}.

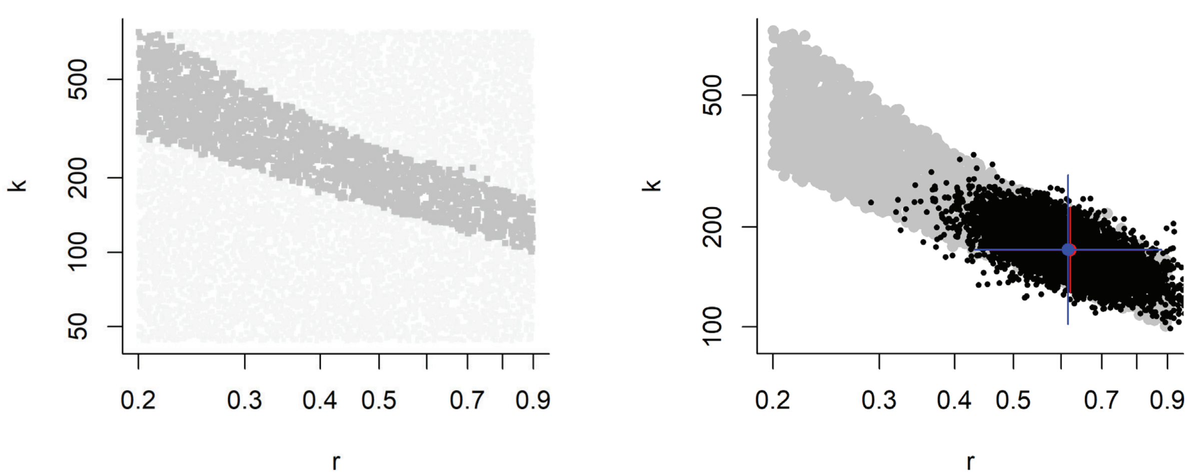

Fig. 2. Search for viable *r*-*k* pairs

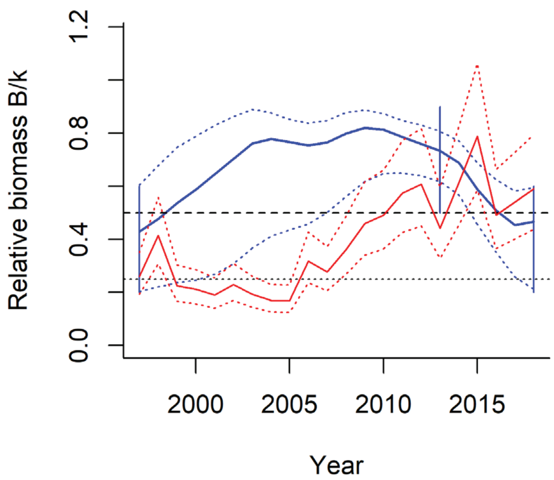

Fig. 3. Relative biomass

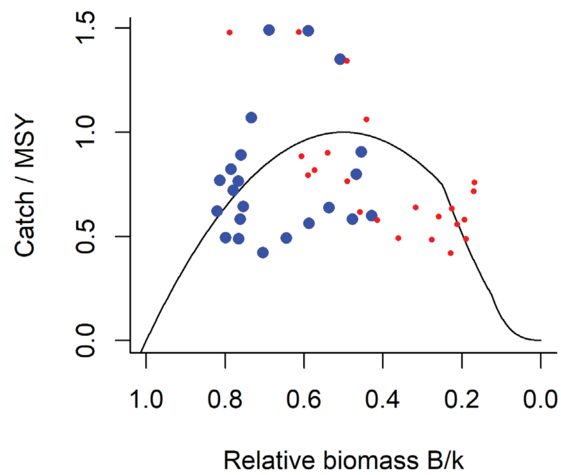

Fig. 4. The ratio of catch to MSY and relative biomass (*B/k*) over years

The relative biomass plot indicated that both in the initial and final 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 intervening years showed a high relative biomass. 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. However the relative biomass fell below MSY by 2015 indicating that the stock of Indian mackerel along AP coast is overfished. The overfished status of Indian mackerel along AP coast is further highlighted in the CMSY/BSM output showing catch relative to MSY over biomass relative to unexploited stock size (Fig.4). The red dots indicate estimates by BSM, and the blue dots indicate estimates by CMSY. The indentation of the parabolas below 0.25 *k* (half of B_{msy}) results from the inclusion of a stock–recruitment model which assumes reduced recruitment at low stock sizes.

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 2. It can be seen from the table that the estimate of MSY is very close by both the approaches with smaller confidence in case of BSM. As BSM takes into account of CPUE, further management plans have been derived based on the BSM results. The landings of Indian mackerel since 2016 has fallen below the estimated MSY.

Table 2. Estimates of MSY and model parameters along with confidence limits

Parameters	CMSY	BSM
MSY	26500 (19200 – 36400)	26600 (20900 - 33800)
r	0.616 (0.431-0.879)	0.623 (0.457-0.848)
k	172000 (102000-289000)	171000 (127000-229000)
Relative biomass in last year (*B*2018/*k*)	0.458 (0.214 - 0.596)	0.532 (0.377 - 0.686)
Exploitation F/(r/2) in last year	0.815	0.7 (0.542 - 0.987)
q	-	6.1e-07 (4.63e-07 - 8.03e-07)
B_{msy}	-	85300 (63500- 115000)
Fishing mortality (F_{msy})	-	0.311 (0.229 - 0.424)
F_{msy} in last year	-	0.218 (0.169 - 0.307)

The plots of landings vs MSY and that of B/B_{msy} (Fig. 5) also indicate the over-fished status of Indian mackerel along AP coast during 2016 onwards. The horizontal dashed line in first plot indicates MSY with lower and upper confidence limit of MSY in grey colour. The bold curve in second plot is the biomass predicted by BSM, with confidence limits (grey colour). The horizontal dashed line indicates B_{msy} and the dotted

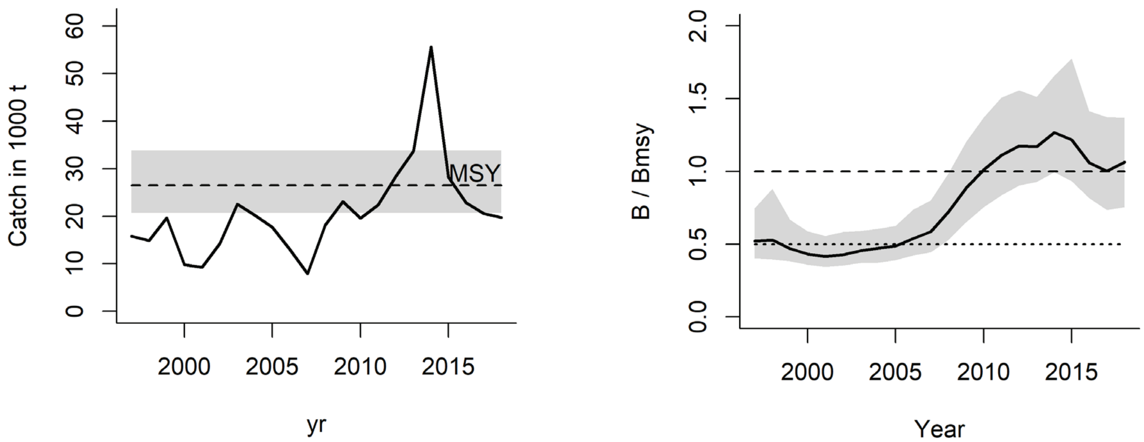

Fig. 5. Catch in comparison to MSY and (B/B_{msy}) over years

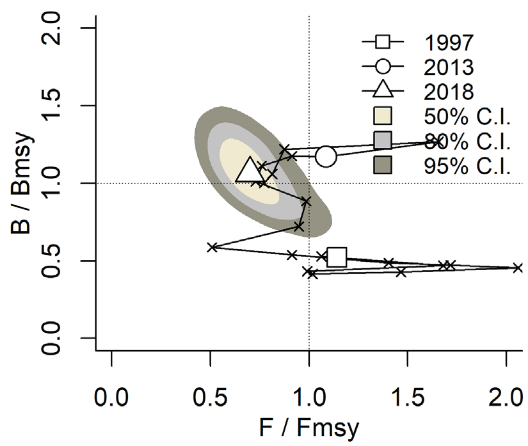

Fig. 6. Development of biomass and exploitation relative to B_{msy} (horizontal dashed line) and F_{msy} (vertical dashed line) for Indian mackerel along AP coast

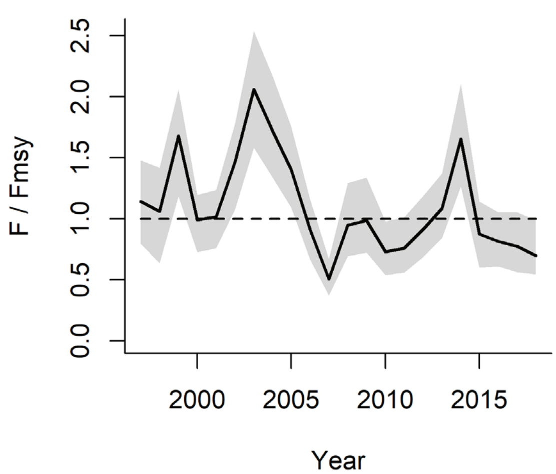

Fig. 7. F/F_{msy} over time for Indian mackerel along AP coast

line indicates half of B_{msy}. The solid line is just above the B_{msy} line during the last two years indicating that current biomass is slightly more than biomass at MSY. Ideally this ratio should be as high as possible. Levels near to 1 indicate that the biomass of the stock of Indian mackerel along AP coast is just at the threshold of being unhealthy.

The plots of current fishing mortality (F) in relation to F at MSY (F_{msy}) (Fig. 6 and 7) indicated that the current fishing mortality is lower than fishing mortality at MSY. However, since current biomass is almost the same level as B_{msy} the stock can be thought to be almost at the edge of unsustainable fishing.

Thus from the above results it can be inferred that the rate of exploitation has been highly fluctuating over period. The current level of exploitation is low as compared to earlier years. Biomass which had been high in intermediate years has declined beyond 2016 due to high exploitation in the intermediate years. The present scenario indicates that a management plan for Indian mackerel along A.P. is needed to ensure its sustainable utilization and that the confidence limit of MSY can serve as guidance for fixing catch limits.

6. CONCLUSIONS

Stock assessment of individual species becomes difficult when a species is targeted by various gears and each gear may harvest more than the species targeted. Since the capacity of the gears vary and also each gear may contain multiple species, the effort made to catch a resource cannot be considered as the sum of duration of operation of all the gears. Here, a new methodology for the standardization of fishing efforts and assessing the stock status of Indian Mackerel (*Rastrelliger kanagurta*) using Bayesian state-space implementation of the Schaefer production model has been discussed. A Monte Carlo method for estimating fisheries reference points from catch using species resilience has also used to assess the stock status in the absence of biomass/ CPUE.

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