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Stock Status and Management of the Rabbitfish *Siganus rivulatus* in the Suez Bay, Gulf of Suez, Egypt.

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ABSTRACT

The Rabbitfish, *Siganus rivulatus* is one of the most popular fishes inhabiting the Red Sea and migrated then widely distributed in the Mediterranean Sea. Monte Carlo method-based Surplus Production Model CMSY+ was used to predict the biological reference points (PRBs) for *S. rivulatus* using catch time series data 2000-2015. The Biological Reference Points for *S. rivulatus* are MSY= 4.04ton, B/B_{MSY}= 0.398ton, Exploitation F/F_{MSY}= 1.03, Carrying Capacity k= 5.62ton, The intrinsic growth rate of the fish population r=0.239 y^{-1}. According to the above results, the current level of fishing pressure should be relatively reduced to ensure the sustainability of *S. rivulatus* in Suez Bay, Gulf of Suez. In addition, by decreasing the fishing pressure the ratio of B/B_{MSY} could be increased from 0.392 to about unity to attain a healthy state

INTRODUCTION

Lack of expertise, scarcity of data, and absence of stock assessment methods suitable for use in data-sparse situations are the reasons for exploited fish stocks remain unassessed in developing countries and regions **(Palomares *et al*., 2018).** These deficiencies have recently been mitigated, at least in part, through the recent development of easy-to-learn computer-intensive stock assessment methods relying primarily on time series of catch data. Among these, the Monte Carlo Catch- Maximum Sustainable Yield (CMSY+) method (**Froese *et al.*, 2017)** to estimate fisheries reference points (MSY, F_{MSY}, B_{MSY}) as well as relative stock size (B/B_{MSY}) and exploitation (F/F_{MSY}) from catch data, a prior for resilience or productivity (r), and broad priors for the ratio of biomass to unfished biomass (B/k) at the beginning, an intermediate year and the end of the time series. Part of the CMSY+ package is an advanced Bayesian state-space implementation of the Schaefer surplus production model BSM (**Froese *et al*., 2017).** The main advantage of BSM compared to other implementations of surplus production models is the focus on informative priors and the acceptance of short and incomplete catch-per-unit-of-effort

(CPUE) data to estimate biomass (B) and the current status of *Siganus rivulatus* in Suez Bay, Gulf of Suez. Also, key fisheries reference points such as intrinsic rate of population increase (r), carrying capacity (k), maximum sustainable yield (MSY), and the terminal ratio B/B_{MSY} are estimated.

The CMSY+ method was first proposed as a Monte-Carlo method by **Martell and Froese (2013),** who were inspired by stock reduction analysis **(Kimura and Tagart, 1982; Kimura *et al*.,1984**); it was then updated to overcome some shortcomings (**Froese *et al.*, 2017).** CMSY+ is used to estimate biomass (B), exploitation rate (F/F_{MSY}), relative stock size (B/B_{MSY}), and fisheries reference points (MSY, r, k) from time series of catch, resilience, and qualitative stock status information at the beginning and the end of the time series (**Froese *et al.*, 2017).** The predictions of the CMSY+ method can be strengthened by the BSM method when relative abundance data (i.e., CPUE data) are available in addition to catch data. Trammel net is a common fishing gear used in small-scale fisheries including *Siganus rivulatus* in the Gulf of Suez. Trammel net is composed of three layers of net with inner netting is slack small between two large mesh netting layers in which the fish will become entangled. Floats on the head rope and mostly weights on the ground rope keep the net more or less vertical

MATERIALS AND METHODS

Sixteen years (2000–2015) of *S. rivulatus* comprising annual artisanal landing from Suez Bay, Gulf of Suez were used in this study. The series of catch data were taken from the General Authority for Fish Resources Development GAFRD, Suez Office.

The total catch of rabbit fish was calculated in ton (t). The estimated average catch of *S. rivulatus* was about 3. 26t, while the minimum catch was 1. 300t in 2008, and the maximum was 6. 04t reported in 2017.

Model CMSY+

Estimation of BRPs from catch and resilience data of *S. rivulatus* was conducted using a Monte Carlo method-based Surplus Production Model SPMs called CMSY+. The CMSY+ can predict biomass using catch time series data.

This research used the CMSY+ approach to assess the Biological Reference Points (BRPs) MSY, B/B_{MSY}, F/F_{MSY}, k (carrying capacity), r (intrinsic growth rate of the fish population) related to *S. rivulatus*.

$$B_{(t+1)} = B_t + r\,(1 - B_t/k)B_t - C_t \qquad (1$$

The biomass exploited in (t + 1) year was $B_{(t+1)}$, existing biomass was B_t, and catch in t year was C_t. Equation (2) was used when stock sizes were severely depleted, and biomass fell below 1/4 k.

$$B_{(t+1)} = B_t + 4\,(B_t/k)\,r\,(1 - B_t/k)B_t - C_t \mid B_t/k < 0.25 \qquad (2$$

The Fish Base resilience score for *S. rivulatus* was “low,” so the prior range for r was 0.14–0.44 used as the input parameter in the CMSY+ (Table, 1)**.** The prior range of k was determined using three assumptions: the unexploited stock size (k) > largest catch in the time series, the maximum sustainable catch (F_{MSY}) is productivity-dependent, and the maximum catch represents a more significant fraction of k in significantly depleted stocks than in lightly depleted stocks. By default, and based on the anticipated degree of depletion, probable biomass ranges (Table, 1) provide prior estimations of relative biomass at the beginning and end of time series data.

The CMSY+ method, since 2017 (**Froese *et al*., 2017)** this technique has been continually updated and improved and is currently accessible as CMSY++ and downloaded from http://oceanrep.geomar.de/33076/ (accessed on 20 August 2021).

Table (1). Distributions of biomass (B), intrinsic rate of population growth (r), and carrying capacity of the fishery (k) ranges as priors for the CMSY+ used for *S. rivulatus***.**

Input Parameters	**Ranges of the Values**
Prior initial relative biomass	0.2–0.6
Prior intermediate relative biomass	0.5–0.9 in a year (2011) default
Prior final relative biomass	0.01–0.3 default
Prior range for r	0.14 – 0.44 expert
Prior range for k	0.00322 - 0.00966

RESULTS

CMSY+ Derived Fisheries Reference Points (BRPs).

First Monte Carlo filtering of r-k space with 20000 points, found 2600 viable trajectories for 2366 r-k pairs. The CMSY+ method delivered important stock information and BRPs (Table, 2). The CMSY+-derived BRPs are considered the management information for the *S. rivulatus* fishery of Suez Bay, Gulf of Suez. The estimated values of k and r were (5.62t), and (0.293 year^{-1}) respectively. The catch fit diagram (Fig. 1A) depicted a gradual decrease and fluctuation from the year 2000 to 2010 and then a slight gradual increase in the last 3 years, in both observed and predicted catch. The highest catch (6.4t) was observed in 2001, while the lowest catch (1.3t) was reported in 2015. There was a remarkable variation between the predicted and observed catch in the last year (2015), which is a bad sign for the sustainability of this fishery

Table 2. Estimated Biological Reference Points BRPs (k, r & MSY) of *S. rivulatus* in Suez Bay, Gulf of Suez with 95% confidence intervals (CI).

k (ton)	r (year^{-1})	MSY (ton)
5.62, (4.18 – 7.55)	0.293 (0.223 – 0.385)	4.04, (3.16 – 5.52)

Where k is the carrying capacity of the fishery.

CMSY+ assessment.

Regarding CMSY+ assessment graphs in Fig. (1) The black curve in **A** shows the time series of catches and the blue curve shows the smoothed data with an indication of the highest and lowest catch in red, as used in the estimation of prior biomass by the default rules. The smoothed blue curve behaves as a bottom arc from 2001 to 2014.

2) Panel **B** shows the explored log *r-k* space and in dark grey the *r-k* pairs which were found by the model to be compatible with the catches and the prior information. The dotted rectangle indicates the range of the priors provided in the ID file. The point in the center of the blue cross is the most likely r-k pair predicted by CMSY+ and horizontal and vertical error bars approximate 95% confidence limits for *r* and *k,* respectively, which are again closer view in Panel **C**.

3) The blue curve in **D** shows the median of the biomass trajectories estimated by CMSY+. The median of the biomass trajectories, reverse the catch data in **A**, behaves as a top arc from 2001 to 2014. The dotted lines indicate the 2.5th and 97.5th percentiles. Vertical blue lines indicate the prior biomass ranges.

4) Panel **E** shows median exploitation (*F*/*Fmsy*) as a blue curve, with the dotted curves indicating 2.5th and 97.5th percentiles. The steep increase in the upper confidence limit in the last year results from catch relative to the lower confidence limit of biomass in panel **D**. The optimum fishing mortality is the fishing mortality yields the Maximum Sustainable Yield of the fishery, thus (F=F_{MSY}, i.e., F/F_{MSY}=1). The exploitation is nearly one in the first and last fishing seasons, and less than one in the rest seasons so it reaches about 0.5 for seasons 2006 to 2010.

5) Panel **F** shows the Schaefer equilibrium curve of catch/MSY relative to *B/k*, indented, pointed by the red arrow, at B/k < 0.25 to account for reduced recruitment at low stock sizes. The blue curve shows the predictions by CMSY+, from the first year (square) to the last year (triangle).

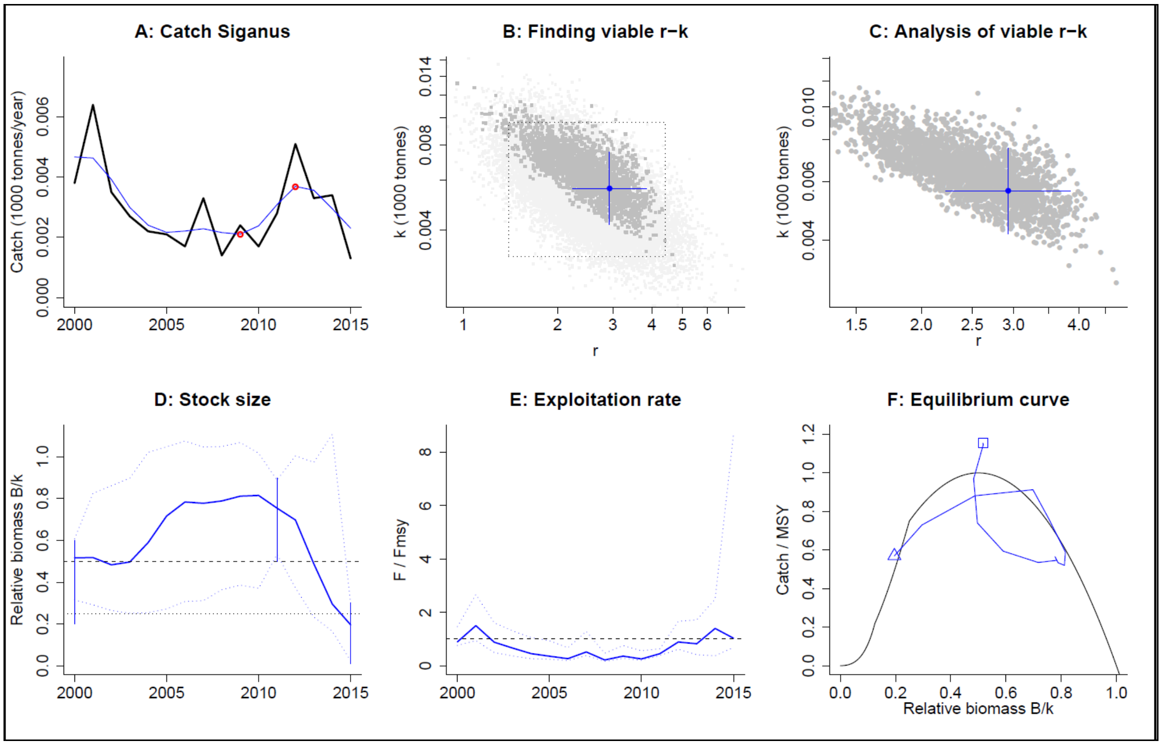


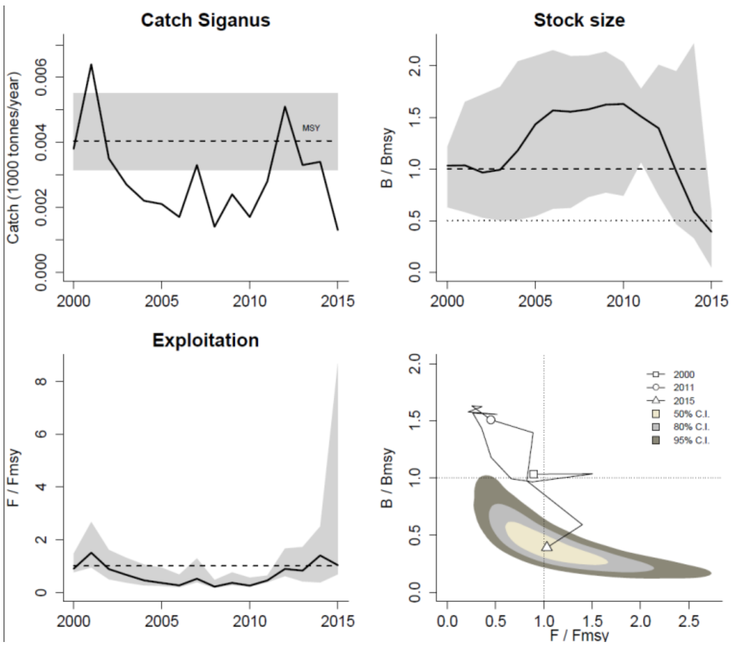
Figure 1. The CMSY+ assessment graphs for *S. rivulatus* in Suez Bay, Gulf of Suez.

Stock Status of S. rivulatus Fishery.

The upper left panel shows the catch relative to MSY, with an indication of 95% confidence limits in grey. The catch of the first year matched nearly the MSY value, but in the second year was higher, 1.75 times MSY exceeding the upper limb of its confidence interval (CI). Considering the period 2003 to 2006 catch fluctuated under MSY value and in 2007 it was involved in the lower edge of CI of MSY. Regarding the year 2012, the catch exceeds MSY but was still in the upper limb of its CI. Catches of years 2014 and 2015 dropped to the lower limb of MSY confidence interval CI.

The upper right panel shows the development of predicted relative total biomass (B/B_{MSY}), with the grey area indicating uncertainty. The biomass of *S. rivulatus* matched the value of biomass of MSY ($B_{\mathbf{MSY}}$**)** in the early years till 2004 and then exceeded it in the next years to 2013. The biomass of the fish dropped in 2014 and 2015 to around half $B_{\mathbf{MSY}}$.

The lower left graph shows relative exploitation (F/F_{MSY}). Relative exploitation fluctuated around unity in the first three years, then it went under unity until 2011. Once again, relative exploitation fluctuated around unity in the last four years.



Figer 4.The stock status of *S. rivulatus* in Suez Bay, Gulf of Suez.

The lower-right panel shows the trajectory of relative stock size (B/B_{MSY}) as a function of fishing pressure (F/F_{MSY}). The "banana" shape around the assessment of the final year triangle indicates uncertainty with yellow for 50%, grey for 80%, and dark grey for 95% confidence levels.

Management of S. rivulatus Fishery.

CMSY+ method assesses whether F/F_{MSY} values < 1 and B/B_{MSY} close to 1, to ensure safe fishing conditions and healthy stock in which biomass levels are enough to harvest the MSY and accordingly the biomass levels are enough for a sustainable state of *S. rivulatus* in Suez Bay.

Table 3. Management information of *S. rivulatus* in Suez Bay, Gulf of Suez based on CMSY+.

Parameter	**Value**	**95% Confident Intervals (CI)/Percentile**	
F_{MSY}	1.46	1.11 - 1.93 (if B > 1/2 B_{MSY} then F_{MSY} = 0.5 r)	
F_{MSY}	1.15	0.872 - 1.51 (r and F_{MSY} are linearly reduced if B < 1/2 B_{MSY})	
MSY	4.04	3.16 – 5.52	
B_{MSY}	2.81	2.09 – 3.77	
Biomass (B_{2015})	1.1	2.5th perc = 0.131,	97.5 perc = 1.66
B/B_{MSY}	0.392	2.5th perc = 0.047,	97.5 perc = 0.59,
F mortality (2015)	1.18	2.5th perc = 0.784,	97.5 perc = 9.95.
Exploitation (F/F_{MSY}) *(P. Parameter)*	1.03	2.5th perc = 0.683,	97.5 perc = 8.67.

Considering management information **Table 3**, B/B_{MSY} is equal to 0.392 i.e., $B < 1/2B_{MSY}$, so the value of F_{MSY} is $1.15y^{-1}$.

Kobe phase plot (Fig. 4) was used to depict the current stock status and exploitation rate relative to target reference points (TRPs) such as F_{MSY}. The Kobe plot is characterized by four colored quadrants (orange, red, yellow, and green) for F/F_{MSY} on B/B_{MSY}. The orange plot denotes the healthy stock that will be depleted by overfishing. The red color plot indicates the overfished and overfishing status in which the biomass cannot produce the MSY. The yellow color plot indicates very low biomass, but the stock has a chance to recover in a sustainable state if fishing pressure is reduced. The green plot is the management targeted area, signifying healthy stock status and sustainable fishing to produce the MSY. The legend in the plot's upper right corner indicates the probability of the stock falling into one of the colored areas over the last year, such as an 0.8% probability of the stock subsiding into the green area, a 52.1% probability of the stock falling into the red area, an 47.1% probability of the stock falling into the yellow area, and a 0.0% probability of the stock falling into the orange area. The stock fell in the green quadrate at the start year of the investigation (2000) and from 2004 to 2012. The stock of the year 2001 fell in the orange quadrate and that of the years 2002 and 2003 fell in the yellow quadrate. The stocks of the years 2014 and 2015 fell in the red quadrate.

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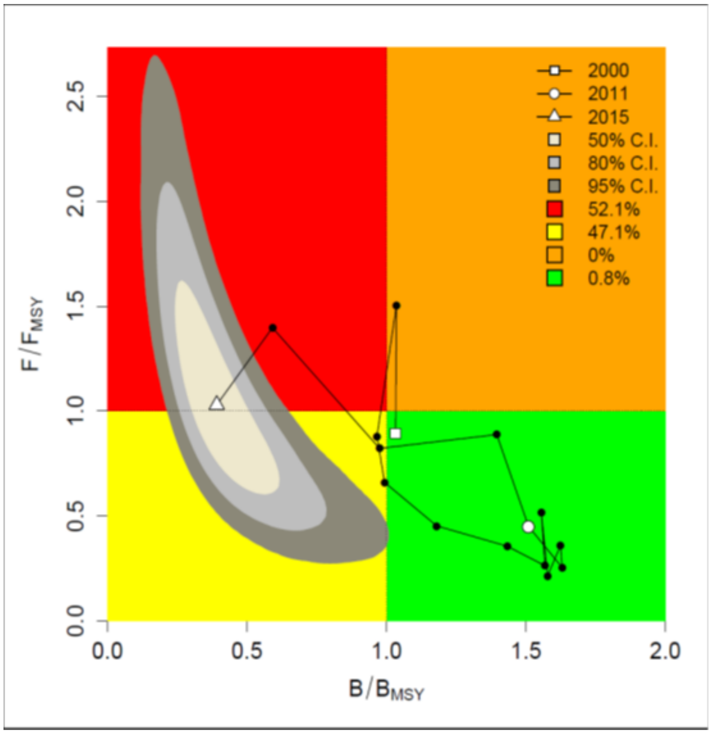

Figure 4. Kobe plot illustrating the concurrent movement of exploitation (F/F_{MSY}) and the relative biomass (B/B_{MSY}) of *S. rivulatus* in Suez Bay, Gulf of Suez

DISCUSSION

Many fishery researchers dealt scientifically with the fish species *Siganus rivulatus*, using the classical methods to estimate the species' biological reference parameters as; the growth coefficient (k), the theoretical maximum length (L_∞), and the theoretical parameter (t_0) pertained to the growth model of von Bertalanffy. For instance, in the territorial waters of Egypt in the Red Sea **(El-Ganainy and Ahmed , 2002**) investigated *S. rivulatus* in the Gulf of Suez using length frequency. **(Mehanna and Abdalla ,2002; Mehanna *et al.* ,2018)** used otolith for the fish in the Red Sea sector. **(El-Drawany, 2015)** used otolith in the Bitter Lakes to study the fish.

Actually, these parameters are of individual growth not of population growth which follows two processes; one for the individual and another for the population. So, in the CMSY+ method; the parameter of the intrinsic increase rate of a population (r) is an important indication to understand a fishery**(Anderson *et al*., 2008; Cheung *et al*., 2010).** Such parameter (r) includes the changes in the size of the individual along its age besides the changes in the number of recruitments in different years. The same corresponds to the different biological reference parameters of the CMSY+ method. CMSY+ investigated 20000 points for the most properly linked r-k, altogether 2600 viable trajectories for 2366 r-k pairs were found. Therefore, this method is mostly objective and such a procedure of estimating r-k may give it priority over the statistical methods, that used the length frequency of the fish species. Such statistical methods are common in tropical and subtropical regions whereas in temperate zones fishery scientists use hard structures as otoliths to age fish, which are more reliable and avoid the possible terrible uncertainty of the statistical methods. Aging fish using the hard structures gives more accurate results but in the case of subtropical and tropical cases, the annulus is mostly unclear, and the otolith may contain chaotic lines and/or ruptures particularly the otoliths of the shallow water areas as *Siganus rivulatus* that lives in depth range 0.5-3.5 meter.

Population Parameters of S. rivulatus.

The intrinsic increase rate of a population (r) is an important indication to understand a fishery **(Anderson *et al*., 2008; Cheung *et al*., 2010).** The estimated (r) is 0.29year^{-1}, revealing a medium growth rate of *S. rivulatus* that is able to add above 29% biomass to the standing population in a year. When r is 0.1, it is mentioned that population size can increase by 10% in a time interval **(Hoggarth *et al*., 2006).** The r value strongly correlates with fisheries resilience related to natural mortality (Froese & Pauly, Fish Base **(Froese *et al*., 2017)** The fisheries resilience value ranged from 0.015–0.1, categorized as low resilience, 0.2–0.8 is medium resilience, and 0.6–1.5 is called high-resilience fishery **(Froese *et al*., 2017)** This study found *S. rivulatus* as a "medium-resilience" fishery.

Maximum Sustainable Yield (MSY) of S. rivulatus.

Regarding the year 2012, the catch exceeded MSY but is still in the upper limb of its confidence interval. Catches of years 2013, and 2014 dropped to the lower limb of the MSY confidence interval and fall far from MSY (about 1.0ton) in 2015. The biomass of the fish dropped in 2014 and 2015 to around half $B_{\mathbf{MSY}}$. As a pelagic fish, *S. rivulatus* is caught in large groups where fishermen search for large aggregations and then surround the fish with a trammel net. Then they make noise to scare them to escape falling into the net. Therefore, fish still yield high catches though the biomass decreases which will be reflected in the next year's catches. Moreover, the population might suffer recruitment overfishing which hinders the fishery longer time to recuperate.

The maximum sustainable yield MSY was 4.04t per year, which was significantly higher than last year's catch (1.3t per year in 2015), indicating acute poverty of fish biomass to yield that value of MSY. Correspondingly, the fishery of *S. rivulatus* in Suez Bay was suffering overfishing through 2012, 2013, and 2014.

Exploitation and Stock Status of S. rivulatus.

Ratio B/B_{MSY} went about unity in the first four years which is the aim of optimum management. In the next eight years, B/B_{MSY} increased to around one and a half however exploitations F/F_{MSY} dropped mostly near zero then increased in the last four years to around unity. In other words, the stock status was about healthy during the first four years, after that the stock increased its biomass by about half more than that of maximum sustainable yield. Although, the exploitations F/F_{MSY} tumbled then rose through the last four years.

The representation of the Kobe phase plot suggests that the current level of fishing pressure should be relatively reduced to ensure the sustainability of *S. rivulatus* in Suez

Bay, Gulf of Suez. In addition, by decreasing the fishing pressure the ratio of B/B_{MSY} could be increased from 0.392 to about unity to attain a healthy state.

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