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Evaluation of the Status of Frigate Tuna *Auxis thazard* (Lacepède, 1800) Fishery in the Tamil Nadu Coast of India

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Abstract

The frigate tuna *Auxis thazard* (Lacepède, 1800) is one of the commercially important tuna species that contribute a major share to tuna fisheries of Tamil Nadu. Information on biological reference points and stock status is necessary for effective fishery management. Hence, a stock assessment study was carried out to understand the status of the stock. The present study was used the Catch and Effort Data Analysis (CEDA) software to investigate stock dynamics by running surplus production models with catch and effort data. Reconstructed time series catch and effort data from 1998 to 2018 were used for the study. Annual landings fluctuated between 555 and 2,523 metric tonnes (MT) with an average catch of 1,732 MT year^{-1}. Based on the diagnostic graph, high R^2 and low root mean square error (*RMSE*) value, the Fox log-normal model was selected as the best-fit model for further analysis of biological reference points (BRPs). The best-fitted Fox log-normal model estimated maximum sustainable yield (*MSY*), biomass yield *MSY* (B_{MSY}) and fishing mortality yield *MSY* (F_{MSY}) as 2,543 MT, 3,723 MT and 0.69 MT, respectively. F_{MSY} and B_{MSY} values were compared with current fishing mortality (*F*) and biomass (*B*). A lower F/F_{MSY} value (0.41) and higher B/B_{MSY} value (1.66) indicated that the frigate tuna stock of Tamil Nadu has not reached to overfishing or overfished status. However, an overall reduction trend of catch per unit effort (*CPUE)* since 2012 indicates that stock is exploited very close to *MSY*. Results from the BRPs showed that the frigate tuna resource off Tamil Nadu were optimally exploited and an increase in effort will lead to the collapse of the fishery in future. Hence, it is recommended to maintain the fishing effort to the present level for ensuring sustainable exploitation.

Key words: Biological reference points; Catch and effort data analysis; Maximum sustainable yield; Stock exploitation; Tuna stock assessment.

1. Introduction

The sustainable development of marine fisheries is an important activity from a social, environmental and economic view. Total catch is an important metric for monitoring and assessing the status of a fishery (George and Gopalakrishnan, 2013). India's fisheries have long been accessible to the public, with limited control, leading to unsustainable

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expansion and development (Devaraj and Vivekanandan, 1999; Satyanarayana *et al*., 2008; Bhathal, 2014; Ansell, 2020). Tamil Nadu is the southeastern maritime state of India, where marine and inland fish production has steadily increased (Tabitha and Gunalan, 2012). Tamil Nadu's marine fisheries have proliferated since 1950, due to the introduction of innovative fishing vessels, new fishing gear, fishing methods and infrastructural facilities. This rapid growth in exploitation resulted in an increased fish catch.

In fisheries management, the concept of sustainable development is always the baseline. However, sustainable management of these renewable but exhausting natural fish stocks is challenging. Most of the world's fishing is biologically and economically unsustainable, much against the belief that fish stocks are inexhaustible (FAO, 1994). Because of the intensive fisheries and the dramatic collapse of fish stocks in India, alarming calls were made to reduce the size of the fishing fleet and fishing efforts. In this context, Tamil Nadu is not an exception. With the large influx of giant mechanized fishing crafts and gears over the years, Tamil Nadu has also seen notable progressions in fishing technology.

More than 80% of the world's marine fish stocks are overexploited or almost fully exploited due to their high nutritional value, local market demand and export demand (Kituyi and Thomson, 2018). India's tuna fisheries are in the initial stages of exploitation due to the adoption of advanced fishing gear (Lecomte *et al*., 2017). Tuna landings contribute 2.93% of India's total marine fish landings (CMFRI, 2019). Tamil Nadu holds the second rank in total tuna production in the country, next to Kerala (CMFRI, 2018). Information on the stock assessment of coastal tuna is limited (Silas *et al*., 1985, James *et al*., 1987; Kasim and Mohan, 2009; Sivadas *et al*., 2020) and less information is available on the tuna fishery of Tamil Nadu (Joseph and Jayaprakash, 2003; Abdussamad *et al*., 2008; Kumar *et al*., 2019; Sivadas *et al*., 2019). Frigate tuna *Auxis thazard* (Lacepède, 1800) is one of the most important neritic tuna species in Indian waters. They live closer to the continental shelf and do not undertake transoceanic migrations (Lecomte *et al*., 2017). *Auxis* spp. contributed 11.9 and 13.1 % of total tuna landings in India and Tamil Nadu, respectively (CMFRI, 2019). Ghosh *et al*. (2012), Mudumala *et al*. (2018) and Dan (2021) provided some information on biological reference points (BRPs) of frigate tuna fishery from Indian waters. However, there is no record of BRPs of frigate tuna stock off the Tamil Nadu coast. Hence, the present study made an attempt to investigate the sustainability status of frigate tuna fisheries off Tamil Nadu.

In India, the Department of Animal Husbandry, Dairy and Fisheries (DADF) submits national fish catch statistics to international organizations such as the FAO. The DADF collects information from the state fisheries departments and central institutes, namely the Central Marine Fisheries Research Institute (CMFRI) and the Fishery Survey of India (FSI) (Malhotra and Sinha, 2007). CMFRI publishes group-wise landing data every year, but there is no record of species-wise landing data (CMFRI, 2019). The effort used for the Indian fishery is not available in any public domain. Hence present study attempted to reconstruct the catch and effort data of frigate tuna from 1998 to 2018. This reconstructed catch and effort data from 1998 to 2018 were utilized to understand the dynamics of tuna fishery and the stock status of frigate tuna fisheries off Tamil Nadu.

2. Materials and methods

The catch and effort statistics of frigate tuna from 1998 to 2018 (21 years) were reconstructed using the handbook of Fisheries Statistics (CMFRI, 2006; 2010; 2011; 2012a; 2012b; 2013; 2014; 2015; 2016; 2017; 2018; DADF, 2009; 2012; 2015; 2018) as well as several other historical fisheries survey reports and State Government reports (GOT, 2004; 2005; 2006; 2010; 2011; 2012; 2013; 2014; 2015; 2016; 2017; 2018; 2019; 2020) following Bhathal (2014). The fishing effort and annual total catch were estimated as million horsepower (HP) days and metric tonnes (MT), respectively. Statewise and species-wise fish landing data was not available for frigate tuna landings of Tamil Nadu during the study period. Catch data of the frigate tuna fishery of Tamil Nadu from 1998 to 2005 was taken from Bhathal (2014). Landing data of frigate tuna from 2006 to 2012 was reconstructed by converting groupwise neritic tuna landing data (DADF, 2012) to species-wise based on the composition of neritic tuna landings (MOA, 2001). Landing data from 2013 to 2018 was collected from CMFRI (2013; 2014; 2015; 2016; 2017; 2018). In Tamil Nadu waters, tunas were harvested with drift gillnets of mesh size of 120-140 mm and net pieces of 40-50 (98.75%), long lines with a hook size of 4 to 8 (0.75%), trawl nets (0.42%) and handlines (0.08%) (Kumar *et al*., 2018; 2019). The first step in the rebuilding of the fishing effort was to collect data (number of boats, fishing days and gear category) from national and state Government documents, research articles, fisheries survey reports, grey literature and databases between 1998 and 2018 (GOT, 2006; 2010; 2011; 2012; 2013; 2014; 2015; 2016; 2017; 2018; 2019; 2020; CMFRI, 2010; 2011; 2012; 2013; 2014; 2015; 2016; 2017; 2018; CMFRI, 2006; 2012a; Bhathal, 2014).

Data were collected and formalized with the essential elements such as vessels with and without engines, including the total number of vessels, total power (HP units), fishing days and crew size (Abinaya and Sajeevan, 2022a). Fishing effort for vessels without engines (HP days) was estimated by integrating the number of vessels, crew size and fishing days. An average crew size of 8 was used to reconstruct the effort of a vessel without an engine (non-mechanized and non-motorized) from 1998 to 2018 following Bhathal (2014). The fishing effort of mechanized and motorized vessels was calculated using the average engine power of vessels with an estimated number of fishing days by each gear sector at a given time. The number of fishing days was calculated assuming that six fishing days were carried out each week of the year. Downtime and spiritual holidays were subtracted from the total number (6 multiplied by the number of weeks in a year) to calculate the actual fishing days. The average number of days spent for fishing with gillnets, liners and hand lines, and trawl nets were 216, 75 and 228 days, respectively. To accommodate variations and differences in fishing power and efficiency, the nominal effort was corrected to a standard type (Bhathal, 2014).

Different approaches have been used to estimate the biological characteristics (MSY, B_{MSY} and F_{MSY}) of species. The ordinary least squares method estimated surplus production functions, especially the Schaefer model, the Fox model, the Schnute model, and the Clark, Yoshimoto and Pooley (CY & P) model (Sin and Yew, 2016). The Schnute Model and the CY & P models have limited use in tropical areas as they were developed for long-lived species (Sparre and Venema, 1998; Lindawati *et al*., 2021). Hence, the biological parameters were evaluated in the present study using the Fox (1970), Schaefer (1954), and Pella-Tomlinson (1969) models.

Reconstructed time series of catch and effort data of frigate tuna fishery was analyzed using the fishery-specific computer program Catch and Effort Data Analysis version 3.1 (CEDA) (MRAG, 2016). CEDA is built to carry out the stock assessment in data-deficient fisheries like the frigate tuna fisheries of Tamil Nadu. CEDA used analytical techniques to support and help stock assessments, resulting in a prediction of current population size, either in numbers or biomass and a better estimate of fishing mortality, by correlating catches with the size of the population (Hoggarrth *et al*., 2006). Surplus production models (SPMs) used in these assessment tools include three types of non-equilibrium models: Fox, Schaefer and Pella-Tomlinson models with three error assumptions (normal, log-normal and gamma). Schaefer (1954) developed the first surplus production model. Here, the logistic population growth model serves as a basis for the Schaefer model:

$$\frac{dB}{dt} = rB(B_\infty - B) \tag{1}$$

Biological reference points can be calculated from the model parameters

$$MSY = {}^{K\,r}/_{4} \tag{2}$$

$$B_{MSY} = K / 2 \tag{3}$$

$$F_{MSY} = r / 2 \tag{4}$$

$$q = CPUEt / B \tag{5}$$

$$K = n\, 1/(n-1)\; X\; B_{MSY} \tag{6}$$

$$r = n\; X\; F_{MSY} \tag{7}$$

Following that, Pella-Tomlinson (1969) recognized a generalized production equation:

$$\frac{dB}{dt} = rB\left({B_\infty}^{n-1} - B^{n-1}\right) \tag{8}$$

And Fox (1970) proposed a Gompertz growth equation:

$$\frac{dB}{dt} = rB(InB_\infty - InB) \tag{9}$$

where *B*, fish stock biomass; *t*, time in the year; *r*, intrinsic rate of population increase; B_∞ and *K*, carrying capacity; *MSY*, maximum sustainable yield; *q*, catchability coefficient; *CPUE*, catch per unit effort; B_{MSY}, biomass corresponding to *MSY*; F_{MSY}, exploitation rate corresponding to *MSY*; *n*, a parameter that controls the shape of the production curve.

Output parameters of CEDA software were *MSY*, *K*, *B*, in MT, catchability coefficient (*q*) (a scaling term) and *r* (per capita change in the population per unit time). CEDA necessitates an initial proportion (IP) input (starting population size over the maximum catch). The fishery began with a virgin population when the initial proportion is set to zero or close to zero, and with an extensively exploited population when it is set to one or close to one. The present study set the initial biomass (B1) as B1=*K* to assure valid results. The carrying capacity (*K*) is the highest population size, density, or biomass that a given area can sustain (Hartvigsen, 2017). Linear regression analysis was carried out to find out the association between catch and effort and the goodness of fit of models (Hanchet *et al*., 1993). Coefficient of determination(R^2) of the goodness of fit model, results of the diagnostic graph and root mean square error (*RMSE*) (Abinaya and Sajeevan, 2022b) were considered for selecting the results of the Fox log-normal model for further investigation on *MSY*, B_{MSY}, and F_{MSY}.

3. Results

The present study reconstructed catch and effort data of frigate tuna of Tamil Nadu from 1998 to 2018 and presented in Table 1. The average annual landings from 1998 to 2018 was 1,732 MT year^{-1} (Standard deviation (*SD*) =565), with the production in 2001 yielding the lowest catch of 555 MT and the production in 2010 yielding the highest catch of 2,523 MT. From 1998 to 2018, the catch of frigate tuna increased with wide fluctuations. The reconstructed effort data for frigate tuna was stable in the initial periods, then registered a decreasing trend since 2006.

Table 1: Total catch, effort and catch per unit effort (*CPUE*) of frigate tuna fishery from the Tamil Nadu coast (1998-2018)

Year	Total catch (in metric tonnes)	Effort (in million HP days)	*CPUE* (in MT/Hp days)
1998	1434	6.17	0.00023
1999	903	6.33	0.00014
2000	1008	6.33	0.00016
2001	555	6.33	0.00009
2002	1004	6.33	0.00016
2003	1832	6.33	0.00029
2004	1582	6.33	0.00025
2005	1415	4.70	0.00030
2006	1415	18.27	0.00008
2007	1865	17.44	0. 00011
2008	2022	16.54	0. 00012
2009	2501	15.64	0. 00016
2010	2523	16.90	0. 00015
2011	2344	16.97	0.00014
2012	2481	14.13	0.00018
2013	1740	13.26	0.00013
2014	1588	14.46	0.00011
2015	1977	14.79	0.00013
2016	1919	14.79	0.00013
2017	1778	14.87	0.00012
2018	2482	14.62	0.00017

The *CPUE* of frigate tuna in Tamil Nadu from 1998 to 2018 is depicted in Table 1. As shown in Table 1, *CPUE* decreased from 1998 to 2001, then increased and peaked during 2005. After that, the *CPUE* showed a decreasing trend with minimum annual fluctuation.

CEDA mandates an initial proportion (IP) that yields trustworthy findings. Employing three-production models (Fox, Schaefer and Pella-Tomlinson model) with a three-error assumption model (normal, log-normal and gamma), a different range of Maximum sustainable yield (*MSY*) was anticipated by using various ranges of initial proportions (0.1 to 0.9). Results are furnished in Table 2. The CEDA package produced different *MSY* results for frigate tuna fishery and was sensitive to input IP values ranging from 0.1 to 0.9 (Table 2). IP value measures the extent of stock exploitation before the investigation. The initial landing

(1,434 MT) surpassed the highest catch (2,523 MT) by a proportion of 50%, hence an IP value of 0.5 was used in the study.

Table 2: Various *MSY* estimated (in metric tonnes) from CEDA software using an initial proportion of 0.1 to 0.9 for frigate tuna fishery from 1998 to 2018

IP	Fox		Schaefer		Pella-Tomlinson	
	normal	log-normal	normal	log-normal	normal	log-normal
0.1	9975	5872	7261	5213	7261	5213
0.2	7932	4877	5216	4251	5216	4251
0.3	7598	3214	4982	3621	4982	3621
0.4	6992	2987	4211	2651	4211	2651
0.5	4008	2582	3635	2086	3635	2086
0.6	3222	2028	2281	1982	2281	1982
0.7	2865	1721	1892	1723	1892	1723
0.8	2423	1466	1526	1532	1526	1532
0.9	1876	1299	1199	1182	1199	1182

The BRPs for three surplus productions with their error assumption models evaluated using CEDA software for frigate tuna fisheries in Tamil Nadu coastal waters using an IP of 0.5 were furnished in Table 3. As shown in Table 3, the Schaefer and Pella-Tomlinson (normal) model projected a greater carrying capacity (K) (12,991 MT) than the Fox model. The Fox (log-normal) model, on the other hand, predicted a better catchability coefficient (q), as well as the Schaefer (normal) model, which revealed a higher intrinsic population growth rate (r) than the other surplus production models. Results of the computed *MSY* value varied from 2,086 MT (Schaefer & Pella-Tomlinson log-normal) to 4,008 MT (Fox-normal). *RMSE* value ranged from 444 MT (Fox-normal) to 524 MT (Schaefer & Pella-Tomlinson- normal). The R^2 values of the Fox model (normal and log-normal) results were 0.09 and 0.15, respectively. The R^2 values for the Schaefer and Pella-Tomlinson models with normal and log-normal error assumptions were 0.10 and 0.06, respectively, but the gamma assumption failed to minimize. The expected high R^2 values of the surplus production models demonstrated a superior fit to the data. The result of the B_{MSY} value varied between 3,723 MT (Fox log-normal) and 6,496 MT (Schaefer & Pella-Tomlinson - normal). The result of the F_{MSY} value varied between 0.45 (Schaefer & Pella-Tomlinson log-normal) and 1.32 (Fox-normal).

Table 3: Biological reference points and intermediate parameters of frigate tuna fisheries in Tamil Nadu from 1998 to 2018

Model	*K*	*q*	*r*	*MSY*	*RMSE*	R^2	*B*	B_{MSY}	F_{MSY}
Fox (normal)	11843	1.42E-08	0.92	4008	523	0.09	8987	4357	1.32
Fox (log-normal)	10121	2.18E-08	0.69	2582	444	0.15	6195	3723	0.69
Schaefer (normal)	12991	1.24E-08	1.12	3635	524	0.10	10426	6496	0.46
Schaefer (log-normal)	10633	2.15E-08	0.78	2086	487	0.06	6082	5317	0.45
Pella-Tomlinson (normal)	12991	1.24E-08	1.12	3635	524	0.10	10426	6496	0.46
Pella-Tomlinson (log-normal)	10633	2.15E-08	0.78	2086	487	0.06	6082	5317	0.45

K, carrying capacity; *q*, catchability coefficient; *r*, intrinsic population growth rate; *MSY*, maximum sustainable yield; *RMSE*, root mean square error; R^2, coefficient of determination; *B*, current biomass; B_{MSY}, biomass giving *MSY* (expressed in metric tonnes); F_{MSY}, fishing mortality giving *MSY*.

Estimated high R^2 and low *RMSE* values of Fox (log-normal) demonstrated an excellent fit to the data (Table 3) in addition to residual plot results. Selected best-fitting Fox log-normal model results are furnished in Table 4. As shown in Table 4, the current biomass (6,195 MT) was more than B_{MSY} (3,723 MT) and fishing mortality (0.28) was less than F_{MSY} (0.69 MT), and the ratio of B/B_{MSY} and F/F_{MSY} values were 1.66 and 0.17, respectively.

Table 4: Biological reference points of frigate tuna fisheries in Tamil Nadu from 1998 to 2018 estimated by fitting Fox log-normal model

B	*F*	*MSY*	B_{MSY}	F_{MSY}	B/B_{MSY}	F/F_{MSY}
6195	0.28	2582	3723	0.69	1.66	0. 40

B, current biomass; *F*, fishing mortality; *MSY*, maximum sustainable yield; B_{MSY}, biomass giving *MSY* (expressed in metric tonnes); F_{MSY}, fishing mortality giving *MSY*; B/B_{MSY}, a ratio of biomass to biomass giving *MSY*; F/F_{MSY}, a ratio of fishing mortality to fishing mortality giving *MSY*.

The equilibrium yield curve for frigate tuna in Tamil Nadu is represented in Figure 1. As illustrated in Figure 1, the estimated B_{MSY} was 3,723 MT, with a maximum yield of 2,582 MT.

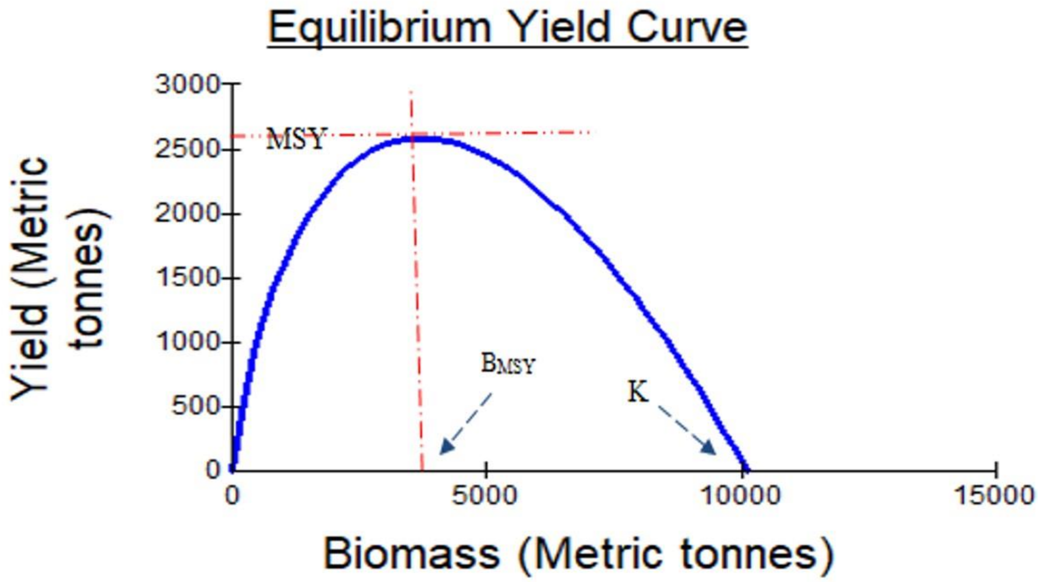

Figure 1: The equilibrium yield curve of the frigate tuna fishery in Tamil Nadu from 1998 to 2018 fitted by the Fox log-normal model

The relationship between expected and observed *CPUE* from 1998 to 2018 is depicted in Figure 2. The expected catch remained stable with slight fluctuation, while observed catches decreased with fluctuation between 1998 and 2018 (Figure 2). The present study used two diagnostic graphs (expected and observed *CPUE* & estimated and observed catches) to show how much the model fits the data. These graphs help to determine the location of a data point on the observed and expected catch graphs on the residual plots. As a result, CEDA can highlight any particular data point as a red square on two diagnostic graphs simultaneously, allowing the user to determine if the point is an outlier or a candidate for exclusions. However, the present study did not exclude any data points from the dataset.

The relationship between estimated and observed catches for all models with an IP value of 0.5 is depicted in Figure 3. Visual inspection demonstrated that the observed catches of normal and log-normal results of the Fox, Schaefer & Pella-Tomlinson models were relatively close to the estimated catch; however, they varied considerably. The estimated and observed catches of the Gamma error model demonstrated a minimization failure to the Fox, Schaefer, and Pella-Tomlinson models (Figure 3).

Linear regression analysis is conducted using catch and effort data from 1998 to 2018 presented in Table 5 and Figure 4. As shown in Table 5, F statistics test the overall significance of the relationship. The relationship between catch and effort data of frigate tuna was statistically significant (p-value < 0.05). A multiple R-value of 0.7 between the two variables indicated that they had a significant and positive association. R^2 and adjusted R^2 were used to determine explained and unexplained variance. According to the results, the regression explained 48% of the total variation in the catch. A histogram of regression analysis over standardized residual is plotted in Figure 4 and a normal P-P plot of regression standardized residuals is illustrated in Figure 5. The residuals of the regression line were normally distributed and confirmed that the regression line satisfies the normality assumption.

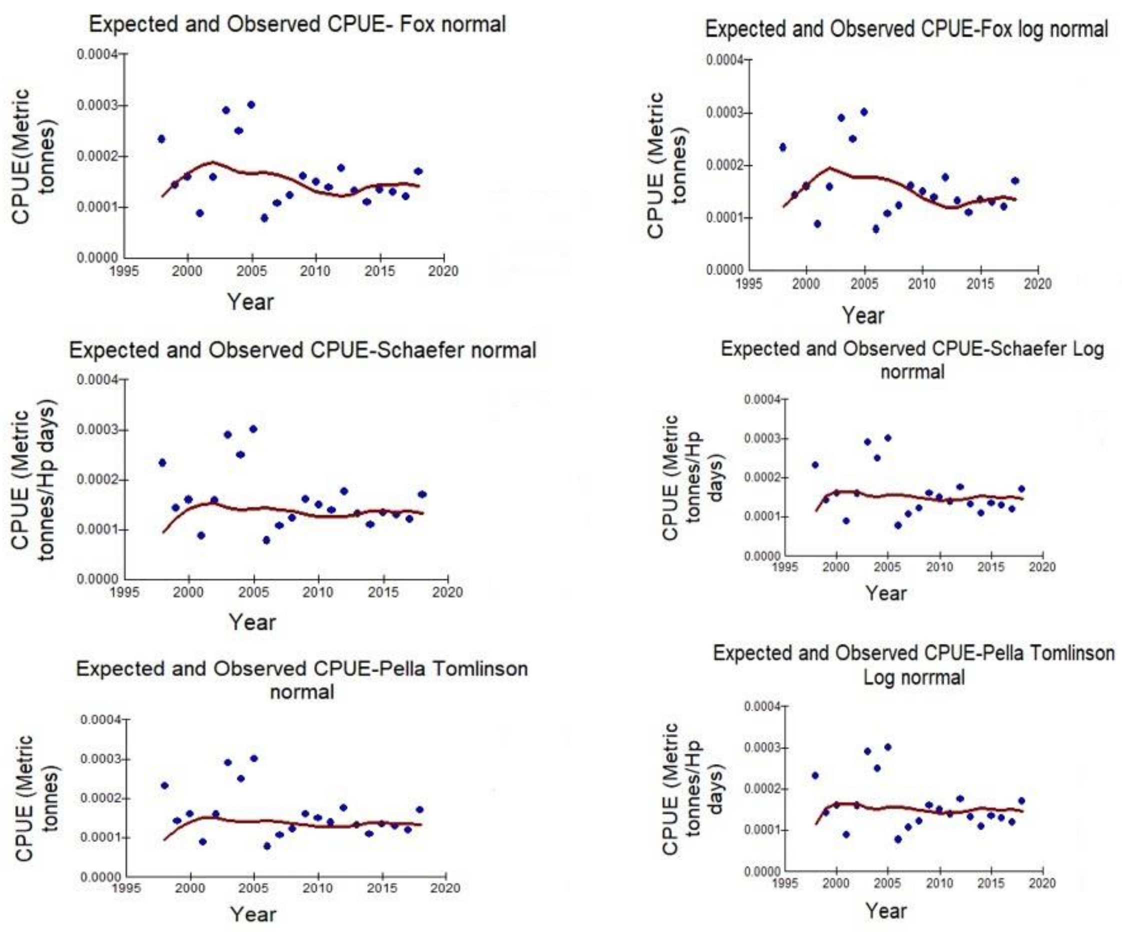

Figure 2: Time series of expected and observed catch per unit effort (*CPUE*) of frigate tuna fishery in Tamil Nadu from 1998 to 2018

4. Discussion

The total landing of frigate tuna in Tamil Nadu in 1998 was 1,434 MT. After a decline of catch to 555 MT in 2001, landings reached their peak of 2,523 MT in 2010. In general, landings registered an increasing trend from 1998 to 2018 with wide fluctuations in some years (Table 1). Kasim and Vivekanandan (2011) observed a decreasing trend in frigate tuna production from 1998 to 2001 and an increasing trend from 2002 to 2010. Increasing trend recorded by the present study concurrent with Kasim and Vivekanandan (2011). Sivadas *et al*. (2019) reported a large-scale increase in fishing efforts after the occurrence of Tsunami. The size of the boat increased from 11-12 meters (m) to 20-23 m overall length, and the fishing net weighing one MT was replaced with more than six MT. The present study recorded a large-scale increase in effort during 2006 and a decrease in fishing effort during subsequent years due to the phasing out of old craft and gears. The sudden increase in fishing efforts resulted in increased landings and *CPUE* during 2007-2012.

In general, the *CPUE* of frigate tuna fisheries showed a declining trend during 1998-2018 (Table 1). The exploitation of the stock close to the *MSY* may be the reason for the reduction in *CPUE* since 2012. Abdussamad *et al*. (2012) reported that frigate tuna in Tamil Nadu waters was very intensively exploited, and production reached very close to the estimated potential. The results of the present study are concurrent with Abdussamad *et al*. (2012) and Sivadas *et al*. (2019). Kirkwood (2001) opined that when fishing and natural mortality increases the population size decline gradually. Although there were random variation on expected and observed *CPUE*, a specific decreasing trend of CPUE was lacking in observed *CPUE* (Figure 2). Hence it can be assumed that changes in fishing and natural mortality of frigate tuna fisheries doesn't reflected as a decline in population size.

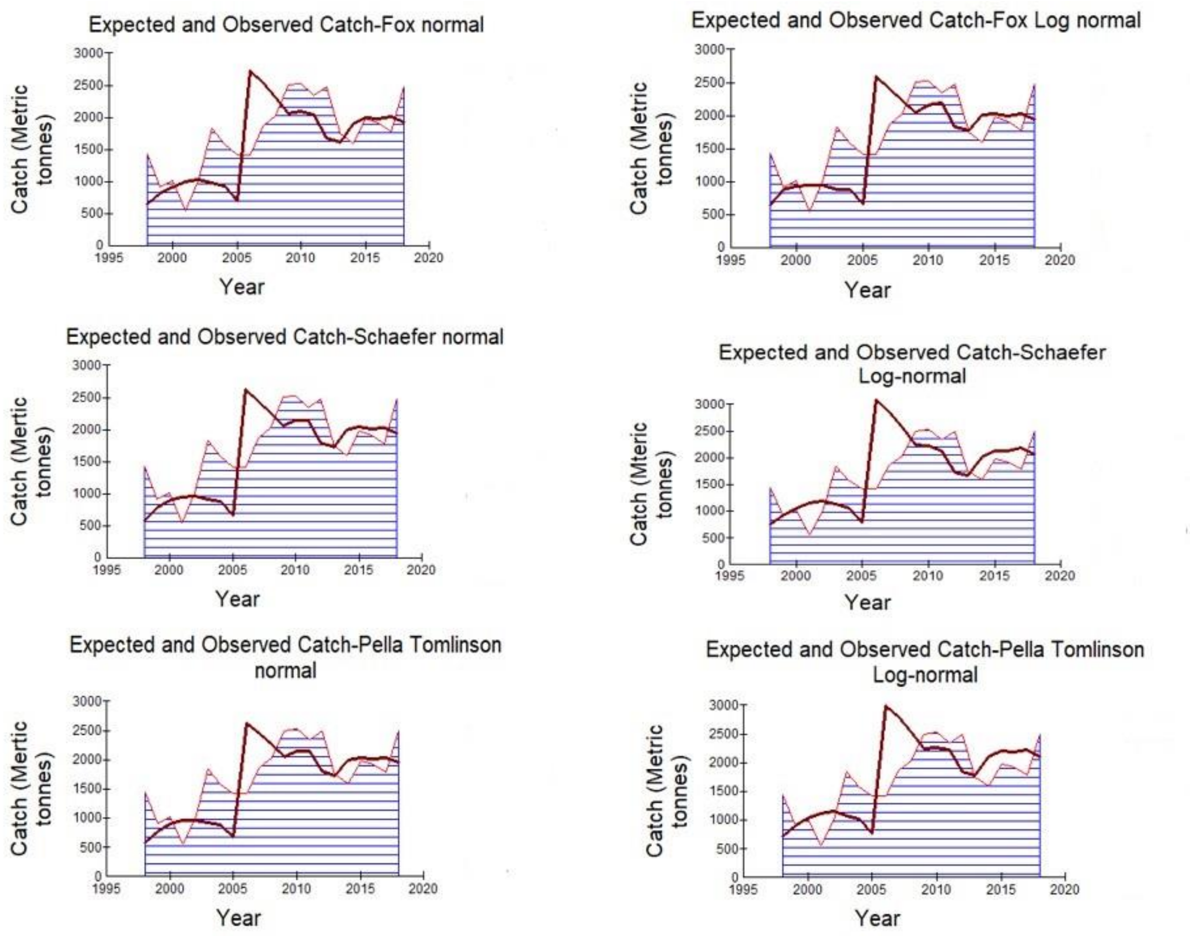

Figure 3: Time series of expected and observed catch of frigate tuna fishery in Tamil Nadu from 1998 to 2018

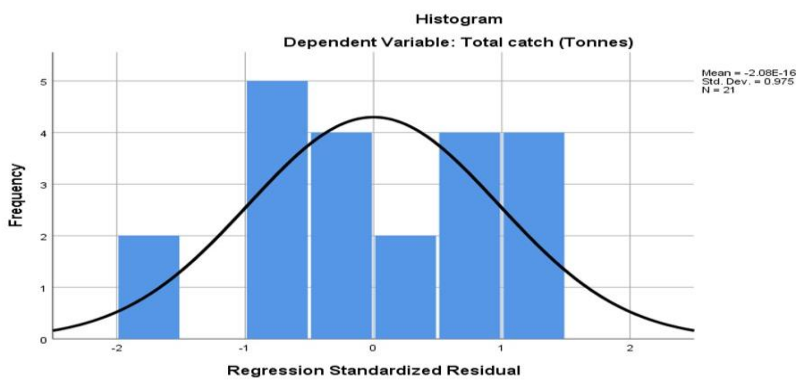

Figure 4: Histogram of regression analysis over standardized residual for frigate tuna fishery from 1998 to 2018

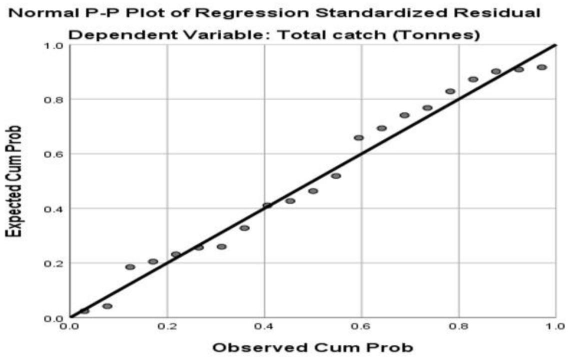

Figure 5: Normal P-P plot of regression standardized residual for frigate tuna fishery from 1998 to 2018

Table 5: Regression output of catch and effort data analysis for frigate tuna fishery from 1998 to 2018

Multiple *R*	R^2	Adjusted R^2	Standard Error	*F*-statistic	*p*-value
0.69447	0.48229	0.45504	35.9723	17.7	0.0004775

Results of the *MSY* estimates indicated that *MSY* values are inversely proportional to IP values (Table 2). Earlier workers reported a similar relationship (Kalhoro *et al*., 2013; Mohsin *et al*., 2018, 2019, 2020, 2021; Talib *et al*., 2017; Abinaya and Sajeevan, 2022a). The estimated BRPs of the Fox, Schaefer and Pella Tomlinson models varied from each other (Table 3). Based on diagnostic plot results, high R^2 and low *RMSE* value, the Fox log-normal model was considered the best-suited model and it made better fits and yielded results near the annual average landings. Hoggarth *et al*. (2006) and Noman *et al*. (2019) recommended that a high R^2 value and strong trend diagnostic plot were considered as a criterion for selecting the best-fit model and Panhwar (2012) suggested that the best-fit model will give results that are close to the annual average landing.

Target reference points (TRPs) and limit reference points (LRPs) are the two categories of reference points in general. TRPs are employed in fisheries management to set desirable fishing limits. *MSY*, F_{MSY}, and B_{MSY} are the three BRPs that have been widely employed in fishery resource management, with *MSY* receiving the most attention (Mohsin *et al*., 2020; Abinaya and Sajeevan, 2022b). Surplus production models are commonly employed in tropical fish stock assessment since they do not estimate cohorts and thus do not necessitate age determination. It can be calculated by using a stock assessment model that incorporates catch and effort statistics and predicts biomass. When the appropriate surplus production model is applied to all species collected by all types of fleets, an immediate *MSY* evaluation for the area is obtained. On the other hand, the challenge of harvesting the same stock by gear of varying effectiveness must be solved by regulating the fishing efforts of all gear active in the fishing (Kuriakose and Kizhakkudan, 2017).

The estimated *MSY* values are compared to the data values. The stock population thrives when the catch quantity is less than the calculated *MSY* value and is much more exploited. Once the stock achieves the *MSY* value, it is stable, and the harvest should be retained at the calculated *MSY* level rather than expanded or diminished. The stock population declines when the catch amount exceeds the actual *MSY* value. The estimated *MSY* of the frigate tuna fishery from Tamil Nadu was 2,543 MT, almost close to the recent catch of 2,482 MT during the 2018 period. BRPs (*MSY*, B_{MSY} and F_{MSY}) estimated by Fox log-normal indicate that the frigate tuna fishery of Tamil Nadu does not come under the status of overfishing and overfished. Estimates of F value were less than F_{MSY} and the F/F_{MSY} ratio was on the lower side. This indicates no overfishing sign of frigate tuna in Tamil Nadu waters. Similarly, the B/B_{MSY} value was higher than 0.5, indicating that the stock was not overfished. *MSY* estimates and landing data since 1998, confirm that the average annual landing never exceeded the *MSY* estimates. Moreover, *MSY* estimated by other models also stood above the annual average landing (1,732 MT year^{-1}) during the study period. Similarly, the F_{MSY} estimates of all models were higher than that of the F value estimated by the present study.

Coastal tuna stocks in Indian waters were being exploited at near-optimal levels (Silas and Pillai, 1985; James *et al*., 1992, 1993; James and Pillai, 1993; Kasim and Abdussamad, 2005; Pillai *et al*., 2005; Pillai and Ganga, 2008). Abdussamad *et al*. (2005) reported that the frigate tuna stock of Tamil Nadu was underexploited in 2005 and was intensely exploited in 2010 (Abdussamad *et al*., 2012). Ghosh *et al*. (2012) and Mudumala *et al*. (2018) reported that frigate tuna stock occurring on the Northwest coast of India showed signs of overexploitation. Dan (2021) reported that Indian Ocean frigate tuna stock is very close to being fished at *MSY* levels and higher catches may not be sustained. The results of the present study overrule the status of overfishing and overfished stock of frigate tuna. However, the reduction trend of *CPUE* from 2012 against a nominal decrease in the fishing effort is an indication that frigate tuna stock in Tamil Nadu reached the level of optimal exploitation. Any increase in fishing effort and overcapitalization may exert fishing pressure on the stock and lead to overfishing. Therefore, it is suggested that the present level of fishing may be maintained without any replacement for phasing out craft for ensuring sustainable exploitation.

5. Conclusion

The total landing of frigate tuna showed an increasing catch trend from 1998 to 2018. The total effort of frigate tuna registered a large scale increase during 2005 as a post-Tsunami effect and showed a decreasing trend since 2006 due to the phasing out of old craft and gears. The biological reference points (*MSY*, B_{MSY} and F_{MSY}) of frigate tuna rule out designating the frigate tuna stock of Tamil Nadu status as overfishing and overfished. However, an overall reduction trend of *CPUE* since 2012 indicates that stock is exploited very close to *MSY*. Hence, any increase in fishing effort results in heavy fishing pressure on fish stock and may lead to overfishing.

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