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Population Dynamics of the Indian Scad *Decapterus russelli* (Rüppell, 1830) in the Natuna Sea, Indonesia

Asep Priatna[1, 2*], Mennofatria Boer[2], Rahmat Kurnia[2], Yonvitner[2, 3]
[1]Research Center For Fisheries, National Research and Innovation Agency, Indonesia
[2]Department of Aquatic Resources Management, Faculty of Fisheries and Marine Sciences, IPB University, Bogor, Indonesia
[3]Center for Coastal and Marine Resources Studies, IPB University, Bogor, Indonesia

[*]**Corresponding Author: asеppri.brpl@gmail.com**

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ABSTRACT

The Indian scad (*Decapterus russelli*) was dominant and the most highly favored small pelagic caught in the Natuna Sea. The stock status of small pelagics in Fisheries Management Area 711 (Karimata Strait, the Natuna Sea, and the South China Sea) is fully exploited and approaching being overexploited. In multi-species fisheries, it is relatively challenging to implement management options based on aggregate stock. The stock status of species-specific requires updates based on appropriate assessment methods. This study aimed to assess the growth, mortality, length at capture, length maturity, and stock status of *D. russelli* in the Natuna Sea based on length-frequency data carried out for seven years at Pemangkat Fishing Port, West Kalimantan, with 19103 fish sampled. The von Bertalanffy growth function was fitted using the TropFishR package to estimate the growth parameters. Natural mortality was estimated using the $M = 4.118K^{0.73}L_{inf}^{-0.33}$ equation, and exploitation rates were estimated using the length-converted catch curve model. The catch length was in the range of 10.2 and 24.4cm. The ELEFAN_GA model provided a better fit, and it was used to obtain the following results: the asymptotic length (L_{inf}) was 23.36cm, the growth coefficient (K) was 0.64, the length at time zero (t_0) was -0.27, and the expected longevity (t_{max}) was 4.39 years. The natural mortality (M) was 1.06 year^{-1}, fishing mortality (F) was 1.03 year^{-1}, and total mortality (Z) was 2.09 year^{-1}. The exploitation status (E) was 0.49, and the length at first capture (SL_{50}) was higher than the length at first maturity (L_{50}), meaning the fish had reached gonad ripening before they were caught. To maintain the exploitation rate at the optimum level (E = 0.5), it is necessary to sustain current fishing efforts while ensuring high monitoring of the implementation of the existing management policy.

INTRODUCTION

The Indonesia Fisheries Management Area 711 (FMA-711) covers the waters of the Karimata Strait, Natuna Sea, and the South China Sea, a strategic location for small pelagic fishing. According to fishery statistics data from the Ministry of Marine Affairs and Fisheries (MMAF) Indonesia, in the 2015–2021 period, the amount of small pelagic landed in FMA-711 was around 172555 metric tons per year, or around 30% of the total of all fisheries commodities **(Satu Data-MMAF, 2021)**. Regarding fisheries landing data of Fishing Port Information Center (FPIC), the top five species compositions of the total catch of small pelagic in FMA-711 during 2015–2019 were *Decapterus russelli*, *Selar crumenophthalmus*, *Selaroides leptolepis*, *Decapterus macrosoma*, and *Amblygaster sirm* with percentages of 30, 14, 10, 8, and 7%, respectively **(FPIC-MMAF, 2019)**. The Indian scad (*D. russelli*) was the dominant catch (41%) by purse seines operating in the Natuna Sea and South China Sea. Other catches include *S. crumenophthalmus*, *D. macrosoma*, *A. sirm*, *Sardinella* sp., and *Rastreliger* sp., with percentages of 17, 11, 8, 4, and 4%, respectively. Small pelagic resources in Natuna and the South China Sea have been exploited long and intensively, mainly by purse seine fleets based in several fishing ports in FMA-711, such as Pemangkat (West Kalimatan), Batam and Karimun (Riau Islands), and Palembang (South Sumatera).

MMAF has conducted the commodity-based stock assessment in Indonesia's FMA. The estimated potential stock of small pelagics in 2015 was 395451 tons year^{-1} with a utilization rate of 1.64 **(Ministerial Decree No. 47, 2016)**, and in 2016 was 330284 tons year^{-1} with a utilization rate of 1.41 **(Ministerial Decree No. 50, 2017)**, showing a decrease in potential and that the level of utilization has exceeded its optimum effort (overexploited). In 2019, the potential was estimated at 536917 tons year^{-1} with a utilization rate of 0.9 **(Ministerial Decree No. 19, 2022)**, indicating a fully-exploited level close to the overexploited one.

In addition to the high utilization rate, the stock status seems to be affected by illegal fishing, especially by foreign vessels, which often occur in the Natuna Sea. In the last five years (2016-2020), the MMAF Fisheries Surveillance Ship has successfully arrested 324 fishing vessels that carried out illegal fishing in the North Natuna Sea, of which 317 were foreign fishing vessels **(Nurhakim, 2021)**. In February 2022, at least 12 Vietnamese and 8 Chinese fishing vessels were suspected of illegal fishing in the North Natuna Sea. The most suspected illegal fishing occurred in May 2022, when 60 foreign fishing vessels belonging to Vietnam were detected **(Indonesia Ocean Justice Initiative, 2022)**. The FMA-711 sea border area was vulnerable to fishing pressure. Illegal fishing, which is still rampant in FMA-711, also impacts the accuracy of the available catch and effort data, hence using these data should be considered in the stock assessment process.

Management options based on aggregate stock are relatively difficult to apply in multi-species fisheries. In addition, the FAO states that aggregate biomass estimation is incompatible with the principles of stock assessment in multi-species fisheries. Indeed, stock assessments of small pelagics at FMA-711 have been conducted for several economic species. In 2003-2005, *D. russelli* and *D. macrosoma* stock status showed high exploitation rates in Natuna and Anambas waters **(Hariati *et al*., 2008)**. The reproductive biology of *D. russelli*, *D. macrosoma*, and *R. kanagurta* caught in the South China Sea in 2003-2005 indicated that the population was dominated by immature gonads **(Suwarso *et***

***al*., 2008)**. From 2012 to 2015, *S. crumenophthalmus* indicated growth in overfishing conditions **(Fauzi *et al*., 2018)**. In 2005-2006, the CPUE of small pelagic species generally tended to decline, presumably due to high fishing effort from other Indonesian and foreign purse seiner **(Hariati *et al*., 2009)**.

The assessment of the stock status of *D. russelli* from the perspective of management measures is still lacking, especially in the Natuna Sea. The *D. russelli* stock assessment gap must be immediately filled to encourage long-term stock management. Therefore, it is necessary to update species-specific stock statuses based on appropriate calculation methods. Stakeholders can make educated choices regarding overall management measures with the assistance of precise estimations of the population status. Additionally, the data gathered from stock assessments help establish management policies.

Understanding the life-history characteristics, such as age, growth, mortality, and reproductive features, such as size at first maturity, sex ratio, and spawning potential ratio, is a prerequisite for investigating effective management strategies. These parameters are crucial for establishing accurate stock assessments and facilitating informed decisions regarding fisheries management **(Alam *et al*., 2021; Amponsah *et al*., 2021)**. According to **Quinn and Deriso (1999**), stock assessment models, which rely heavily on substantial data sets like catch time series, absolute or relative abundance indices, fishing effort, and age structure, have traditionally been the only means to obtain this crucial information.

Surprisingly, data-poor conditions exist for more than 80% of global fish stocks, severely limiting the possibility of accurate stock assessments and leading to poor management practices **(Costello *et al*., 2012)**. Due to illegal fishing, this data limitation is especially severe in boundary areas viz. the Natuna and the South China Sea, making it more challenging to carry out accurate stock assessments **(Nurhakim, 2009)**.

Conventional stock assessment techniques of fitting data to population dynamics models do not apply to exploited fisheries where data are inadequate. In such fisheries, length-frequency data from commercial catches are often the primary data collection because ithey are relatively economical and easy to collect **(Hordyk *et al*., 2015a; Mildenberger *et al*., 2017)**. Many length-based stock assessment methods have been developed to estimate several indicators and stock status with uncertainty considerations. The electronic length frequency analysis (ELEFAN) is one such approach that is widely used to estimate growth and mortality parameters based on length frequency (LF).

The primary objective of this study was to employ robust assessment approaches for periodically sampled LF data to estimate growth, mortality, length at first capture, length maturity, and exploitation rates of *D. russelli* under the existing exploitation regime. This was done in light of the requirement for species-specific stock status due to the lack of updated information on *D. russelli* stock assessments in the Natuna Sea. In addition, for multi-species, such as small pelagics in FMA-11, the current aggregate stock status is relatively tricky to use as a basis for fisheries management. The current study should provide crucial insights for the efficient and long-term management of *D. russelli* populations.

MATERIALS AND METHODS

1. Study area

The current study was carried out at Pemangkat fishing port, West Kalimantan. The sampling site is the enormous landing base for small pelagic purse seiner in FMA-711 (Fig. 1), with scad fish as the targeted species. This location is noted for fish landings, with fishing contributing about 74% of the total production of *Decapterus* spp. in FMA-711 landed at Pemangkat Fishing Port **(FPIC-MMAF, 2019)**. The Natuna Sea is a fishing ground for purse seiners from Pemangkat, operated using light fishing without fishing aggregate devices, with a 1-inch mesh size. We assumed that the length distribution caught by purse seiners could independently represent the population and catch composition. Furthermore, ease of accessibility to obtain and traceability of fish samples are considerations for sampling in this location.

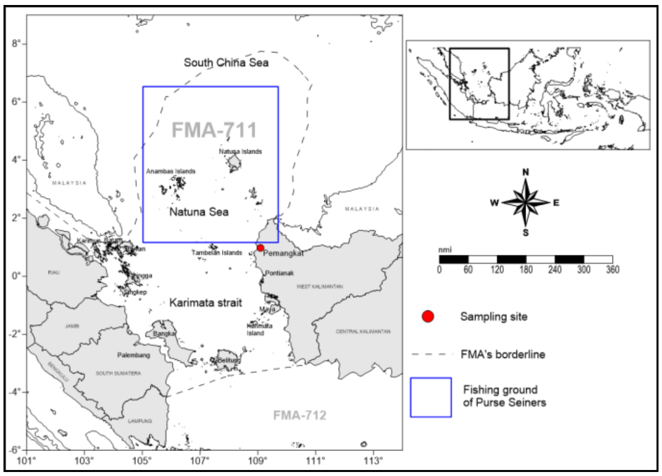

Fig. 1. Sampling location and fishing grounds for small pelagic purse seiners in the Natuna Sea

2. Data collection

Samples of *D. russelli* were collected monthly and randomly from purse seiners from 2015 to 2021 (Table 1). In total, 19103 fish were sampled during the study period. The individual measurement of fork length (FL) was used for constructing length-frequency distribution (LFD) with a length interval of 1cm. Biological sampling, including measurements of length-weight, sex, and gonad maturity level, was conducted on a total of 4,059 individuals as sub-samples. The FL was measured using a measuring board with a precision of 0.1cm and digital scales with an accuracy of 0.1 and 0.01 grams for individual weight and gonad.

The fish sub-sample underwent dissection to ascertain the sex and maturity stage of their gonads. The sex and maturity were macroscopically determined based on gonad development, such as color, shape, and size. The "Standard Gonad Maturity Scale" (Five-point maturity scale for partial spawners) **(Effendie, 2002)** was used to determine the maturity stage. Specimens were divided into five stages, i.e., I-Immature, II-maturing virgin and recovering spent), III-ripening, IV-ripe, and V-spent. Considering the small number of fish with ripe gonads (fully mature), it was determined that the gonad from stage III was in the mature stage.

Table 1. The monthly sampling for data collection at the Pemangkat fishing port

Year	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
2015				xy	xy	xy	x	Xy	xy	xy	xy	y
2016			xy	xy	xy	xy		Xy	xy	xy	xy	
2017				x	x	x	x	X	xy	x	xy	x
2018			xy	x	x	xy	x	X	xy	x	xy	x
2019			x	x	x	x	x	X	x	x	x	
2020			x	x	x	x	x	Xy	xy	xy	xy	xy
2021			xy	xy	xy	xy	xy	Xy				

x: measurement FL, xy: sub-samples (FL, LW, gonad maturity), blank: no sampling.

3. Length-frequency distribution

Using year-round LF data, the biological stock characteristics of *D. russelli* were evaluated. According to **Mildenberger *et al*. (2017)**, the LF data were aggregated over seven years (2015-2021) and analyzed simultaneously for each month. The TropFishR package's "lfqModify()" and "lfqRestructure()" functions were used to divide the LF data into 15-length classes and to convert them into monthly catches **(Taylor & Mildenberger, 2017)**.

4. Growth parameters

Growth curves were constructed using each model's fit algorithms and the "lfqFitCurves" function. The goodness of fit estimator (Rn) was calculated based on the number of positive peaks that the von Bertalanffy growth function (VBGF) curve crossed. According to **Taylor and Mildenberger (2017)**, $R_n = 10(^{ESP/ASP})/10$, where ASP is the "available sum of peaks," which may be regarded as the maximum possible score and is calculated as the sum of the highest values in positive scored peaks (i.e., runs of positively scored bins). ESP is the "estimated sum of peaks," or the sum of restructured data scores crossed by the estimated growth curves.

Ten optimization model approaches integrated into the TropFishR package were used to obtain the maximum Rn score from cumulative scores for growth parameters calculated and optimized by each model. The VBGF formula follows $L_t = L_{inf} (1-e^{-K(t-t0)})$, and the growth performance index $Ø' = \log_{10} (K) + 2\log_{10} (L_{inf})$ **(Pauly & Munro, 1984)**. L_{inf} is asymptotic length, K is the growth coefficient, t_0 is theoretical age when the length is 0cm, and L_t is the length at age-t. LFD typically does not have actual age information. Instead, sampling dates are used as time (t) in running the TropFishR package

(Mildenberger *et al.*, 2017). This t_0 and expected longevity (t_{max}) can be derived using the equation $\log(-t_0) = -0.3922 - 0.2752 \log L_{inf} - 1.038 \log K$, and $t_{max} = 3/K + t_0$ **(Froese *et al.*, 2000)**.

5. Mortality and exploitation rate

The natural mortality (M) was calculated based on the available life history and environmental parameters **(Kenchington, 2014)**. It was estimated following the equation $M = 4.118K^{0.73}L_{inf}^{-0.33}$ (**Then *et al.*, 2015**), which ran with the "fishmethods" package integrated into TropFishR. The total mortality (Z) was computed using the Linearized length converted catch curve (LCC) method, which was the slope between Ln N/t and the relative age, analyzed using the "catchCurve()" function in the TropFishR package. Fishing mortality (F) was calculated as F = Z – M, and the exploitation rate was E = F/Z **(Sparre & Venema, 1998)**.

6. Length at first capture

The yearly LFD was used to calculate the length at first capture (SL_{50}) of *D. russelli*. Analyzed data were modeled using a logistic curve and an intersection point of 50% of the cumulative frequency **(King, 2007)**: $SL = 1/(1 + \exp(a - bL))$. The equation is transformed into linear form to get the intercept (a) and slope (b): $\ln(1/SL_C - 1) = a - bL$, where SL is the estimated length, L is the mid-length of a class interval, and SL_C = relative cumulative of LF. SL_{50} obtained from -a/b.

7. Length at maturity

The sub-sample of female fish was aggregated with a size class of 1cm bins, and the percentage of mature fish was plotted against size bins. Length at maturity was estimated as a standard logistic curve of the form: $P_L = (1 + e^{-\ln(19)*(L-L_{50})/(L_{95}-L_{50})})^{-1}$, where P_L is the proportion of mature fish at length class L, and L_{50} and L_{95} are the lengths at which 50 and 95% of the fish in that length class are mature. Two-parameter logistic curve fitted to the proportion of mature individuals per length class using Excel-solver with minimum sum of square function. Logistic curves were fitted using non-linear least-squares estimation, and the corresponding 95% c.l. Fitting of the logistic curve to the data provided both L_{50} and L_{95}. Using the L_{50} and L_{95} parameters and a length measurement input into the P_L equation allows the prediction of the proportion of mature fish at that length **(Longenecker, 2020)**.

8. Data analysis

The TropFishR package in R **(Taylor & Mildenberger, 2017)** was utilized to assess the population parameters of *D. russelli* encountered during the study. The TropFishR package contains procedures such as ELEFAN to estimate the L_{inf} and K, which serve as inputs for the estimated M, and the LCC model for estimating the Z. These population parameters are the biological reference points. Statistical significance levels were set to 0.95, and all computations were performed in R- version 4.0.3 **(R Core Team, 2017)**.

RESULTS

1. Length-frequency distribution

The LFD of *D. russelli* ranged from 10.2 to 24.4cm. The size class of 16–19cm dominated the catch, comprising about 58% of the composition of the total sample. The yearly estimated mean lengths from 2015 to 2021 were 17.4 ± 1.9, 17.7 ± 1.8, 17.2 ± 1.8, 17.7 ± 1.9, 17.4 ± 2.0, 17.8 ± 1.8, and 17.1 ± 2.0, respectively (Fig. 2a). Moreover, the mean length was 17.5 ± 1.9 for seven years of aggregate data.

The LF data were restructured into 15 length classes with 1cm bin size and analyzed during the sampling period to estimate L_{inf} and K. We determined the class interval score setting by moving average (MA) = 7 **(Mildenberger *et al*., 2017a; Mildenberger *et al*., 2017b)**. The direction of the histogram (Fig. 2b) denotes positive (black, shown as peaks when the indicator Rn is calculated) and negative (white, shown as troughs) scored bins.

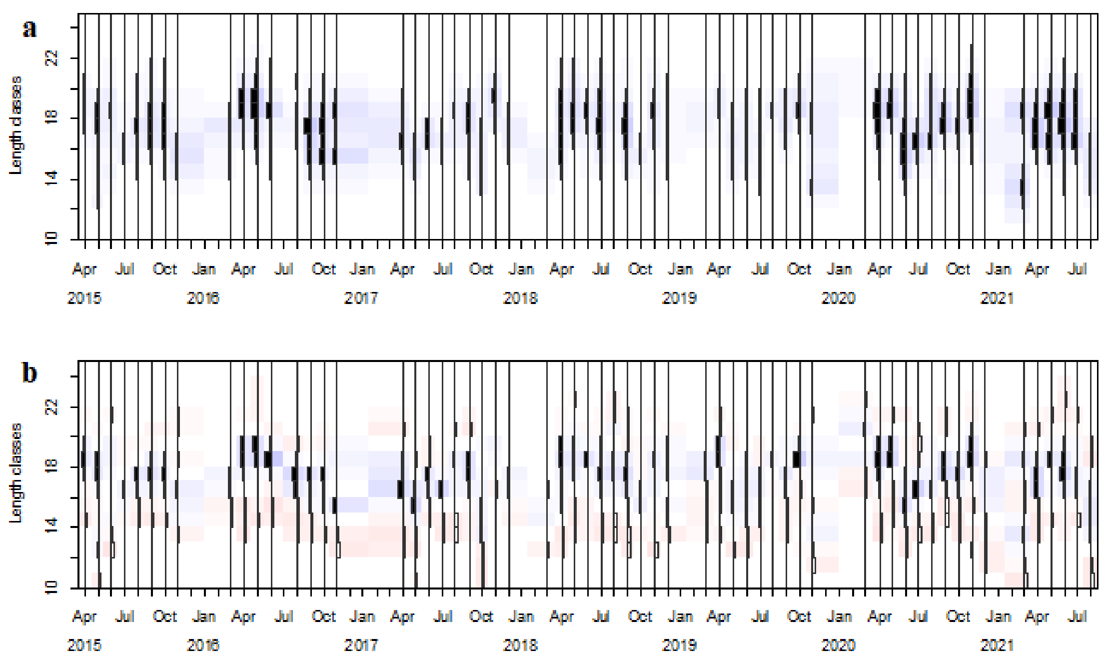

Fig. 2. The length frequency data of *D. russelli* is depicted in catches (a) and restructured data with MA= 7 (b)

2. Growth parameters

Ten approaches to a model were used to estimate the growth parameters of *D. russelli* (Table 2). Applying ELEFAN_GA in conjunction with seasonal oscillation was the most accurate and reproducible of the methods, with an Rn value of 0.28 indicating this. Rn has a maximum value of 1.0. Nevertheless, it is essential to remember that the actual Rn is highly species-dependent **(Taylor & Mildenberger, 2017)**.

Table 2. The growth parameters of *D. russelli* were estimated using ten model approaches in TropFishR

Model	Parameters								
	L_{inf} (cm)	K (year^{-1})	t_anchor	C	ts	t_0 (year)	t_{max} (year)	Ø' (year^{-1})	Rn_max
1	23.76	0.57	0.19	0	0	-0.30	4.96	2.51	0.19
2	23.76	0.59	0.27	0	0	-0.29	4.79	2.52	0.22
3	23.55	0.52	0.04	0	0	-0.33	5.43	2.46	0.22
4	23.41	0.43	0.78	0	0	-0.41	6.57	2.37	0.17
5	23.06	0.63	0.27	0	0	-0.28	4.49	2.53	0.24
6	23.00	1.00	0.22	0	0	-0.17	2.83	2.72	0.19
7	23.23	0.62	0.30	2.53		-0.28	4.53	2.53	0.23
8	23.13	0.61	0.07	0.54	0.76	-0.29	4.67	2.51	0.22
9	23.61	0.62	0.37	2.54		-0.28	4.59	2.54	0.23
10	23.36	0.64	0.49	0.65	0.70	-0.27	4.39	2.55	0.28

Note: Model K-Scan (varies K, L_{inf} is fixed); 1) cross' method, 2) K-Scan. Response Surface Analysis (varies L_{inf} and K); 3) cross' method (used in FiSAT), 4) cross' method (bin with maximum score crossed), 5) optimize' method (default), 6) RSA. Optimization Algorithms; 7) ELEFAN-SA without seasonal oscillation, 8) ELEFAN-SA with seasonal oscillation, 9) ELEFAN-GA without seasonal oscillation, 10) ELEFAN-GA with seasonal oscillation.

The estimated VBGF parameters L_{inf}, K, t_0, and t_{max} of *D. russelli* provided using the ELEFAN GA method were 23.36 cm, 0.64 year^{-1}, -0.27 year, 4.39 year, respectively. The VBGF was described by $L_t = 23.36 \times (1\text{-}e^{(-0.64(t+0.27))})$ (Fig. 3). The Ø' was estimated at 2.55 years^{-1}, with R_n of 0.28. In general, parameters Ø' estimated by ELEFAN_GA were higher than another model approach.

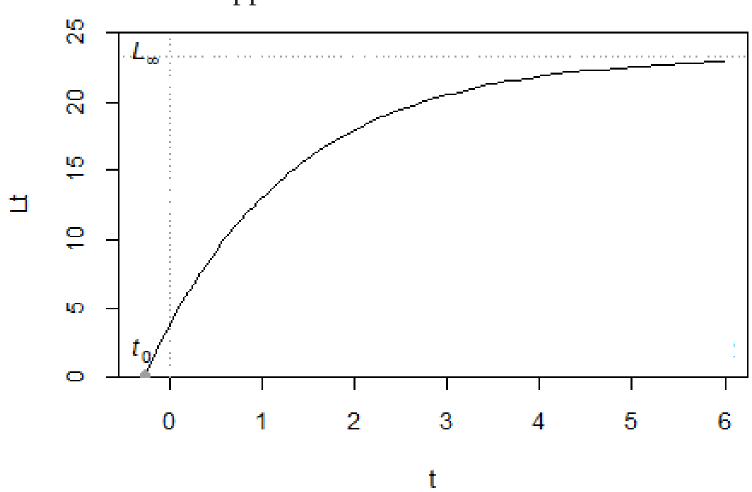

Fig. 3. The curve of von Bertalanffy growth of *D. russelli*

Five length classes were identified by applying ELEFAN_GA approaches to LF data (Fig. 4). The growth rate of *D. russelli* in the Natuna Sea is illustrated as follows: the first size class, consisting of 10cm in April 2017, had an FL of approximately 13.5cm in

October 2017. Fish released after April 2017 had an FL of 17.5cm in August 2018 for the second class. *D. russelli*, composed of the third to five-length classes, grew slower (Fig. 4). Fish reveal a rapid growth throughout their early life stages, often within the first three years. Afterward, their growth rate gradually slows exponentially during the following years **(Mallawa, 2011)**. The K value of *D. russelli* (0.64) in the Natuna Sea was slightly more than 0.5, exhibiting signs of moderate growth to reach L_{inf}.

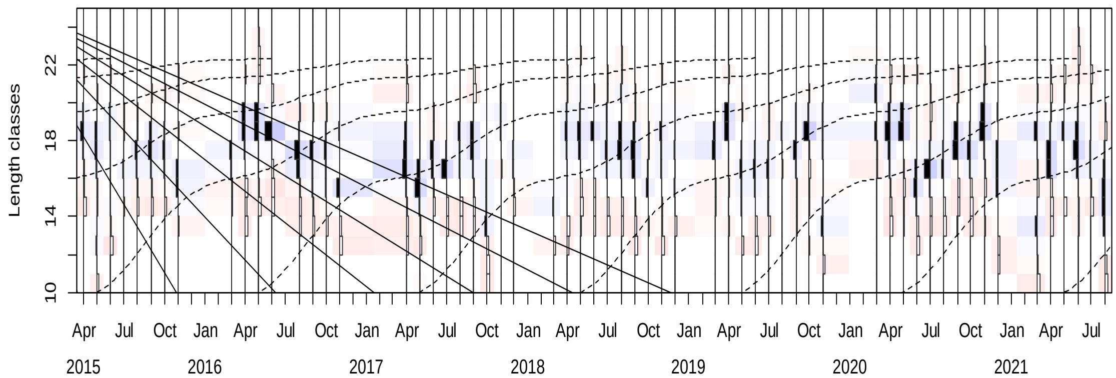

Fig. 4. The graphical fit of estimated growth curves plotted by ELEFAN_GA (dashed lines) through the LF data of *D. russelli* during sampling time

3. Mortality and exploitation rate

The L_{inf} and K derived through the ELEFAN_GA with seasonal oscillation approach were then used to calculate M and were estimated to be 1.06 year^{-1}. The instantaneous Z estimated by function "catchCurve()" in TropFishR was presented as a rate of 2.09 ± 0.08 year^{-1} (Fig. 5). Hereafter, the F- value was estimated to be 1.03 year^{-1} and the existing E was 0.49 year^{-1}, which indicates that the stock of *D. russelli* is below the optimal limit (E = 0.5) or underexploited **(Gulland, 1983)**.

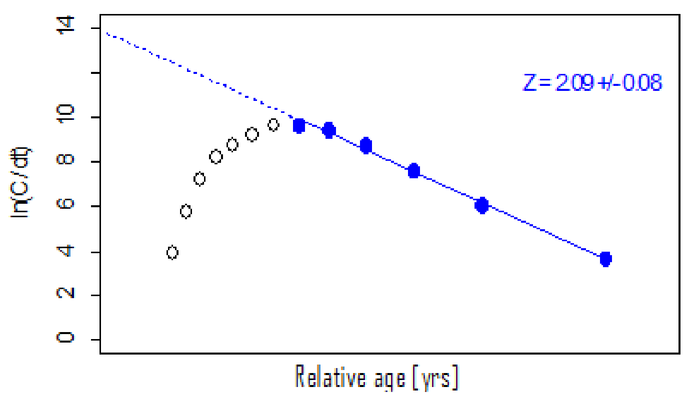

Fig. 5. Linearized length-converted catch curve for the estimated total mortality

4. Length at first capture and length at maturity

The SL_{50} from 2015 to 2021 was estimated at 16.93, 17.37, 16.59, 17.23, 16.78, 17.23, and 16.25cm, respectively. SL_{50} = 16.79cm and SL_{95} = 19.25cm for seven years aggregate. The L_{50} in 2015 and 2021 were 16.59 and 14.81cm, respectively. The L_{50} = 15.42cm and L_{95} = 19.48cm were aggregated during the sampling period (Fig. 6).

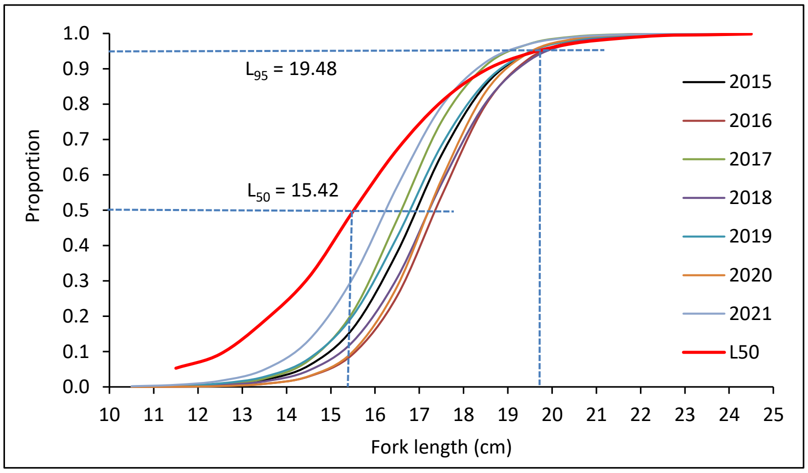

Fig. 6. The catch curve's selectivity estimated length at 50% (SL_{50}) and 95% (SL_{95}) captured for each year, and female length at 50% (L_{50}) and 95% (L_{95}) matured

The fitting curve of LFD represents a slight negative skewness, in which about 60% of the catch composition had FL higher than SL_{50} (16.79cm), and about 79.5% were matured with FL higher than L_{50} (15.42cm), which means that the majority of the catch was a large size and adult fish (Fig. 7).

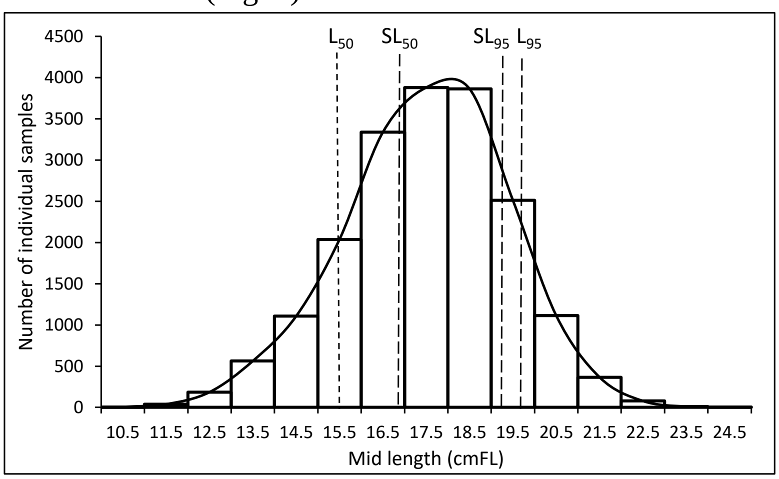

Fig. 7. The length at which 50% (SL_{50}) and 95% (SL_{95}) were captured and female length at 50% (L_{50}) and 95% (L_{95}) matured on length frequency distribution

DISCUSSION

The present study applies several model approaches to estimating L_{inf} and K as crucial variables to obtain M, F, and Z as input on the length-based stock assessment. The higher Rn value from ELEFAN_GA_seasonal oscillation indicates that this model performs better than other approaches in estimating growth parameters. The

ELEFAN_GA method is preferable for approximating global optimization in a large search space for an optimization problem **(Taylor & Mildenberger, 2017)**.

In the ELEFAN method, the first thing to pay attention to is setting the class interval score or moving average during the initial LF restructuring process and determining the L_{inf}, where LF restructuring was found to affect parameter estimation errors significantly. The TropFishR package can determine the number of size classes considered by the MA calculation, which is different from the static setting (MA = 5) in FiSAT I. The MA value setting is based on the number of size classes covering the class width in the smallest group, reflecting the youngest group after recruitment into the fishery **(Mildenberger *et al*., 2017a; Mildenberger *et al*., 2017b)**.

There were differences in the growth forms of *D. russelli* compared to the previous studies in other areas (Table 3). The difference may be due to differences in size structure caused by differences in sampling periods, fish sample sizes, and fishing areas **(Moazzam *et al*., 2005)**. Differences in environmental parameters, food availability, predation, exploitation, and fishing gear type can influence growth parameters **(Ghosh *et al*., 2016)**. Habitats with sufficient nutritional content or the availability of natural food can support optimal fish growth, while intensive fishing activities do not allow fish to grow larger, and hence their maximum length tends to be smaller **(Suwarso & Wujdi, 2015)**. Differences in growth parameter values (1.01 to 2.28) can also be caused by differences in geographical location, water conditions, and food supplies **(Effendie, 2002)**. If the species perceive poor survival in a particular environment, they are likely to grow with small bodies rapidly, exhibit early spawning, and have a short lifespan **(King, 2007)**. According to **Widodo (1988)**, differences in growth parameters are more influenced by the composition of the sample size than by the method used.

The Ø' is considered a valuable tool for comparing the growth curves between populations of the same species or different species that belong to the same family **(Park *et al*., 2013)**. Most studies regarding the population parameters of *D. russelli* in Indonesian waters (Table 3) did not report growth performance values. From this study, the growth performance index (Ø' = 2.55 $year^{-1}$) was in line with estimates for *D. russelli* from Vizhinjam **(Sreenivasan, 1982)**, *D. macrosoma* in Tawi-Tawi (**Aripin & Showers, 2000)** and Mackerel Scad in South China Sea **(Xu *et al*., 2023)** that reported Ø' of 2.67, 2.68 and 2.68, respectively. The similarity Ø' of those studies indicates the reliability of the estimated L_{inf} and K **(Sparre & Venema, 1998)**. This is because Ø' expresses a commonality between the growth patterns of different fishes **(Pauly, 1991)**.

However, the Ø' from other studies have a slight difference, such as estimates of *D. russelli* from Kakinada **(Murty, 1991)** and Mumbai waters **(Jaiswar, 2001)** of 2.76 and 2.91, respectively. *D. macrosoma* in Palawan **(Ingles & Pauly, 1984)** and Antique **(Magallanes *et al*., 2022)** were 2.82 and 2.84, respectively. The mackerel scad in Banda Sea **(Silooy *et al*., 2019)** and Java Sea **(Bintoro *et al*., 2020)** were 2.79 and 3.06, respectively.

Table 3. The growth parameters of the Indian scad (*D. russelli*) in other studies

No	L_{inf} (cm)	K ($year^{-1}$)	t_0	M	Data period	Location	References
1	29.62	0.60	-0.66	0.00	September to December 2020	Ternate, Maluku Sea	Ahmad *et al*. (2021)
2	31.50	0.88	-0.18	1.63	February to March 2020	northern and western waters of Aceh	Damora *et al*. (2021)
3	26.16	0.63	-0.20		July - August 2019	Bali Straits	Lelono *et al*. (2021)
4	28.28	0.83	-0.18		January - March 2020	southern waters of East Java	Lelono *et al*. (2021)
5	24.63	0.63	-0.27		December 2019	Madura Straits	Lelono *et al*. (2021)
6	23.60	0.60	-0.28		March - August 2014	Natuna Sea	Faizah and Sadiyah (2020)
7	22.10	1.70	-0.32	1.48	January – April 2019	Java Sea (Remban-Central Java)	Nur Khasanah *et al*. (2020)
8	25.00	0.58	-0.29		February - July 2018	Sumenep waters-East Java	Bintoro *et al*. (2019)
9	25.60	0.95	0.00	1.81	September, 2007 to August, 2009	Mumbai waters	Panda *et al*. (2012)
10	27.70	1.24	-0.34	2.10	Sept 2004 to May 2007	Mumbai waters	Poojary *et al*. (2011)
11	27.10	1.22		2.08	September, 2000 to August, 2002	Malabar, Indian coast	Manojkumar (2007)
12	23.19	0.70	-0.16		1998	Karnataka coast, India	Rohit and Shanbhogue (2005)
13	24.00	1.42		2.63	September 1996 - August 1998	Mumbai waters	Jaiswar *et al*. (2001)

As stock indicators, the biological reference points F/M, M/K, and F/Z are better suited since they are more resistant to uncertainties in model parameters, e.g., natural stock variability, sampling errors, inaccurate growth estimates, mortality, and exploitation. It has been demonstrated that the formula we used to estimate M performs better than the Alverson-Carney's method based on K and t_{max} and Pauly's method based on water temperature, L_{inf} and K **(Then *et al*., 2015)**.

The slightly lower F than M (F/M = 0.97) confirmed no overfishing for the *D. russelli* population. The ratio F/M is slightly lower than necessary to achieve the maximum (1.0). This sensitivity to fishing operations does not outweigh predation, illness, or environmental changes. The F ≈ M shows that this species is appropriately exploited. When fish reach a size appropriate for capture, mortality within the population can be attributed to natural and fishing mortality.

The M/K ratio was 1.63, which falls within the ideal range of 1.5 to 2.5 **(Beverton & Holt, 2012)**. It has consistently varied between 1.12 and 2.5 for most fishes **(Macer, 1977)**. The M/K in this investigation was within the acceptable defined range. Extreme variations in ambient temperature, habitat degradation, predator predation, cannibalism, spawning, and old age are all potential causes of natural mortality **(Widodo & Suadi, 2006)**.

The optimum exploitation rate (E_{msy}) occurs when M and F are equal (E = 0.5 year^{-1}). Suppose E < E_{msy} means that the stock status is still underexploited or healthy **(Gulland, 1983)**. This study obtained an E current of 0.49 year^{-1}, reaching Emsy, which indicated not experiencing overfishing, and pointed out the optimum fishing pressure and underexploited *D. russelli* stock in the Natuna Sea. The E value was 0.49, meaning that 49% of the mortality rate resulted from fishing activities during this research.

In addition, the K value of *D. russelli* was higher than 0.5 (K> 0.5). According to **Sparre and Venema (1998)**, fish with a sluggish K take longer to achieve their maximum length, whereas fish with a high K require short time. The faster fish reach the maximum size, the faster they reach mature gonads and spawn, and the lifespan is not disturbed, even though there is a high level of exploitation.

Fisheries management is managing the E is under or not to exceed the threshold (E = 0.5); this is done by regulating the F **(Mehanna *et al*., 2017)**. The exploitation rate greatly influences a population's recruitment process, and a higher level can reduce the optimacy of the recruitment process **(Mallawa & Amir, 2019)**. In 2015, MMAF began implementing the moratorium (Ministerial Decree No. 56, 2014) and banned transshipment (Ministerial Decree No. 57, 2014) on capture fisheries in FMA of Indonesia. Therefore, from 2015 to 2017, purse seiners based on Java's north coast, such as Pekalongan and Tegal, whose previous fishing in the Natuna Sea, gradually shifted fishing grounds to the Java Sea and the Makassar Strait, thus reducing the fishing effort of small pelagic in the Natuna Sea.

Previous studies on the *D. russelli* population in Indonesia waters, such as in the Java Sea that landed at the Tasikagung fishing port of Rembang, Central Java, reported it has an under-exploitation status (E = 0.49 year^{-1}) **(Nur Khasanah *et al*., 2020)**. However, the results of this study differed from those of **Ahmad *et al*. (2021)** in that *D. russelli* landed at the Nusantara Fishing Port of Ternate, North Maluku, and in the northern and western waters of Aceh **(Damora *et al*., 2021)**, suggesting that the *D. russelli* population has been overexploited, with an E value of 1 and 0.58 year^{-1}, respectively. The differences in fishing mortality are caused by differences in the distribution of fish sizes or age groups, especially the temporal and spatial migration of small pelagic and schooling behavior. In addition, the fishing mortality rate is generally influenced by the level of fishing effort; the higher the fishing intensity, the greater the impact on the mortality coefficient. Meanwhile, according to **Koolkalya *et al*. (2017)**, different mortality rates are caused by different stocks and fishing pressures on the population.

The length at maturity function provides information on the proportion of mature individuals at any given size. The L_{50} is the length at which 50% of individuals at that length are mature. Most analyzed *D. russelli* belonged to adult-size classes, with SL_{50} under current fishing pressure of 16.25cm and L_{50} of 15.42cm. The dynamics of the SL_{50}

have insignificant fluctuations, with the variance of SL_{50} from 2015 to 2020 being 0.09cm, indicating that the LFD of *D. russelli* was relatively constant under the constant mesh size (1 inch) of the purse seine during the study. However, it is of concern that SL_{50} decreased by approximately 1cm from 2020 to 2021, indicating that the fish caught were getting smaller although the size caught was still larger than the mature size.

The SL_{50} was greater than the L_{50}, indicating that the process of recruiting or regenerating fish in nature is going well because it is suspected that the fish were caught after spawning first, hence, the principle of sustainability is still occurring **(Froese, 2004)**. It can also be assumed that small fish or immature gonads have a different place to live than mature fish. The fishing activity did not affect the spawning, recruitment, and growth processes during the research period. The F value was relatively equivalent to M, revealing that fishing was not the main contributor to the loss of *D. russelli* rather than naturally induced mortality within the Natuna Sea. According to both conditions, the Indian scad fishery in the Natuna Sea is in equilibrium. The exploitation model in the current study assumed a constant growth and mortality rate, failing to account for the influence of environmental variability, predation, and food availability on population growth, mortality, and reproductive success **(Hollowed *et al*., 2013)**.

The length classes of fished *D. russelli* are more significant than the desired size classes. The SL_{50} was 9% higher than the L_{50}, or 1.08 L_{50}, and excellent yields could be maintained. According to **Prince *et al*. (2020)**, having SL_{50} 20% bigger than L_{50} conserves at least 20% of the spawning potential ratio and ensures a fishery's sustainability. In addition, approximately 50% of SPR is achieved, and yields can be optimized if SL_{50} is set at 1.05–1.15 L_{50} and 1.3–1.4 L_{50} **(Prince & Hordyk, 2019)**.

The selectivity and maturity curve estimates suggest that the current fishing selectivity primarily focuses on catching large and mature *D. russelli*. It implies that overfishing is unlikely for the assessed stock. However, the fish caught were indicated to be getting smaller in the last period of this study, with SL_{50} in 2021 being about 1cm below SL_{50} in 2020.

Regarding $SL_{95} < L_{95}$, it indicates that large fish were caught before they reached the mega spawner. The LFD (Fig. 7) indicates that there are fewer (8.5%) mega spawners with a length > L_{95} (19.70cm), which indicates the possibility of recruitment overfishing. According to **Froese (2004)**, the mega-spawner's availability of less than 20% indicated an overexploitation. These indications should be a warning to consider mesh size that correlates with selectivity at SL_{95}. The long-term sustainability of mega spawner stock is projected to enable more extraordinary fishing efforts and may improve the reproductive capability of the *D. russelli* population in the Natuna Sea (FMA-711).

The exploitation rate of *D. russelli* by purse seiners in the Natuna Sea was equivalent to the optimum level. Therefore, it is necessary to maintain the current fishing efforts, such as the number of purse seiners, mesh size, and fishing days, for effective management strategies, with high monitoring of the implementation of the current management policy to avoid overexploitation.

CONCLUSION

Adult *D. russelli* contributed more to the number of catches in the Natuna Sea. According to the exploitation rate equivalent to the optimum level, the species is not experiencing overfishing. This species is predominantly harvested at a length greater than the length at first maturity, indicating that the stock is sustainable. The current fishing effort does not alter the recruitment potential of the stock. The current fishery stock exploitation practices are appropriate for sustainable management. Therefore, in terms of effective management strategies, it is necessary to maintain the current fishing efforts. However, management policy implementation should be accompanied by high monitoring, considering the low abundance of mega spawners.

The current study provides information regarding the stock status of *D. russelli* caught by purse seiners in the Natuna Sea, despite the limited reference data. It is an apparent reference for developing harvest control rules to achieve sustainability. Long-term data monitoring are recommended to better understand the stock status of the species and its role in the ecosystem. The data on catch-effort, length-frequency, and biological aspects are collected continuously to obtain high-quality data and reduce the uncertainty of the analysis results. A more comprehensive and sophisticated strategy is required to ensure the long-term management of the *D. russelli* population and other fisheries.

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