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Status of Indian marine fish stocks: modelling stock biomass dynamics in multigear fisheries

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A biomass dynamics modelling study to derive biological reference points and management requirements of 223 commercially important fish stocks in different maritime states of India was conducted. Two decades (1997–2016) of fishery-related data on the harvest of resources by different types of fishing fleets formed the input. The multigear nature of the fishery situation was solved by introducing a gear standardization parameter into the biomass dynamics model. The relative positions of the fish stocks were depicted through Kobe plots generated for the ten maritime states/union territory, and the fish stocks were categorized, based on the status, into sustainable, overfished, recovering, and overfishing. The results indicate that 34.1% of the assessed fish stocks in the country are sustainable, 36.3% are overfished, 26.5% are recovering, and 3.1% are in the overfishing status. Regionally, the percentage of sustainable fish stocks were high along the southwest coast (51.6%), overfished stocks were high along the northwest coast (54.2%), and recovering fish stocks were high along the northeast coast (47.8%). The national mean B/B_{MSY} was estimated as 0.86, which is a strong reason for strengthening fisheries management. Fishing fleets harvesting overfished stocks were examined for each maritime state, and recommendations regarding reduction in annual fishing hours are made.

Keywords: biomass dynamics model, maximum sustainable yield, multigear fishery, stock status

Introduction

The marine fisheries sector in India contributes significantly to the food and nutritional requirements of its people, supports the livelihood of nearly four million people by providing income and employment (CMFRI-FSI-DoF, 2020), and earns foreign exchange worth US$6.68 billion through export (MPEDA, 2020). The sector depends on the renewable marine living natural resources, and its harvest and control at sustainable levels through appropriate management measures is highly important. The 6068-km coastline of mainland India is shared by nine maritime states and two union territories (UTs). The maritime states are West Bengal and Odisha on the northeast coast; Andhra Pradesh, Tamil Nadu, and Puducherry (UT) on the southeast coast; Kerala, Karnataka, and Goa on the southwest coast; and Maharashtra, Gujarat, and Daman Diu (UT) on the northwest coast. Periodic assessment of stocks of different marine fishery resources in each maritime state, for deriving management reference points such as maximum sustainable yield (MSY), is an essential requirement for implementing control measures to keep the harvest at sustainable levels.

A national-level study about the catch dynamics of major marine fishery resources during 1950–2010 using six decades of data on 26 resource group landings in India was carried out by Sathianandan *et al.* (2011) who classified them based on their status. Other important studies of national level fish harvest for examining the status of marine fishery resources in India include those by Silas *et al.* (1976), Alagaraja *et al.* (1982), George *et al.* (1983), Alagaraja (1987), James *et al.* (1987), Srinath (1987), Devaraj and Vivekanandan (1999), and Mohamed *et al.* (2010). Microlevel assessment of the stock status of commercially important species at the national level through population dynamics studies using data on length distribution, fish catch, and fishing effort were reported during 1991–1995 by different authors (Pillai *et al.*, 1991; Bennet *et al.*, 1992; James *et al.*, 1992; Reuben *et al.*, 1992; Thiagarajan *et al.*, 1992; Yohannan *et al.*, 1992; Meiyappan *et al.*, 1993; Nair *et al.*, 1993; Rao *et al.*, 1993; Sukumaran *et al.*, 1993). More recently, stock assessments in India have focussed on resources of high commercial value such as shrimps (Chakraborty *et al.*, 2018), cephalopods (Jasmin *et al.*, 2018), and pelagic fishes (Ghosh *et al.*, 2016; Das *et al.*, 2019) without addressing the multigear nature of the fisheries. Reviewing the status of global fisheries, Hilborn *et al.* (2020) stated that as most unassessed fisheries are in tropical and subtropical regions dominated by highly diverse mixed fisheries, the single-species stock assessment and management practices used in temperate countries are impractical. Regulating overall fishing pressure so that ecosystem-wide benefits are optimized was suggested as a way forward.

Among different fish stock assessment approaches, an important and widely used method is through modelling of the stock biomass dynamics of the resource using time-series data on fish catch and fishing effort as inputs. Schaefer (1954) introduced the basic surplus production model to describe the biomass dynamics in the management of marine fisheries. Several modifications of this method are in vogue throughout the world. The complexity of multispecies and multigear fisheries, as in the tropics, makes the biomass dynamic modelling exercise challenging. A variant of this model was used by Balan and Sathianandan (2007) to assess the ringseine fishery in Kerala, one of the maritime states of India, and later by Sathianandan and Jayasankar (2009) for the management of marine fisheries in Kerala, through simulations.

The Indian Council of Agricultural Research (ICAR)-Central Marine Fisheries Research Institute (ICAR-CMFRI), Kochi, India has a well-established data collection and estimation system for generating information on species-wise and fishing gear-wise marine fishery resources landings and fishing effort for different maritime states every month using skilled observers in fish landing ports. The method developed by ICAR-CMFRI follows a scientific sampling scheme named "Stratified Multistage Random Sampling Design (SMRSD)" (Sukhatme *et al.*, 1958; Srinath *et al.*, 2005), which has been in operation since 1960. The historic information so generated is stored in the National Marine Fishery Resources Data Centre (NMFDC) of ICAR-CMFRI. Since maritime states in India have separate fisheries management laws and regulations, they are considered as the basic management units. The objective of this study, therefore, is to determine sustainable harvest levels for all commercially important marine fishery resources in each maritime state/UT through modelling of biomass dynamics of the fish stocks using time-series data on fish landings and fishing effort. For the fish stocks which are overfished in each state, an effort reduction plan to recover the populations is attempted.

Material and methods

Catch and effort data

The input data required for the biomass dynamics modelling of fish stocks are: (i) time-series of landings of the species/species group by different fishing gears, (ii) time-series of total landings by these fishing gears obtained by summing over all the species caught by the gears, and (iii) time-series of fishing hours expended by these fishing gears for catching these species. Altogether 223 such datasets were used in this study, which were obtained from the NMFDC database of ICAR-CMFRI.

In the marine fisheries sector in India, fishing is currently carried out by 42,985 mechanized, 97,659 motorized, and 25,689 non-mechanized fishing crafts which land their catches in 1269 landing centres including fishing harbours (CMFRI-FSI-DoF, 2020). There are more than 30 craft and gear combinations (fleets) in the fishery. The important categories of fishing crafts in the mechanized sector are trawlers, gillnetters, liners, purse seines, ringseines, and dolnets. The liners and about 45% of the trawlers make 40–60 multiday fishing trips per annum, and all other mechanized fishing crafts make around 240 single-day trips per annum. The motorized and non-mechanized fishing crafts undertake up to 300 single-day trips per annum. Considering these facts, an approximate calculation gives 44.7 million trips by these fishing vessels which land their catches in the 1269 landing centres each year. Complete enumeration and recording of the catch data require huge manpower, thus restricting its feasibility. Using a logsheet for catch data collection was found to be impractical as only a few species are recorded in logsheets, even when there are a very high number of species caught by vessels, especially by multiday trawlers. In tropical countries where the diversity of marine fishery resources is very high, the most practical fishery data collection approach is a scientific sampling scheme.

Through SMRSD, the ICAR-CMFRI has been monitoring the marine fish harvest along the Indian coast since 1960. This SMRSD employs stratification over space and time, demarcating the entire Indian coast into 75 non-overlapping regions called fishing zones based on criteria such as fishing intensity, number of landing centres, and geographical boundaries (Srinath *et al.*, 2005). The number of landing centres in the fishing zones varies, as do the number of fishing vessels operating from landing centres, and there is substratification within zones depending on the intensity of fishing. Based on the intensity of fishing, landing centres are classified into High-Intensity Landing Centres (HiLC), Major Landings Centres (MaLC), and Minor Landing Centres (MiLC). Out of the 1269 landing centres, 52 are HiLC (300 or more vessels in operation), 37 are MaLC (100–299 vessels in operation), and the remaining are MiLC (less than 100 vessels in operation). The sampling coverage is more for HiLC than that for MaLC and still less for MiLC. In the data collection system, dedicated technicians with species identification skills visit the landing centres according to work schedules generated under SMRSD and record different aspects of the fishery from sampled boats. The data thus generated are centrally processed and stored in the NMFDC, which holds historic fishery data at different aggregation levels.

Statistical model

The methodology adopted for the estimation of MSY was based on three versions of biomass dynamic models. The basic model had the following expressions, one for calculation of biomass of a species for successive periods termed as the process equation (1) and the other relating biomass to catch and fishing effort known as the observation equation (2):

$$B_{t+1} = B_t + r\, B_t\left(1 - \frac{B_t}{K}\right) - C_t \tag{1}$$

$$C_t = q\, B_t\, f_t \tag{2}$$

In the multispecies and multigear fishery situation prevailing in India, a species is usually caught by multiple fishing gears (fishing fleets) and, similarly, a fishing gear catches many species. Here, the fishing effort expended by a specific fishing gear results in the catching of many fish species, and attributing the total fishing effort expended by the fishing gear to individual species is a challenging task. This issue is addressed here by incorporating an additional set of gear standardization parameters (λs with values summing to unity) in the catch equation in addition to the proportion of catch of the species in the total catch by the gear. Thus, for each species, the expression for standardized fishing effort f_t was derived considering the fishing effort of all the g fishing gears in which the species is caught (equation 3). By replacing f_t in equation 2, we get the modified catch equation suitable for the multigear situation (equation 4):

$$f_t = \sum_{i=1}^{g} \lambda_i\, P_{i,t}\, f_{i,t} \tag{3}$$

$$C_t = \sum_{i=1}^{g} (\lambda_i\, P_{i,t}\, f_{i,t})\; q\, B_t \tag{4}$$

The following two modified versions of the above-explained process equations were also attempted for modelling individual resources corresponding to each maritime state to estimate MSY. The observation equation (4) remained the same for all three models.

$$B_{t+1} = B_t + r\, B_t\left[1 - \left(\frac{B_t}{K}\right)^{\mu}\right] - C_t \tag{5}$$

$$B_{t+1} = B_t + r\, B_t\left[1 - \left(\frac{B_t}{K}\right)^{\mu}\right] - m\, B_t - C_t \tag{6}$$

The symbols used for the above models are: B_t is the biomass of the stock corresponding to year t, C_t is the quantity harvested in year t, $f_{i,t}$ is fishing effort in hours spent by fleet type i in year t, $P_{i,t}$ is the observed proportion of the species/resource in the catch by gear type i in year t, r is the intrinsic annual growth rate in biomass of the species/resource, q is the overall catchability coefficient in catching the species/resource, K is the carrying capacity for the species/resource, λ_i is a gear standardization parameter introduced for gear type i, μ is a curvature parameter, and m is an additional parameter introduced to meet the possibility of negative net production in biomass even when there is no harvest.

In models (5) and (6), a curvature parameter μ was added for better model fit, and an additional term with parameter m was used in model (6) to represent the situation of higher natural mortalities resulting in negative net production in biomass. The expressions for MSY and sustainable level biomass (B_{MSY}) and fishing effort at MSY (f_{MSY}), in terms of model parameters corresponding to the three process equations (1), (5), and (6), are given in Table 1.

Table 1. Mathematical expressions used for calculation of maximum sustainable yield (MSY), biomass (B_{MSY}) and fishing effort (f_{MSY}) corresponding to MSY levels.

Process equation	Model		
	MSY	**B_{MSY}**	**f_{MSY}**
1	$\frac{rK}{4}$	$\frac{K}{2}$	$\frac{r}{2q}$
5	$\frac{rK\mu}{(\mu+1)(\mu+1)^{\frac{1}{\mu}}}$	$\frac{K}{(\mu+1)^{\frac{1}{\mu}}}$	$\frac{r\mu}{q(\mu+1)}$
6	$\frac{(r-m)K\mu}{(\mu+1)}\left(\frac{r-m}{r(\mu+1)}\right)^{\frac{1}{\mu}}$	$K\left(\frac{r-m}{r(\mu+1)}\right)^{\frac{1}{\mu}}$	$\frac{(r-m)\mu}{q(\mu+1)}$

All parameters in the models were estimated through maximum likelihood (ML) estimation derived by incorporating the observation error term ϵ_t in the catch equation (equation 7). The error terms ϵ_t were assumed to be distributed identically and independently as $N(0,\sigma^2)$ leading to the expression for the negative log-likelihood (excluding constants) given as equation (8), which was minimized for estimating all the model parameters with $\sum_{i=1}^{g} \lambda_i = 1$ as an additional constraint for λ during minimization. An upper bound of 3 was set for the curvature parameter μ so that B_{MSY} will not go beyond 63% of the carrying capacity K as a precautionary approach as well as giving allowance for harvest. Higher values of μ will introduce more control over the harvest.

Computer software developed under the ADMB environment (Automatic Differentiation Model Builder version 11.2, the freeware developed by David Fournier) was used for the ML estimation:

$$C_t = \sum_{i=1}^{g} (\lambda_i\, P_{i,t}\, f_{i,t})\; q\, B_t e^{\epsilon_t} \tag{7}$$

$$-\ln(L) = \frac{n}{2}\ln(\sigma^2) + \frac{\sum_{t=1}^{n}\left\{\ln(C_t) - \ln\left[\sum_{i=1}^{g} (\lambda_i\, P_{i,t}\, f_{i,t})\; q\, B_t\right]\right\}^2}{2\sigma^2} \tag{8}$$

As the model was non-linear, quantifying the model fit was difficult. For a good fit, the x–y plot of observed and model-predicted values is expected to be closer to the line bisecting the first quadrant. In such cases, the correlation between the two will be close to 1.

The goodness of fit of the model derived based on ML estimation for each fish stock was determined by computing the correlation between the observed and model-predicted values of landings and also by visually examining the closeness of the plot of observed landings time-series and its model-predicted values. Among the three models, the first model with lesser parameters was the initial choice, and when it did not yield a satisfactory fit, the second and third models were attempted sequentially.

To classify each of the marine fishery resources according to their stock status, we used two quantities: (i) ratio of current biomass to the sustainable level of biomass (B/B_{MSY}), and (ii) ratio of the current level of fishing mortality to its sustainable level (F/F_{MSY}) derived from a similar ratio of fishing effort (f/f_{MSY}).

To depict the status of the stocks during 2016 (final year of the assessment period), the *x–y* scatter plots of F/F_{MSY} against B/B_{MSY} (Kobe or phase plot; Restrepo, 2011) for all the resources considered were shown on the same graph separately for each maritime state. The four quadrants of the graphs were marked by drawing two perpendicular lines corresponding to $F/F_{MSY} = 1$ and $B/B_{MSY} = 1$, and points falling in the four quadrants indicate the different status of the resources. Table 2 shows a summary of the four possible cases in a Kobe plot along with the terms used to represent stock status.

Estimation of optimum fishing effort

After obtaining the sustainable levels of standardized fishing effort f_{MSY} for each fish stock, it was necessary to recommend actions in terms of understanding and regulating fishing effort of different categories of fishing fleets existing in the multispecies multigear fishery. The following procedure was carried out to achieve this.

Suppose there are n overfished stocks and g fishing gears that account for the landings of these fish stocks. Since these are overfished stocks, the quantity β_s defined below will be greater than 1 for all fish stocks ($s = 1, \ldots, n$):

$$\beta_s = \frac{f_{cur,\ s}}{f_{MSY,\ s}} \tag{9}$$

where $f_{cur,\ s}$ and $f_{MSY,\ s}$ are the standardized fishing effort at the current and MSY levels, respectively, for the fish stock s. Let $Q_{i,\ s}$ denote the proportion of catch of species s accounted by gear i so that $\sum_{i=1}^{g} Q_{i,s} = 1$ for each fish stock (s = 1,. . .,n). We obtained the redistribution of β_s of fish stock s among g fishing gears based on the proportions $Q_{i,\ s}$ as:

$$R_{i,s} = \beta_s\ Q_{i,s} \text{ so that } \sum_{i=1}^{g} R_{i,s} = \beta_s \tag{10}$$

Since we are interested in deriving the percentage reduction in fishing effort of the fishing gears considered to enhance the biomass of the overfished stocks, we computed the average of $R_{i,\ s}$ values of fish stocks as $-R_i$, for each fishing gear i, considering the values of only those overfished stocks which have high catch proportion ($Q_{i,\ s}$ values). The required percentage reduction PD_i in fishing effort for the i^{th} fishing gear was then obtained as:

$$PD_i = 100\left(1 - \frac{1}{-R_i}\right) \tag{11}$$

The consolidated national average of ratios (B/B_{MSY}, F/F_{MSY}, and C/C_{max}) were obtained as geometric means taken over all the 223 fish stocks for all the years.

Table 2. Summary of the four possible cases in Kobe plot for each fish stock and the terms used to indicate stock status.

Case	Location of the resource in the plot of F/F_{MSY} against B/B_{MSY}	$\frac{F}{F_{MSY}}$	$\frac{B}{B_{MSY}}$	Colour	Stock status
I	First quadrant	>1	>1	Orange	overfishing
II	Second quadrant	>1	<1	Red	overfished
III	Third quadrant	<1	<1	Yellow	recovering
IV	Fourth quadrant	<1	>1	Green	sustainable

Results

Information regarding the fishery and details such as the maritime states, regions, length of the coast with the percentage to the national total, average annual landings during 2014–2016 with the percentage to total national production, and number of fish stocks assessed along with percentage accounted by the assessed fish stocks towards landings are given in Table 3. Estimates of MSY for the assessed fish stocks along the west and east coasts are given in Tables 4 and 5 respectively, along with the status of the stocks marked in parenthesis. Supplementary information on model parameter estimates for each maritime state is given in Tables S1–S20. Out of the 223 fish stocks studied, the first model was found suitable for 23 fish stocks, and the remaining 200 gave a good fit with the second model; hence, the third model was not applied.

Table 3. Fishery-related details and number of fish stocks assessed for different maritime states (average annual catch during 2014–2016 with the percentage to national production, number of fish stock assessed with percentage accounted by them to the state total annual catch).

		Length of the coast		Average annual landings		Number of stocks assessed		
						Species		
State/union territory	Region	km	%	Million tonnes	%	Single	Group	Catch %
Gujarat & Daman Diu	Northwest	1621	26.7	0.817	23.1	7	13	56.9
Maharashtra	Northwest	720	11.9	0.301	8.5	10	18	69.2
Goa	Southwest	104	1.7	0.094	2.7	2	9	69.5
Karnataka	Southwest	300	4.9	0.482	13.6	8	18	89.4
Kerala	Southwest	590	9.7	0.527	14.9	8	17	81.0
Tamil Nadu	Southeast	1076	17.7	0.694	19.6	8	20	72.5
Puducherry	Southeast	45	0.8	0.063	1.8	4	17	71.5
Andhra Pradesh	Southeast	974	16.1	0.276	7.8	6	12	39.8
Odisha	Northeast	480	7.9	0.132	3.7	5	22	85.2
West Bengal	Northeast	158	2.6	0.156	4.4	19		68.9

Table 4. Estimates of MSY (in tonnes) and status of fish stocks (in parenthesis) in states/UTs along the west coast: (s): sustainable; (r): recovering; (o): overfished; (g): overfishing.

Fish stock	Gujarat and DD	Maharashtra	Goa	Karnataka	Kerala
Anchovies		15 (g)		8303 (s)	36 581 (o)
Black pomfret		2303 (o)	980 (s)	2550 (o)	2824 (s)
Bombayduck	89 637 (r)	36 256 (s)			
Catfishes		15 532 (o)	2947 (r)		353 (r)
Cephalopods	87 933 (r)			29 922 (r)	42 302 (s)
Crabs	23 660 (o)	1352 (o)		3980 (s)	7230 (r)
Croakers			1758 (s)		13 356 (s)
Frigate and bullet tunas	11 625 (o)	4657 (r)		1422 (s)	
Grenadier anchovy		14 492 (r)			
Hilsa shad	1125 (g)	451 (r)			
Horse mackerel		8645 (s)		6768 (s)	6927 (s)
Indian mackerel		36 894 (o)		79 044 (o)	82 089 (s)
Little tunny	3809 (g)	3600 (o)		5989 (s)	12 730 (s)
Lizardfishes	19 212 (o)	2042 (o)	1490 (s)	33 143 (s)	
Non-penaeid prawns		78 285 (r)			
Oil sardine		19 941 (o)	79 009 (o)	115 384 (r)	288 207 (s)
Other carangids		8246 (r)	19 828 (s)		23 588 (s)
Other clupeids	7071 (o)	6382 (o)	2430 (s)	7072 (o)	11 153 (o)
Other perches	25 668 (o)	1093 (o)		20 961 (o)	12 730 (o)
Other sardines			13 564 (s)	11 520 (o)	28 975 (s)
Penaeid prawns	43 303 (o)	39 900 (o)	5347 (r)	19 825 (s)	30 296 (o)
Rays	1908 (o)	1058 (r)		608 (s)	
Ribbonfish	125 412 (o)	19 077 (r)	4336 (r)	29 015 (r)	37 022 (r)
Rockcods				12 631 (r)	7833 (s)
Scads		1401 (o)		32 622 (o)	56 437 (o)
Seerfish	8107 (s)	7126 (s)		7721 (r)	10 674 (r)
Sharks	12 861 (r)	12 604 (s)		1293 (s)	4207 (o)
Silver pomfrets	11 561 (o)	7524 (r)		917 (o)	2339 (s)
Silverbellies		715 (r)		6436 (r)	7340 (s)
Skipjack tuna					1256 (g)
Soles	11 070 (o)	4041 (o)		14 955 (s)	26 450 (s)
Spotted seerfish	6533 (r)	6461 (s)		921 (s)	411 (g)
Threadfin breams	39 517 (o)			59 122 (o)	
Thryssa	9750 (o)	1662 (o)	1875 (s)	9150 (s)	
Wolf herring	6948 (o)				

Northwest coast

The northwest coast covers 38.6% of the total coastline, with 1.12 million tonnes as the average annual marine fish harvest contributing 31.6% towards the total national production. The marine fish harvest along the northwest coast is from the maritime states of Gujarat (65.8%), Maharashtra (26.9%), and UT of Daman Diu (7.3%). Nearly 93.3% of the harvest from this region is by mechanized fishing vessels, whereas 6.5% is by outboard fishing vessels and only 0.2% by non-mechanized fishing crafts. Assessment of 48 fish stocks in the region was done, of which 20 are of Gujarat and Daman Diu and 28 are of Maharashtra. These assessed fish stocks covered 56.9 and 69.2%, respectively, of the total marine fish harvest from these states (Table 3).

The Kobe plot (Figure 1a) shows that in Gujarat and Daman Diu, out of the 20 fish stocks assessed, 13 are overfished, two are with overfishing status, four are recovering, and only one is in a sustainable status. Crabs, frigate and bullet tunas, lizardfishes, other clupeids, other perches, penaeid prawns, rays, ribbonfish, silver pomfrets, soles, threadfin breams, Thryssa, and wolf herring are the overfished stocks. Five fishing gears together accounted for 63.5–99.9% of the harvest of the overfished stocks in Gujarat and Daman Diu (Table 6) and were considered for determining the required reduction in fishing hours to enhance the stock biomass of overfished stocks. It was estimated that the total annual fishing hours of mechanized multiday trawlnets has to be reduced by 44% to rebuild the biomass of overfished stocks to a sustainable level.

The Maharashtra Kobe plot (Figure 1b) indicates that five fish stocks are sustainable, one is in an overfishing status, nine are recovering, and 13 are overfished (black pomfret, catfishes, crabs, Indian mackerel, little tunny, lizardfishes, oil sardine, other clupeids, other perches, penaeid prawns, scads, soles, and Thryssa). Five fishing fleets in Maharashtra together harvest 84.9–99.6% of the overfished stocks (Table 7) and were considered for determining the required percentage reduction in total annual fishing hours. The analysis indicates that to rebuild the biomass of the overfished stocks in Maharashtra, a 50% reduction in total annual fishing hours of mechanized multiday trawlers and a 7% reduction in total annual fishing hours of mechanized dolnets are necessary.

Southwest coast

The southwest coast covers 16.4% of the total coastline, and the average annual marine fish harvest from the region is 1.10 million

Table 5. Estimates of MSY (in tonnes) and status of fish stocks (in parenthesis) in states/UTs along the east coast: (s): sustainable; (r): recovering; (o): overfished; (g): overfishing.

Fish stock	West Bengal	Odisha	Andhra Pradesh	Tamil Nadu	Puducherry
Anchovies		5441 (r)			
Barracudas				17 822 (s)	1804 (o)
Black pomfret			9115 (r)		
Black pomfrets				1747 (s)	
Bombayduck		4967 (o)	2365 (s)		
Catfishes	15 466 (o)	12 653 (o)			1321 (o)
Cephalopods				32 954 (o)	
Crabs	2193 (o)	3734 (o)		20 347 (s)	
Croakers	24 827 (s)	45 885 (r)		15 608 (s)	1723 (o)
Frigate and bullet tunas					683 (o)
Goatfishes		8356 (r)		12 730 (o)	1014 (o)
Grenadier anchovy	13 102 (s)		510 (s)	1352 (s)	
Hairfin anchovies	6879 (s)	6328 (s)			
Hilsa shad	51 101 (o)				
Horse mackerel		4289 (o)	6491 (o)		
Indian mackerel		12 736 (o)	41 375 (r)	21 210 (g)	
Leatherjackets		3040 (r)			
Little tunny		1108 (r)	9248 (r)	9765 (r)	538 (r)
Lizardfishes		3872 (r)	5564 (o)	9722 (r)	989 (o)
Non-penaeid prawns		8301 (o)	5329 (r)	4554 (s)	
Oil sardine				155 082 (r)	7992 (s)
Other carangids	933 (s)			26 409 (s)	2417 (o)
Other clupeids	16 952 (s)	18 078 (o)		17 289 (s)	2463 (o)
Other perches	3234 (s)	4103 (o)		25 737 (r)	1427 (o)
Other sardines	4794 (s)	15 648 (r)		109 573 (o)	8565 (r)
Penaeid prawns	36 187 (o)	49 328 (r)	28 106 (o)	31 492 (s)	3509 (o)
Pig-face breams				17 392 (r)	
Rays		1705 (s)	7103 (r)	13 642 (s)	2039 (o)
Ribbonfish	10 981 (s)	28 575 (r)	26 978 (s)	14 310 (s)	1018 (o)
Rockcods			609 (r)		
Scads		1093 (s)	6632 (r)	22 405 (r)	
Seerfish		2789 (s)		24 938 (s)	1126 (o)
Sharks	2784 (r)	2226 (s)	4929 (s)	6728 (s)	115 (s)
Silver pomfrets	13 545 (r)	4630 (s)	5847 (r)	4085 (r)	
Silverbellies	14 009 (r)	5763 (r)			8256 (r)
Skipjack tuna			4100 (o)	3616 (o)	
Soles	8038 (o)	6660 (r)	2255 (r)		208 (s)
Spotted seerfish	8203 (s)		4089 (o)	963 (g)	
Threadfin breams				11 161 (o)	1668 (o)
Threadfins		603 (s)			
Thryssa	7720 (r)	3045 (o)		11 125 (s)	1129 (o)
Wolf herring	10 532 (s)				

tonnes accounting for 31.1% of national production. On the southwest coast, 8.5% of the marine fish harvest is from Goa, 43.7% is from Karnataka, and 47.8% is from Kerala. A major portion of the harvest from this region is by mechanized fishing crafts (75.7%), and the remaining by motorized fishing crafts (21.8%) and non-mechanized country crafts (2.5%). Modelling and assessment of 62 fish stocks of the maritime states in the southwest region were carried out, of which 11 were from Goa, 26 were from Karnataka, and 25 from Kerala (Table 3).

In Goa, the Kobe plot (Figure 1c) shows seven fish stocks as sustainable, three as recovering, and the remaining one as overfished (oil sardine). The Kobe plot for Karnataka (Figure 1d) revealed that 12 fish stocks were in sustainable status, eight were overfished, and six were recovering in 2016. The fish stocks with overfished status were black pomfret, Indian mackerel, other clupeids, other perches, other sardines, scads, silver pomfrets, and threadfin breams. The five major fishing fleets together account for 75.8–99.0% of the harvest of overfished stocks (Table 8). A 62% reduction in total annual fishing hours of mechanized multiday trawlnets is necessary to rebuild the biomass of the overfished stocks to sustainable levels.

For Kerala state, the Kobe plot (Figure 2a) indicated that in 2016, 13 fish stocks were sustainable, six stocks were overfished, four stocks were recovering, and two stocks were in overfishing status. Anchovies, other clupeids, other perches, penaeid prawns, scads, and sharks were the overfished stocks. The five major fishing fleets together harvest 78.2–94.6% of the overfished stocks (Table 9). Based on this, a reduction in total annual fishing hours of mechanized multiday trawlnets by 34%, outboard ringseines by 43%, and mechanized multiday hooks and lines by 27% to enhance the biomass of overfished stocks in Kerala to sustainable levels is recommended.

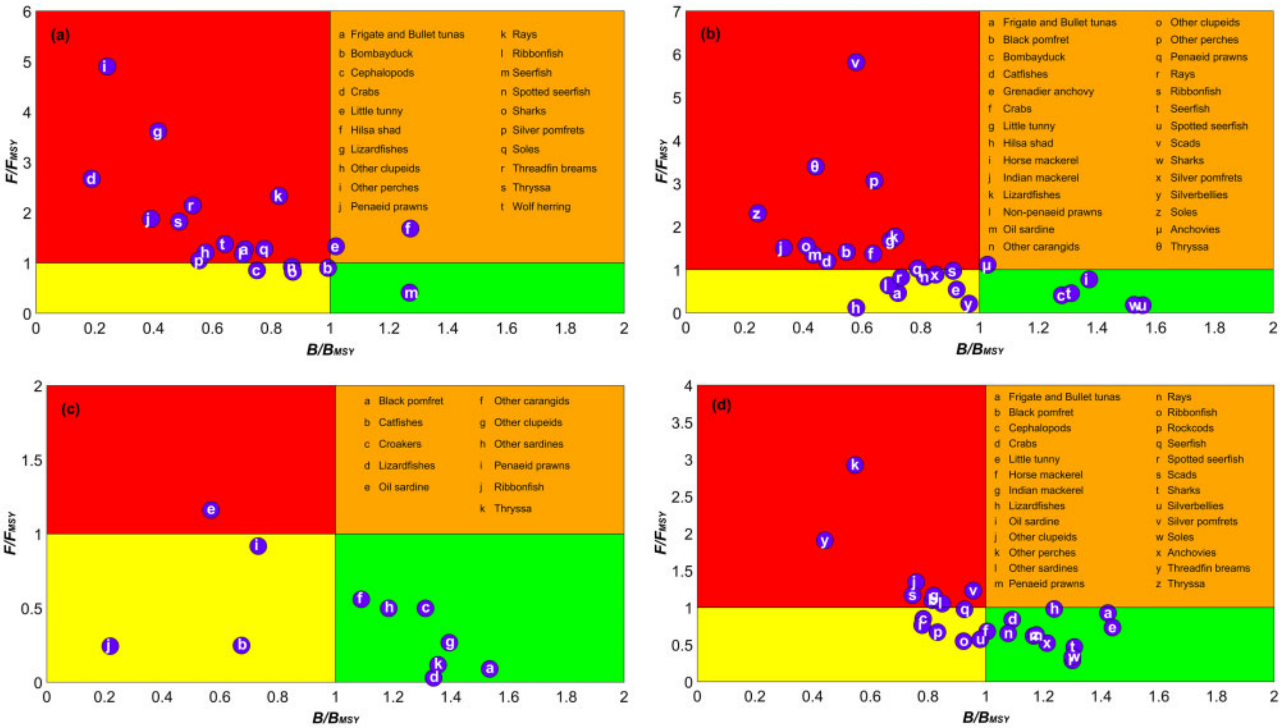

Figure 1. Kobe plot showing stock status of (a) 20 fish stocks in Gujarat and Daman Diu, (b) 28 fish stocks in Maharashtra, (c) 11 fish stocks in Goa, and (d) 26 fish stocks in Karnataka.

Table 6. Harvest percentage of overfished stocks in Gujarat and Daman Diu by the five major fishing fleets (MDTN: mechanized multiday trawlnets, MGN: mechanized gillnets, OBGN: outboard gillnets, and MDOL: mechanized dolnet).

Fish stock	MDTN	MGN	OBGN	MTN	MDOL	Total
Crabs	77.4	1.1	1.8	2.9	7.7	90.9
Frigate and bullet tunas	3.8	27.5	55.1	0.3	0.0	87.0
Lizardfishes	98.4	0.2	0.6	0.3	0.4	99.9
Other clupeids	39.8	9.3	9.0	0.3	5.1	63.5
Other perches	87.3	2.9	1.2	0.3	4.4	96.1
Penaeid prawns	64.4	0.2	0.0	3.8	26.0	94.4
Rays	46.3	12.6	4.6	0.2	6.8	70.5
Ribbonfish	85.9	0.2	1.7	2.7	8.7	99.2
Silver pomfrets	27.0	35.4	7.7	0.5	10.7	81.3
Soles	65.7	1.2	6.0	5.7	19.5	98.1
Threadfin breams	99.4	0.1	0.0	0.1	0.3	99.9
Thryssa	63.1	1.2	15.4	7.2	11.8	98.7
Wolf herring	33.1	7.6	29.8	1.3	1.0	72.8
Estimated effort reduction (%)	44.0	0	0	0	0	

Table 7. Harvest percentage of overfished stocks in Maharashtra by the five major fishing fleets (MDTN: mechanized multiday trawlnets, MGN: mechanized gillnets, MPS: mechanized purse seines, OBGN: mutboard gillnets, and MDOL: mechanized dolnet).

Fish stock	MDTN	MGN	MPS	MTN	MDOL	Total
Black pomfret	30.3	34.2	21.5	5.2	8.4	99.6
Catfishes	24.0	19.4	42.9	3.3	8.4	98.0
Crabs	57.0	2.8	0.1	9.6	20.2	89.7
Indian mackerel	18.3	13.5	59.6	2.4	0.4	94.2
Little tunny	6.9	30.1	59.5	0.1	0.7	97.3
Lizardfishes	96.1	0.4	0.0	3.1	0.0	99.6
Oil sardine	3.6	1.2	80.0	1.1	0.3	86.2
Other clupeids	9.6	50.4	6.2	1.6	28.0	95.8
Other perches	75.6	6.2	4.3	2.6	6.9	95.6
Penaeid prawns	76.9	0.2	0.1	8.5	12.1	85.7
Scads	64.0	11.7	18.5	3.7	1.0	98.9
Soles	51.8	1.1	0.1	39.2	6.2	98.4
Thryssa	26.0	23.8	0.1	7.2	26.3	83.4
Estimated effort reduction (%)	50.0	0	0	0	7	

Southeast coast

The maritime states of Tamil Nadu, Andhra Pradesh, and the UT of Puducherry together form the southeast coast which covers 34.5% of the total coastline. The average annual marine fish harvest from this region is 1.03 million tonnes, which is 29.2% of the national total. The state of Tamil Nadu contributes 67.2%, Puducherry 6.1%, and Andhra Pradesh 26.7% of the harvest from the southeast coast. Marine fish harvests by the three broad categories (sectors) from this region are mechanized 68.6%, motorized 27.1%, and non-mechanized 4.3%. The number of fish stocks assessed for the southeast region is 67, of which 28 are of Tamil Nadu, 21 are of Puducherry, and 18 are of Andhra Pradesh; these stocks accounted for 72.5, 71.5, and 39.8%, respectively, of the total fish harvest in these states.

The Kobe plot status of fish stocks of Tamil Nadu in 2016 (Figure 2b) indicated that 14 fish stocks were sustainable, five were overfished, seven were recovering, and two were in overfishing status. The overfished stocks were cephalopods, goatfishes, other sardines, skipjack tuna, and threadfin breams. The five major fishing fleets considered for determining the reduction in fishing effort accounted for 77.5–96.4% of the harvests of the five overfished stocks in Tamil Nadu (Table 10). For enhancing the biomass levels of overfished stocks to sustainable levels, 21 and 30% reduction in total annual fishing hours of mechanized single-day trawlnets and mechanized gillnets, respectively, are required. The Kobe plot for Puducherry (Figure 2c) showed that 15 fish stocks were overfished, three were recovering, and the remaining three were sustainable. The overfished stocks in the UT were barracudas, catfishes, croakers, frigate and bullet tunas, goatfishes, lizardfishes, other carangids, other clupeids, other perches, penaeid prawns, rays, ribbonfish, seerfish, threadfin breams, and Thryssa. The five major fishing fleets together are responsible for 93.6–99.7% of the 15 overfished stocks in Puducherry (Table 11). It is recommended that the total annual fishing hours should be reduced by 62% for mechanized multiday trawlnets, 10% for mechanized single-day trawlnets, and 16% for mechanized gillnets in Puducherry for enhancing the biomass of overfished stocks to sustainable levels. The Kobe status plot of Andhra Pradesh (Figure 2d) indicated that nine were recovering fish stocks, five were overfished, and four were sustainable. Horse mackerel, lizardfishes, penaeid prawns, skipjack tuna, and spotted seerfish were the overfished stocks. In Andhra Pradesh, six types of fishing fleets harvesting 69.8–91.1% of the five overfished stocks (Table 12) were considered for further analysis. Results of the optimum fishing effort analysis showed that a reduction in total annual fishing hours of mechanized multiday *sona* trawlnets, outboard gillnets, and outboard hooks and lines by 42, 39, and 19%,

Table 8. Harvest percentage of overfished stocks in Karnataka by the five major fishing fleets (MDTN: mechanized multiday trawlnets, MPS: mechanized purse seines, OBRS: outboard ringseines, OBGN: outboard gillnets, and MDPTN: mechanized multiday paired trawlnets).

Fish stock	MDTN	MPS	OBRS	OBGN	MDPTN	Total
Black pomfret	40.5	49.8	1.1	0.2	4.4	96.1
Indian mackerel	39.7	43.6	4.5	7.4	1.2	96.4
Other clupeids	21.1	2.1	31.7	18.7	2.2	75.8
Other perches	91.8	3.1	0	0.6	3.4	98.8
Other sardines	41.1	42.7	8.4	4	0.5	96.6
Scads	86.8	8.1	1	0	3.9	99.9
Silver pomfrets	44.4	11.8	1.1	9.6	2.9	69.9
Threadfin breams	87.6	0.0	0.0	0.0	10.7	98.3
Estimated effort reduction (%)	62.0	0	0	0	0	

Table 9. Harvest percentage of overfished stocks in Kerala by the five major fishing fleets (MDTN: mechanized multiday trawlnets, OBRS: outboard ringseines, MHL: mechanized hooks and lines, MRS: mechanized ringseines, and MTN: mechanized single-day trawlnets).

Fish stock	MDTN	OBRS	MHL	MRS	MTN	Total
Anchovies	11.7	62.6	0.0	19.5	0.8	94.6
Other clupeids	6.9	51.6	0.5	17.7	1.6	78.2
Other perches	71.4	13.8	0.6	0.7	0.6	87.2
Penaeid prawns	50.8	13.7	0.0	3.5	17.0	85
Scads	64.4	15.0	0.4	4.5	0.2	84.5
Sharks	6.1	2.2	75.8	0.3	0.1	84.6
Estimated effort reduction (%)	34.0	43.0	27.0	0	0	

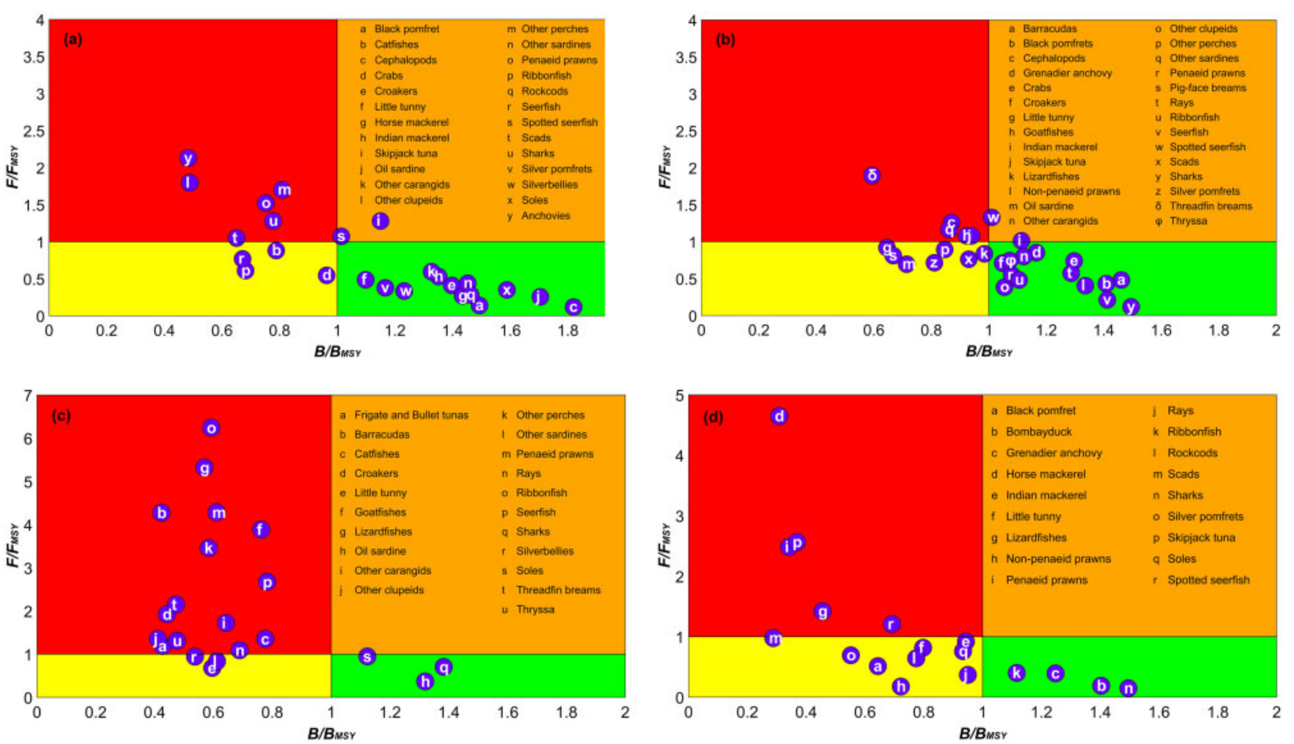

Figure 2. Kobe plot showing stock status of (a) 25 fish stocks in Kerala, (b) 28 fish stocks in Tamil Nadu, (c) 21 fish stocks in Puducherry, and (d) 18 fish stocks in Andhra Pradesh.

respectively, are necessary to rebuild the biomass of overfished stocks to sustainable levels.

Northeast coast

There are two states along the northeast coast, namely Odisha and West Bengal, covering 10.5% of the total coast, with 0.29 million tonnes as the annual average marine fish production (8.1% of the national total). The contribution from Odisha towards the production along the northeast coast was 45.8% and that from West Bengal was 54.2%. Harvest in this region by mechanized fishing vessels was 87.6%, motorized fishing vessels was 8.1%, and by non-mechanized 4.3%. For the two maritime states in the northeast region, a total of 46 fish stocks were assessed, of which 27 were of Odisha and 19 were of West Bengal.

The Odisha Kobe plot (Figure 3a) revealed that out of the 27 fish stocks, 11 were recovering, nine were overfished, and seven were sustainable in 2016. Bombayduck, catfishes, crabs, horse mackerel, Indian mackerel, non-penaeid prawns, other clupeids, other perches, and Thryssa are the overfished stocks demanding effort reduction of fishing fleets harvesting them. The six fishing gears together harvest 77.1–89.5% of the overfished stocks in the state (Table 13). The effort reduction analysis indicated that the total annual fishing hours of mechanized multiday trawlnets in Odisha need to be reduced by 14% to rebuild the biomass of the nine overfished stocks to a sustainable level. The West Bengal Kobe plot (Figure 3b) showed ten stocks as sustainable, four recovering, and five overfished. Catfishes, crabs, Hilsa shad, penaeid prawns, and soles were the overfished stocks. The five major fishing fleets together harvest 91.7–98.7% of the overfished stocks in the state (Table 14). The optimum effort analysis indicates the need for a 24 and 19% reduction in total annual fishing hours by mechanized gillnets and mechanized multiday trawlnets, respectively.

Table 10. Harvest percentage of overfished stocks in Tamil Nadu by the five major fishing fleets (MDTN: mechanized multiday trawlnets, MTN: mechanized single-day trawlnets, MGN: mechanized gillnets, OBGN: outboard gillnets, OBHL: outboard hooks and lines, and MRS: Mechanized ringseines).

Fish stock	MDTN	MTN	MGN	OBGN	OBHL	Total
Cephalopods	41.7	50.6	0.1	1.3	2.7	96.4
Goatfishes	25.2	59.0	0.0	11.1	0.4	95.8
Other sardines	6.6	55.8	0.0	15.9	0.0	78.4
Skipjack tuna	0.6	2.0	68.9	1.9	4.1	77.5
Threadfin breams	33.9	52.9	0.0	6.2	1.5	94.5
Estimated effort reduction (%)	0	21.0	30.0	0	0	

Table 11. Harvest percentage of overfished stocks in Puducherry by the five major fishing fleets (MDTN: mechanized multiday trawlnets, MTN: mechanized single-day trawlnets, MGN: mechanized gillnets, OBRS: outboard ringseines, and MDN: mechanized driftnets).

Fish stock	MDTN	MTN	MGN	OBRS	MDN	Total
Barracudas	87.4	8.5	0.1	0.0	3.7	99.7
Catfishes	85.1	6.7	3.0	0.0	4.1	98.9
Croakers	83.3	9.7	0.0	0.0	2.5	95.4
Frigate and bullet tunas	0.0	0.0	99.7	0.0	0.0	99.7
Goatfishes	64.8	27.3	0.1	0.0	1.4	93.6
Lizardfishes	90.3	8.7	0.0	0.0	0.8	99.8
Other carangids	75.6	15.2	5.2	0.7	0.0	96.7
Other clupeids	95.2	2.8	0.0	0.0	0.0	98.0
Other perches	89.0	6.8	0.0	0.0	0.6	96.4
Penaeid prawns	90.1	6.0	0.0	0.0	1.9	98.0
Rays	78.5	4.7	9.2	0.0	2.0	94.5
Ribbonfish	77.9	16.8	0.1	0.0	1.3	96.1
Seerfish	78.3	9.6	4.8	0.0	5.7	98.4
Threadfin breams	89.0	10.7	0.0	0.0	0.0	99.7
Thryssa	36.9	9.2	0.0	48.6	0.0	94.7
Estimated effort reduction (%)	62.0	10.0	16.0	0	0	

Ratio relationships

The national level relationships among ratios of biomass, fishing pressure, and fish catch (Figure 4) agree with the general concepts of fisheries. The geometric mean of biomass ratio B/B_{MSY}, which was initially very low (0.5), had a steady increase during 2004–2012 and declined thereafter. The fishing pressure ratio F/F_{MSY} remained almost steady (between 0.5 and 0.6) in the initial years, and thence showed an upward trend from 2012 onwards, which coincides with the decrease in the biomass ratio. The average (all stocks/all states/20 years) B/B_{MSY} ratio was 0.86. The C/C_{max} ratio showed an increasing trend, but remained below 0.5 in all the years, indicating increasing fishing pressure on the fish stocks.

Discussion

Most capture fisheries extract more from the sea than can be replaced by reproduction and growth of the exploited species (Pauly *et al.*, 1998; Grainger, 1999; Watson and Pauly, 2001). This phenomenon of overfishing is quite widespread throughout the world, and its main cause is the excessive number of fishing boats and the excessive number of hours they spend fishing. Controlling fishing effort in a multispecies multigear context is extremely

Table 12. Harvest percentage of overfished stocks in Andhra Pradesh by the six major fishing fleets (MDSOTN: mechanized multiday sona trawlnets, MDTN: mechanized multiday trawlnets, OBGN: outboard gillnets, MBSGN: mechanized bottom set gillnets, OBHL: outboard hooks and lines, and IBBSGN: inboard bottom set gillnets).

Fish stock	MDSOTN	MDTN	OBGN	MBSGN	OBHL	IBBSGN	Total
Horse mackerel	20.5	8.5	18.9	0.0	21.6	0.3	69.8
Lizardfishes	59.1	25.7	6.2	0.0	0.0	0.1	91.1
Penaeid prawns	49.5	27.9	1.5	0.0	0.0	1.3	80.2
Skipjack tuna	0.5	0.3	0.0	38.2	8.7	30.7	78.4
Spotted seerfish	31.8	16.1	14.7	0.0	7.1	2.6	72.3
Estimated effort reduction (%)	42.0	0	39.0	0	19.0	0	

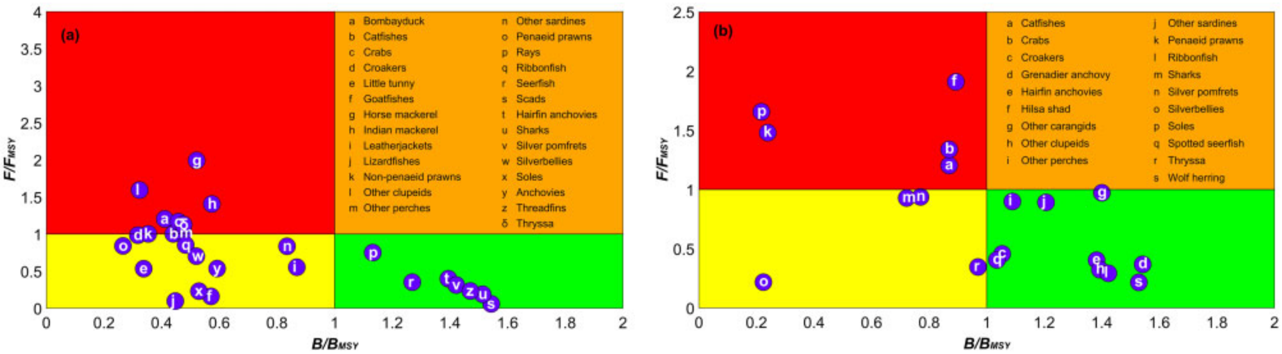

Figure 3. Kobe plot showing stock status of (a) 27 fish stocks in Odisha and (b) 19 fish stocks in West Bengal.

Table 13. Harvest percentage of overfished stocks in Odisha by the six major fishing fleets (MDTN: mechanized multiday trawlnets, OBGN: outboard gillnets, IBDN: inboard driftnets, OBRS: outboard ringseines, OBHL: outboard hooks and lines, and OBDN: outboard driftnets).

Fish stock	MDTN	OBGN	IBDN	OBRS	OBHL	OBDN	Total
Bombayduck	86.8	0.0	0.0	0.0	0.0	0.2	87.1
Catfishes	37.5	1.2	11.7	0.0	21.6	5.1	77.1
Crabs	74.1	11.5	0.2	0.0	0.0	0.1	86.0
Horse Mackerel	51.8	6.8	16.7	0.6	0.3	13.3	89.5
Indian mackerel	30.7	15.5	0.6	32.1	0.0	0.8	79.6
Non-penaeid prawns	84.3	0.0	0.0	0.0	0.0	0.1	84.4
Other clupeids	49.6	9.2	13.0	3.7	0.1	9.3	84.8
Other perches	66.6	1.8	1.1	0.0	13.5	0.9	83.9
Thryssa	73.9	7.0	0.6	1.1	0.0	0.0	82.6
Estimated effort reduction (%)	14.0	0	0	0	0	0	

Table 14. Harvest percentage of overfished stocks in West Bengal by the five major fishing fleets (MDTN: mechanized multiday trawlnets, MGN: mechanized gillnets, IBBN: inboard bagnets, MBN: mechanized bagnets, and MHL: mechanized hooks and lines).

Fish stock	MDTN	MGN	IBBN	MBN	MHL	Total
Catfishes	20.3	58.7	0.4	0.3	12.4	92.1
Crabs	44.2	0.0	47.6	3.3	0.0	95.1
Hilsa shad	2.5	96.2	0.0	0.0	0.0	98.7
Penaeid prawns	75.8	1.1	10.9	3.9	0.0	91.7
Soles	70.7	0.0	17.1	7.2	0.0	94.9
Estimated effort reduction (%)	19.0	24.0	0	0	0	

difficult and is the very area where fisheries management in the tropics often fails. Out of the 223 Indian fish stocks of 41 marine fishery resources (species/species groups) assessed, 20.6% are from the northeast region, 30.1% from the southeast region, 27.8% from the southwest region, and 21.5% from the northwest region. These fish stocks accounted for nearly 70% of the total marine fish harvest in India. The consolidated assessment results indicate that 34.1% of the assessed fish stocks in the country are sustainable, 36.3% are overfished, 26.5% are recovering, and 3.1% are in overfishing status (Figure 5). The highest percentage of sustainable fish stocks were in Goa, West Bengal, and Kerala (63.6, 52.6, and 52.0%, respectively), the highest percentage of overfished stocks were in Puducherry, Gujarat and Daman Diu, and Maharashtra (71.4, 65.0, and 46.4%, respectively), and the highest percentage of recovering fish stocks were in Andhra Pradesh, Odisha, and Maharashtra (50.0, 40.7, and 32.1%, respectively). At a regional level, the percentage of sustainable fish stocks was more along the southwest coast (51.6%), overfished stocks were more along the northwest coast (54.2%), and recovering fish stocks were more along the northeast coast (32.6%).

In 2017, among the FAO's 16 Major Fishing Areas, the Mediterranean and Black Sea (Area 37) had the highest percentage (62.5%) of stocks fished at unsustainable levels, followed by the Southeast Pacific 54.5% (Area 87) and Southwest Atlantic 53.3% (Area 41) (FAO, 2020). In contrast, the Eastern Central Pacific (Area 77), Southwest Pacific (Area 81), Northeast Pacific (Area 67), and Western Central Pacific (Area 71) had the lowest proportion (13–22%) of stocks fished at biologically unsustainable levels. According to the same report, between 60 and 70% of the fish stocks are fished sustainably in the Indian Ocean region, although details of assessments are not available. Regional assessments of fish stock status such as this study help us to understand where we need to manage better and also help to make global assessments.

The consolidated biomass, effort, and catch ratios indicate the poor status of the Indian national fish stocks after 2011, with a steep increase in effort and decrease in biomasses and catch. The average B/B_{MSY} ratio was 0.86, below that estimated for other Asian countries which also have multispecies and multigear fisheries. For example, the average B/B_{MSY} was reported as 1.16 in China, 1.08 in Indonesia, 0.90 in the Republic of Korea, and 1.94 in Bangladesh (Costello *et al.*, 2016). However, the scientific rigour of the assessment methodology used is not uniform. The uncontrolled increase in effort has had a serious effect on biomass, and that is the reason why this study has recommended a decrease in effort in many of the fisheries investigated. Fortunately, nearly 30% of the stocks are in recovering status and can be made sustainable by reducing fishing pressure. The recent National Policy on Marine Fisheries (GOI-NPMF, 2017) highlights the need for stricter scientific and participatory management of marine fisheries. The need for breaking down the area of management into smaller units (zonal management) has also been highlighted by Mohamed *et al.* (2018).

The national biomass ratios show a steady increase from 1997 to 2011 without much change in effort. Much of India's marine

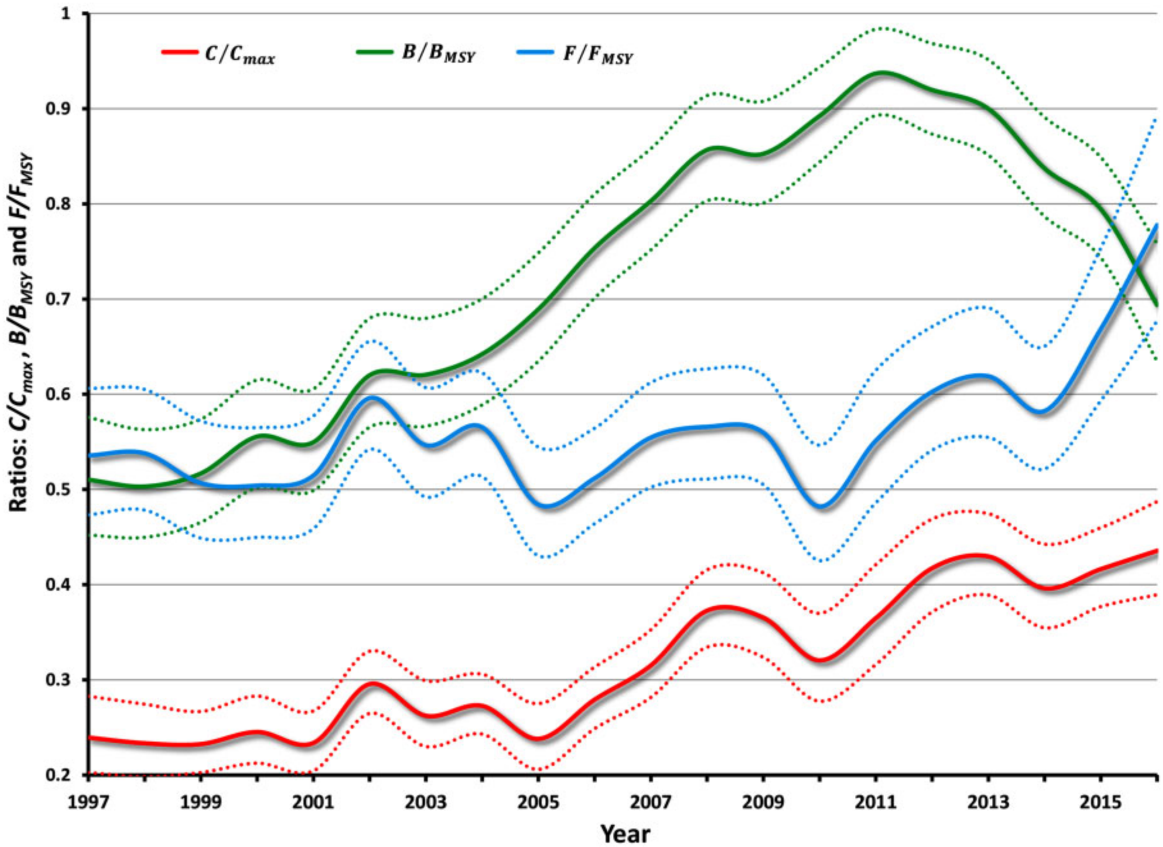

Figure 4. Trend in annual mean ratios of biomass (B/B_{MSY}), fishing mortality (F/F_{MSY}), and fish catch (C/C_{max}).

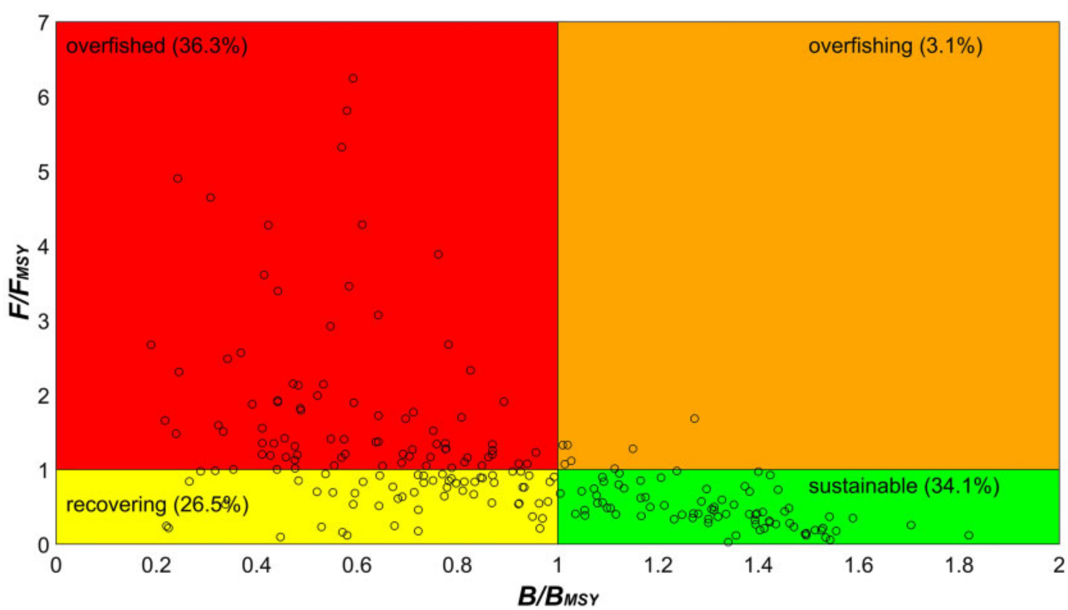

Figure 5. Kobe plot indicating the stock status of 223 fish stocks in India.

fisheries have seen a continuous expansion of fishing grounds to deeper areas (within the continental shelf) as the inshore resources get depleted (Zacharia *et al.*, 1996; Devaraj and Vivekanandan, 1999). Besides, there has been a manifold increase in fishing efficiency due to the adoption of new technologies (Gopal and Edwin, 2013). From 2011, a steep increase in the effort ratio does not see a parallel increase in biomass and catch. This indicates that currently a limit to expansion has been reached, and it remains to be seen whether fishers, with or without the aid of the Government, will again innovate to circumvent this block.

The high percentage (54.2%) of overfished stocks along the northwest coast can be because of the very high number of fishing vessels in the states of Gujarat and Daman Diu and Maharashtra and the consequent fishing pressure on the resources. The number of mechanized fishing vessels in this region together accounts for nearly half (49.7%) of the national total (CMFRI-FSI-DoF, 2020). Besides, the mechanized multiday trawlnet fleet accounts for the harvest of the majority of overfished stocks. On the other hand, the southwest coast, particularly Kerala, has a high percentage (52%) of sustainable fish stocks, and this could be because of the recent regulations to curtail overcapacity and overfishing (Mohamed, 2017).

The national-level data on landings during 2014–2016 reveals that among the fish stocks examined, stocks of the top five resources with a maximum contribution towards total landings are oil sardine (*Sardinella longiceps*), Indian mackerel (*Rastralliger kanagurta*), other sardines (*Sardinella gibbosa*, *Sardinella fimbriata* etc.), penaeid prawns (*Metapenaeus* spp., *Parapenaeopsis* spp., *Penaeus* spp. *etc.*), and ribbonfish (*Trichiurus lepturus*), in order of importance. Commercial exploitation of oil sardine stocks is confined mainly to the southern states, and its consumption is restricted to the southwest region. In the present study, 0.288 million tonnes is the MSY estimate for oil sardine in Kerala from where the major portion of oil sardine is harvested. An earlier study, based on spectral models using long time-series data on landings during 1950–1992, predicted 2010–2011 as years of peak landings of oil sardine in India (Sathianandan and Alagaraja, 1998). In the years 2011 and 2012, the harvest of oil sardine in Kerala was 11.8 and 38.7%, respectively, above the MSY, which is suspected to be one of the reasons, besides climatic factors (Kripa *et al.*, 2018; Rohit *et al.*, 2018), for the drastic reduction in abundance and availability in the fishery thereafter. Conversely, the results of the current study indicated higher biomass levels in 2016, labelling oil sardine as sustainable in Kerala. More valid conclusions regarding the status of oil sardine stocks, which is of a highly fluctuating nature, can be obtained if we use biomass dynamics models with climatological and hydrological parameters as its components.

In this large, complex multispecies multigear fishery, though there are 20 different types of fishing fleets harvesting the overfished stocks in ten maritime states/UTs, recommendations are made only for nine types of fishing fleets. Reduction in fishing hours is recommended to build up the biomass of the overfished stocks. The classic theory of fishing holds that the biomass of fish stocks primarily depends on fishing pressure; for stocks to be at or above the abundance that would produce MSY (B_{MSY}), fishing pressure or mortality (U) must be reduced to U_{MSY} (Hilborn *et al.*, 2020). Because the major concern has been about stocks at low abundance, globally many management actions have been aimed at rebuilding overfished stocks.

This study shows that many stocks, which previously were in an abundant or sustainable category, are now overfished (Kobe phase plot trajectories—not shown). The number of stocks in the overfishing category is very low (3–6%), indicating that the transition from sustainable to overfished happens very rapidly. Stock status appears to change rapidly with time in the tropics (Mohamed and Veena, 2016). In many of the local, small, tropical, short-lived species, short-term fluctuations are not significant, even if caused by excessive fishing pressure. Small and short-lived species could recover fast (1–5 years), but in the case of large and long-lived species, recovery time (5–10 years) is prolonged (Mohamed and Veena, 2016). Over the past decades, an increasing number of studies have reported recoveries of depleted marine populations and degraded ecosystems, and there have been significant advances in understanding recoveries in the ocean (Lotze *et al.*, 2011). Ten years was sufficient for recovery among the 153 overfished stocks (those depleted below 0.5 B_{MSY}), but not for stocks driven to collapse (below 0.2 B_{MSY}), which had longer and more variable recovery times (Hilborn *et al.*, 2020). Stricter management and improved governance have enabled the rebuilding of some fish populations (Rosenberg *et al.*, 2006; Worm *et al.*, 2009).

The biomass dynamics modelling study carried out on 223 fish stocks of 41 marine fishery resources of India under a multigear and multispecies fishery situation revealed that 79 fish stocks of 35 resource groups are overfished, and it is necessary to reduce the total annual fishing hours of nine different categories of fishing fleets harvesting marine fishery resources in the country by varying levels.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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Data availability

The entire data set used for the study is from the database—National Marine Fishery Resources Data Centre of Central Marine Fisheries Research Institute (under the Indian Council of Agricultural Research, Ministry of Agriculture and Farmers Welfare, Government of India). As a national (government) database, there are restrictions on its availability in the public domain.

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