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Length-Based Stock Assessment of the Mackerel Scad, *Decapterus macarellus* (Cuvier, 1833) From the Tanzanian Coastal Waters

Joseph Salawa Sululu[1,2] | Blandina Robert Lugendo[2] | Paul Tuda[3] | Benaiah Lameck Benno[4]

[1]Tanzania Fisheries Research Institute (TAFIRI), Dar es Salaam, Tanzania | [2]Department of Aquatic Sciences and Fisheries Technology, University of Dar es Salaam, Dar es Salaam, Tanzania | [3]Leibniz Centre for Tropical Marine Research (ZMT), Bremen, Germany | [4]St. Joseph University in Tanzania (SJUIT), Dar es Salaam, Tanzania

Correspondence: Joseph Salawa Sululu (jsululu02@gmail.com)

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ABSTRACT

This study aimed to conduct a stock assessment of *Decapterus macarellus* from Tanzanian coastal waters to determine its current stock status and provide appropriate management recommendations. We used a suite of length-based methods, including the Electronic Length Frequency Analysis (ELEFAN) programme to estimate growth parameters and catch curves to evaluate exploitation fishing and mortality parameters; Length-Based Spawning Potential Ratio (LBSPR) to calculate the spawning potential ratio (SPR), length-based indicators (LBI) to assess sustainable fishing levels and length-based reference point (LBRP) to determine the target reference point (RP) for stock spawning biomass (SB). The results indicated that this small pelagic species grows fast, with a growth rate (K) of 0.74 year^{-1} and a growth performance index (Φ') of 2.88. However, the stock is currently at risk of overfishing due to high fishing pressure ($F/M > 1$) and an elevated exploitation rate ($E = 0.71$), which resulted in a very low SPR (SPR = 0.11) and SB below the target RP. Yield-per-recruit analysis revealed that the current fishing effort ($F_{curr} = 2.57$) far exceeded the precautionary limit ($F_{0.1}$) and surpassed the fishing mortality rate that maximizes yield per recruit ($F_{max} = 1.73$). This excessive effort largely impacted mega-spawners, reducing their proportion in the catch to a critically low percentage (9%). On the basis of these findings, the study recommends reducing the current fishing effort to $F_{0.1}$ (0.84) by limiting the number of ring nets, implementing seasonal closures during peak spawning periods and operating in deeper waters (40–200 m) to protect juveniles and minimize mega-spawner capture.

1 | Introduction

The mackerel scad, *Decapterus macarellus*, is a small pelagic species within the Carangidae family. It is primarily caught by ring or purse seine nets, both in the commercial and artisanal fisheries (Bianchi 1985; Ohshimo et al. 2014; Silooy et al. 2019). The species can attain a maximum size of 46 cm, with a common size of 30 cm (Prado and Bearez 2004). These fishes are found in large, fast-moving schools (Ramlochan 2016), with large shoals of adult individuals inhabiting clear oceanic waters at depths of 40–200 m (Silooy et al. 2019; Ramlochan 2016; Widiyastuti et al. 2020), where tiny fishes such as anchovies are rarely or never found. Small schools of juveniles of *D. macarellus* have sometimes been reported in near-deep waters (McNaughton 2008).

The mackerel scad spawn at a depth range of between 20 and 100 m, where pelagic eggs hatch into free-floating larvae (Ramlochan 2016; Honebrink 2000; Weng and Sibert 2000). The juveniles grow in sheltered inshore waters where they later on recruit into adult schools and move into nearshore open waters (Ramlochan 2016; Veira 2019). Because of its schooling behaviour, *D. macarellus* is prone to heavy exploitation and is a common target for fishers employing encircling fishing nets such as ring nets. In Tanzanian shallow waters, *D. macarellus* is usually caught along with other small pelagics, such as anchovies and clupeids, mainly using ring nets with light attraction during moonless nights (Anderson and Samoilys 2016).

D. macarellus and other species within the *Decapterus* genus are carnivorous fishes that play a significant role as economically important resources in human food systems across tropical and subtropical waters (Ohshimo et al. 2006; Shiraishi et al. 2010). The economic importance of this species in Tanzania is based on its high demand for local consumption and for the export market to neighbouring countries (Sekadende et al. 2020), such as Kenya (Jiddawi and Öhman 2002), Uganda, Congo-DRC, Zambia, Malawi, Burundi and Rwanda (Clotilde and Christophe 2015).

D. macarellus is among Tanzania's most important small pelagic fish after *Dussumieria acuta* (Kevern and Dave 2015). Moreover, this species, along with other marine small pelagic fishes, constitutes a major source of protein and food for coastal communities in Tanzania, particularly for low-income households (van Hoof and Kraan 2017). The smaller size of this species compared to other scad species (Bianchi 1985) makes it relatively cheaper, more readily available and easier to process and transport. Consequently, fishing pressure on small pelagics, and specifically on the mackerel scad, has increased tremendously. For instance, the number of ring nets targeting small pelagic fishes in Tanzanian coastal waters increased by 27% between 2018 and 2020 (Sekadende et al. 2020).

Despite its economic significance, *D. macarellus* lacks baseline life history information necessary for effective management, not only in Tanzanian waters but also in the Southwest Indian Ocean (SWIO) region as a whole. Besides, the species lacks long-term series data for stock assessment, and little research has been conducted on its abundance (Sekadende et al. 2020). High demand coupled with limited biological data threatens the species' survival and may lead to stock decline if overexploitation persists (Zhai and Pauly 2019). To establish an appropriate baseline for management and ensure sustainable exploitation of this species, comprehensive information on population dynamics and stock status is essential (Silooy et al. 2019; Melnychuk et al. 2017; Alam et al. 2021).

In the absence of long-term fisheries data for stock assessment, alternative data-limited stock assessment approaches can be used to infer stock status on a precautionary basis (Chong et al. 2019). Data-limited approaches take advantage of the relatively scarce data to estimate life history parameters and fisheries reference points (RPs), which can be used to determine stock status (Froese and Binohlan 2000). Nevertheless, it is of paramount importance to choose a suite of data-limited methods that matches the data quality and considers the uncertainty associated with the approach (Rosenberg et al. 2018). In data-limited fisheries, length frequency data from either artisanal or industrial catches are the primary data type collected because they are relatively inexpensive and easy to collect (Hordyk et al. 2015; Mildenberger, Taylor, and Wolff 2017; Alam et al. 2022). Data-limited assessment approaches, which make use of such data, are progressively applied to report on the regional status of fisheries across many stocks, thereby providing essential inputs for management decisions in the absence of long-term series data (Costello et al. 2012; Hordyk et al. 2016; Dowling et al. 2019).

It is well known that in fisheries science there are not sufficient resources, both in terms of financial and human, to meet the growing demand to collect data and undertake species stock assessments. In most countries, including Tanzania, appropriate and adequate data collection programmes are in place for some species of high commercial value (Kilduff, Carmichael, and Latour 2009). Similar to most of the world's fish stocks, *D. macarellus* is a small pelagic species and among the data-poor stocks that lack substantial data sets (catch at age, catch per unit effort, life-history parameters etc.) in Tanzania. Therefore, it becomes difficult to assess this stock with long-term fisheries data that can build the most robust estimates for the establishment of management strategies.

Length frequency data sampling, particularly in tropical regions, typically represents a single-year data set. However, most analytical methods used to interpret fish population data are less effective with only 1 year of data, as it is difficult to distinguish between recruitment and fishing mortality, which leads to high uncertainty (Chong et al. 2019). Despite this drawback of the length-based data-limited technique, using time-series data does not always guarantee better stock estimates (Dowling et al. 2019). More importantly, reliable estimates depend on the validity of the assumptions of the analytical methods and the life history attributes of the fish (Carruthers et al. 2014; Chong et al. 2019). Although fish stock assessments typically use time-series data, the quality of the data and the validity of the methods are often more significant in determining the reliability of the assessment (Chong et al. 2019). Therefore, data-limited approaches can still provide some valuable and reliable insights into the stock status of fish, provided that appropriate analytical methods are applied to the available data (Pons et al. 2019).

This study employed four data-limited length-based stock assessment approaches, namely, length-based indicators (LBIs), length-based RP (LBRP), Electronic Length Frequency Analysis (ELEFAN) programme and Length-Based Spawning Potential Ratio (LBSPR), to quantitatively assess the stock status of *D. macarellus* from Tanzanian coastal waters. Fish samples for the study were collected from artisanal ring net fishers, and length-frequency data (LFQ) were the key inputs for assessing stock dynamics. LBI was applied to assess sustainable fishing levels, whereas the LBRP evaluated spawning biomass (SB) RPs and selectivity patterns. Growth parameters were estimated using the ELEFAN programme, and LBSPR was used to assess the reproductive health of the stock. Mortality parameters (total, natural and fishing) were calculated using length-converted catch curve analysis and biological RPs (BRPs) ($F_{0.1}$, $F_{0.5}$ and $F_{\max}$) were derived from per-recruit models in TropFishR.

A number of data-limited, length-based stock assessment methods have been developed to estimate biological parameters and assess stock dynamics. The four data-limited length-based stock assessment approaches were chosen for their robustness and reliability in providing practical management advice under poor data conditions. The LBI and LBSPR were recommended by the ICES WKLIFE V workshop (ICES 2015) as effective tools for reliable stock assessments. These methods are robust due to their sensitivity to biological assumptions and parameter inputs (Rudd, Thorson, and Sagarese 2019).

ELEFAN method, applied through the TropFishR R package, was chosen for its improved optimization procedures, which enhance the estimation of uncertainties and hence give more reliable estimates compared to the older FISAT II version (Gayanilo, Sparre, and Pauly 2005). Besides, the integration of the new indicator 'P_{obj}' into the LBRP framework represents a significant advancement. This indicator incorporates the Cope and Punt decision tree, enhancing the interpretation of catch length composition data under varying fishery conditions by considering fishery selectivity patterns. Additionally, P_{obj} has a stronger correlation with SB than individual LBI indicators, such as P_{mat}, P_{opt} or P_{mega} (Cope and Punt 2009). Consequently, applying the LBRP framework provides a basis for developing harvest control rules that enable proactive fisheries management under data-limited conditions. These methods collectively ensure a comprehensive and reliable approach to assessing stock dynamics and informing management decisions.

Our goal is to provide a comprehensive baseline that can be used to make precautionary management decisions and improve the fisheries data collection strategy for the mackerel scad (*D. macarellus*) and other small pelagic fish in Tanzanian waters.

2 | Materials and Methods

2.1 | Study Site

Fish samples were collected from fishers at two landing sites, Kasera in Tanga City on Tanzania's northeastern coast and Customs in Bagamoyo on Tanzania's mid-eastern coast (Figure 1). The two sites were chosen on the basis of high catch records of small pelagics and the dominance of ring net fishery (Clotilde and Christophe 2015; Ministry of Livestock and Fisheries 2020), which is the main fishing method for small pelagics.

Marine fisheries in Tanga and Bagamoyo are predominantly artisanal and concentrated in shallow waters (Clotilde and Christophe 2015). Both areas host diverse marine resources, including small pelagics (anchovies, clupeids, carangids, sardines and mackerels), large pelagics (tunas and tuna-like species), coral reef fishes, demersal species and molluscs (Sekadende et al. 2020). Additionally, Bagamoyo exhibits unique significance as a prawn fishing ground, contributing notably to Tanzania's prawn landings (Mwakosya 2016).

The artisanal sector dominates fisheries in both areas, accounting for over 90% of all catches (Sekadende et al. 2020). Artisanal fishers typically use vessels like dug-out canoes and planked boats and employ gears such as gillnets, handlines and ring nets. Small pelagic fisheries are reported to make a substantial, though likely underestimated, contribution to coastal livelihoods and food security in Tanzanian marine areas, including Tanga and Bagamoyo (Mayala 2018). The 2018 survey showed that Tanga accounts for up to 45% of fishers mainly engaging in small pelagic fishery in mainland Tanzania. Ring nets, with mesh sizes of 8–10 mm in Tanga and 6–12 mm in Bagamoyo, are extensively used to catch small pelagics, including anchovies, clupeids, *Decapterus* spp. and mackerels (Ministry of Livestock and Fisheries 2020). Kasera is Tanga's primary landing site for small pelagics, supporting approximately 70% of the municipality's population through fish consumption and trade (Mwaipopo and Mahongo 2020). On the other hand, Customs in Bagamoyo is the largest landing site in terms of landings and serves as a hub for auctioning fish (both small pelagics and larger species) from various fishing grounds within Bagamoyo's coastal waters (Tobey et al. 2013).

Monsoon winds significantly influence small pelagic landings in both areas, with higher landings during the calmer northeast monsoon compared to the southeast monsoon (Clotilde and Christophe 2015). Moreover, Tanga's coastal waters, located within the Pemba Channel and influenced by the East African Coastal Current (EACC), experience coastal upwelling during the northeast monsoon. This upwelling enhances phytoplankton growth, which supports high productivity in the small pelagic fishery in the area (Margareth et al. 2020).

2.2 | Sensitivity Analysis

Sensitivity analysis was conducted on the four data-limited methodologies used in this study: LBIs, LBSPR, LBRP and the ELEFAN method. The primary input parameters analysed were von Bertalanffy growth parameters (L_∞, K), natural mortality to growth coefficient ratio (M/K), length at maturity (L_{mat}) and size at first capture (L_{c50}) and at (L_{c75}). Parameter bias simulation was carried out as per Hordyk et al. (2015), whereas each parameter was varied by ±10%, ±20% and ±30% to evaluate its influence on model outputs. Therefore, model recalibration was done whereby each methodology was recalculated with biased input parameters. This step involved systematically varying the key input parameters used in each methodology (e.g., L_∞, M/K, L_{mat}) to establish controlled biases. After recalibrating the models with biased input parameters, the primary indicators produced by each methodology were calculated and recorded. The sensitivity metrics provide quantitative measures of how changes in input parameters impact model outcomes. Thereafter, evaluation was done by comparing indicators across bias scenarios to identify the most sensitive parameters. This was done by comparing the magnitude of changes for each indicator under the different bias scenarios (e.g., ±10%, ±20% and ±30% for L_∞, M/K and L_{mat}), also by identifying the parameters that cause the greatest variability in key indicators, as these are considered the most sensitive.

2.3 | Fish Sampling

Fish samples were collected from local fishers who operate ring nets. The ring net fishery is conducted during the moonless nights with the help of light attraction devices, where one or more lamp skiff boats are used to attract the schools of fish, around which the net is set. The gear is normally operated by motorized boats with a fishing crew of between 15 and above fishers (Clotilde and Christophe 2015). The ring nets in Tanga had mesh sizes of about 8–10 mm, were 80 m in length and were operated at a depth of up to 12 m, whereas those in Bagamoyo had mesh sizes of

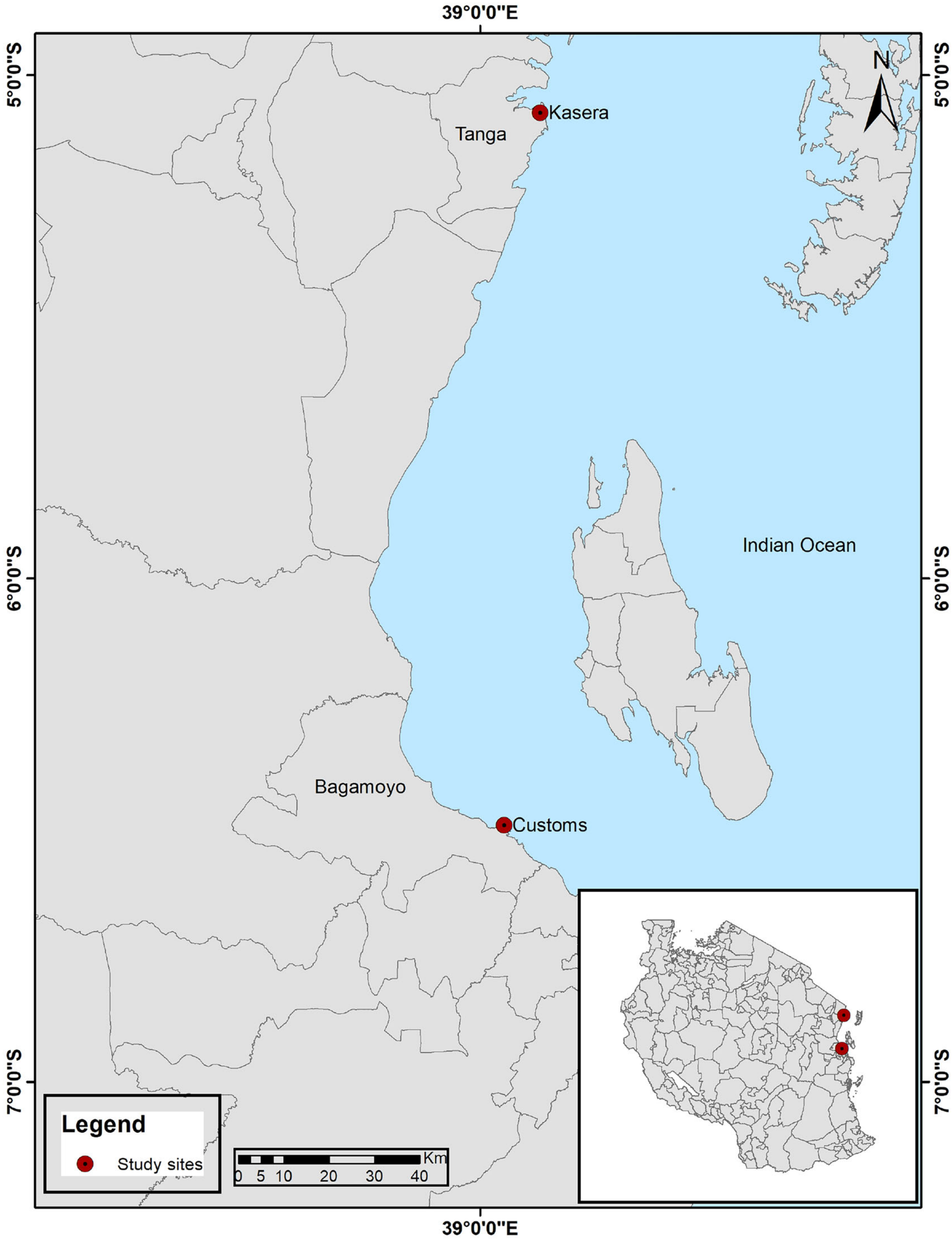

FIGURE 1 | Map of the study sites: Kasera in Tanga and customs in Bagamoyo, Tanzania.

6–12 mm, 100 m in length and were operated at a maximum depth of 20 m. Sampling was conducted for 4–6 days in each month for 20 months (from February, 2019 to September, 2020). Once a sample was obtained, *D. macarellus* were sorted out, and after the confirmation of their species identification using field guides by Bianchi (1985) and Smith (2003), they were kept in a separate cool box containing ice so as to slow down microbial activity before undertaking some measurements. Then, each individual fish was measured for total length (TL) using a measuring board and total weight (TW) by an electronic balance, to the nearest 1 cm and 0.01 g, for TL and TW, respectively.

2.4 | Data Analysis

2.4.1 | Length-Based Assessment

For the first-level assessment, a simple fishery indicator–based approach proposed by Froese (2004) was applied to the length frequency data to assess catches for evidence of growth and recruitment overfishing. Froese (2004) proposed three simple indicators: (I) 'P_{mat}', which measures the percentage of mature specimens in the catch, with >90%–100% as the reference target point, based on the formula: P_{mat} = % fish in sample >L_m, where

L_m is the length at first maturity; (II) 'P_{opt}', which measures the percentage of fish caught at optimum length, with >90%–100% as the reference target point, and the formula is given as P_{opt} = % fish between 0.9 L_{opt} and 1.1 L_{opt}, where $\log(L_{opt}) = 1.053 \times \log(L_m) - 0.0565$, as per Froese and Binohlan (2000). However, (III) is 'P_{mega}', which measures the percentage of the large, old fish in the catch, with 0% as a target, but if the catch reflects the age and size structure of the stock, inclusion of 30%–40% mega-spawners in the catch represents a healthy age structure and is desirable, but when it declines to less than 20%, it raises concerns. This indicator is calculated by the formula: P_{mega} = % fish $>L_{opt}$ + 10% of L_{opt} (Froese 2004). The three indicators were estimated from the length frequency data using the calculated length at maturity (L_{mat}) estimated directly from the fish gonads (Sululu, Lugendo, and Benno 2022).

For the second-level assessment, the decision tree to assess stock sustainability using LBRP (Cope and Punt 2009) was explored as an extension to the LBI approach. In addition to the three indicators proposed by Froese (2004), the LBRP adds a third indicator, 'P_{obj}', which is the sum of the three indicators ($P_{obj} = P_{mat} + P_{opt} + P_{mega}$), used to distinguish between fishery selectivity patterns and construct a decision tree for the determination of whether the SB is at or above the target RP.

2.4.2 | Estimation of Growth Parameters

Further to the LBI approaches, the growth parameters for the *D. macarellus* were estimated from the binned length frequency data. The data from the two landing sites were pooled together to generate the sex-combined monthly LFQ. The raw length frequency data were pooled in bin sizes based on the largest TL ($L_{\max}$) observed in the sample, based on the recommendation by Wang et al. (2020), where

$$\text{Optimum bin size (OBS)} = 0.23 \times L_{\max}{}^{0.6}$$

The TropFishR (Mildenberger, Taylor, and Wolff 2017), an R package–modified version of ELEFAN of the FISAT II (Gayanilo, Sparre, and Pauly 2005), was used to estimate the von Bertalanffy growth function (VBGF) asymptotic length (L_∞) and growth constant (K) from length frequency data. In addition, the TropFishR estimates the parameter t_{anchor}, which describes the fraction of the year in which annually repeating growth curves cross the length axis equal to zero (Mildenberger, Taylor, and Wolff 2017). The TropFishR is a package which includes a more powerful optimization procedure for estimating uncertainties.

ELEFAN was also used to generate inputs for estimation of mortality parameters using the catch curve. The modified ELEFAN, with the genetic algorithm (ELEFAN_GA) function (Mildenberger, Taylor, and Wolff 2017), was used to fit the seasonalized VBGF (Gayanilo and Pauly 1997) to the LFQ:

$$L_t = L_\infty(1 - \exp(-(K(t - t_0) + S(t) - S(t_0))))$$

where $S(t) = (CK/2\pi)\sin 2\pi(t - t_s)$, C is a constant indicating the amplitude of the oscillation, typically ranging from 0 to 1, and t_s is the fraction of a year (relative to the age of recruitment, $t = 0$) where the sine wave oscillation begins (i.e., turns positive).

The estimated growth parameters were compared to estimates from the growth performance index (Φ') (Pauly and Munro 1984), where

$$(\Phi') = \log_{10}K + 2\log_{10}L$$

Suitable moving average (MA = 7) value for the length data, applied to enhance cohort visualization in the length-frequency plots, was selected after restructuring the data based on different MA values and the rule of thumb established by Taylor and Mildenberger (2017) regarding the number of bins spanning the youngest cohorts.

2.4.3 | Mortality Parameters and Exploitation Rate

The total mortality (Z) was estimated using the linearized length-converted catch curve (Pauly 1983), as follows:

$$\text{Log}\left(\frac{N_i}{dt_i}\right) = a + bt$$

where N_i corresponds to the number of individuals in length class i, whereas dt_i is the time needed by the fish to grow in that length class i, a is the intercept, b corresponds to $-Z$ and t is the relative age (age $- t_0$) (Pauly, Moreau, and Abadb 1995).

On the basis of the growth parameters, the natural mortality rate (M) was computed employing the empirical formula as per Then et al. (2015):

$$M = 4.118\, K^{0.73} L_\infty{}^{-0.33}$$

where K and L_∞ are growth parameters of VBGF

The fishing mortality rate (F) was computed on the basis of the relationship:

$$F = Z - M$$

The exploitation rate (E) was determined on the basis of the equation:

$$E = \frac{F}{Z}$$

where Z is total mortality, M is natural mortality and F is fishing mortality.

2.4.4 | Length at First Capture (L_{c50})

The length at first capture (L_{c50}), or the length at which 50% of the fish sampled are retained by the gear, was estimated using the ascending left arm of the length-converted catch curve. This arm was also used to calculate L_{c75}, the length at 75% capture, which corresponds to the cumulative probability at 75% (Pauly 1987).

TABLE 1 | Size distribution of *Decapterus macarellus* from the ring net catches.

Year	N	Min. size (cm)	Max. size (cm)	Mean size (cm) ± SE
2019	5900	5.6	27.5	15.2 ± 0.05
2020	7151	6.8	19.2	16.0 ± 0.02

2.4.5 | Yield Per Recruit (YPR), BRPs and Fishing Regime

The length-based YPR model by Thompson and Bell (1934) was used to estimate the three BRPs: fishing mortality that produces the maximum yield ($F_{\max}$), fishing mortality that results in a 50% reduction of the biomass ($F_{0.5}$) and the fishing mortality that corresponds to 10% of the slope of the YPR curve at the origin ($F_{0.1}$). These RPs are helpful tools to infer the impact of a given management control measure, such as regulations on fishing effort or gear selectivity (e.g., net mesh size) (Mildenberger, Taylor, and Wolff 2017).

2.4.6 | Estimation of the Spawning Potential Ratio (SPR) by LBSPR

The output from the TropFishR can be used to estimate the SPR RPs. SPR is the ratio of the per-recruit spawning stock biomass between the unfished and fished state (Goodyear 1993; Prince et al. 2015). The inputs required for estimating the SPR, M/K ratio and L_∞ were derived from the results of the ELEFAN routine, whereas length at 50% sexual maturity was estimated by the logistic regression model using open BUGS computer software (CMFRI 2017). Standard SPR values, which correspond to conventional RPs for stock assessments, range from 20% to 40%, but the appropriate level varies depending on the life history characteristics of the species. For instance, highly productive species such as small pelagic may have a target RP (TRP) of 30% (Nadon et al. 2015).

3 | Results

3.1 | Length-Based Assessment

A total of 13,051 *D. macarellus* individuals were collected for a period of 19 months (February, 2019 to September, 2020). The length-frequency distribution ranged from 5.6 to 27.5 cm TL. Overall, the median and the mean size of the fish caught were 15.9 and 15.6 cm, respectively. The exploited individuals' mean (±SE) size in the 2 years indicated only a very slight variation (Table 1); hence, the data were pooled together.

The results of the Froese's indicators (Figure 2) showed that most (81.7%) individuals caught were mature, with 18.3% being immature. The Cope and Punt decision tree resulted in a similar observation, which indicates that the fishery captured both juveniles and mega-spawners,

$$P_{obj} < 1 = \left(P_{mat}0.30 + P_{opt}0.43 + P_{mega}0.09\right) \text{ and} P_{opt} + P_{mega} > 0$$

According to the LBRP approach established by Cope and Punt (2009), the indicator P_{obj} reveals that if P_{obj} is less than 1 and $P_{\text{opt}} + P_{\text{mega}}$ is greater than 0, the fishery is targeting both juveniles and mega-spawners.

3.2 | Growth Parameters

The fitted VBGF curves to the raw and restructured LFQ show that new recruits appear in the fishery in September (Figure 3). The seasonalized oscillation provided a better fit to the data ($R_n = 0.3$), giving an estimate of 31.9 cm and 0.74 year^{-1} for the L_∞ and K, respectively (Figure 3 and Table 2). The estimated t_{anchor} ($t_{\text{a}} = 0.177$) suggests that the peak reproduction for *D. macarellus* takes place at the beginning of February. Two possible cohorts were estimated by the VBGF model (Figure 3) with a growth performance index value (Φ') of 2.88 (Table 2).

3.3 | Mortality, Exploitation Rate and Selectivity

The length-converted catch curve analysis estimated a total mortality (Z) of 3.63 year^{-1}, a natural mortality (M) of 1.06 year^{-1} and a fishing mortality (F) of 2.57 year^{-1}. This resulted in an exploitation rate of 0.71 (Figure 3 and Table 3). The size at 50% (L_{c50}) and 75% (L_{c75}) capture of *D. macarellus* was estimated at 13.6 and 14.3 cm TL, respectively (Figure 4B and Table 3).

3.4 | Yield and Biomass Per Recruits and SPR

The yield-per-recruit analysis with the assumptions of a trawl selection resulted in the following summary statistics: $F_{\max} = 1.73$ year^{-1}, $F_{0.1} = 0.84$ year^{-1} and $F_{curr} = 2.57$ year^{-1} (Figure 5), which suggests that the stock has been overfished because $E > 0.5$. The yield isopleth (Figure 6) results demonstrate that the current effort ($F_{curr} = 2.57$ year^{-1}) is way beyond the precautionary limit ($F_{0.1} = 0.84$ year^{-1}) and surpasses the fishing mortality rate that maximizes YPR ($F_{\max} = 1.73$ year^{-1}). According to the TropFishR estimates of the relative fishing effort (F/M) and the SPR, *D. macarellus* is showing signs of overfishing ($F/M > 1$; SPR < 0.3).

4 | Sensitivity Analysis

4.1 | Electronic Length Frequency Analysis

L_∞ and K biases affected growth performance index (Φ'), mortality estimates and exploitation rates. Increasing L_∞ by 20% resulted in an 18% decrease in the exploitation rate (E), whereas decreasing L_∞ by 20% increased E by 22%.

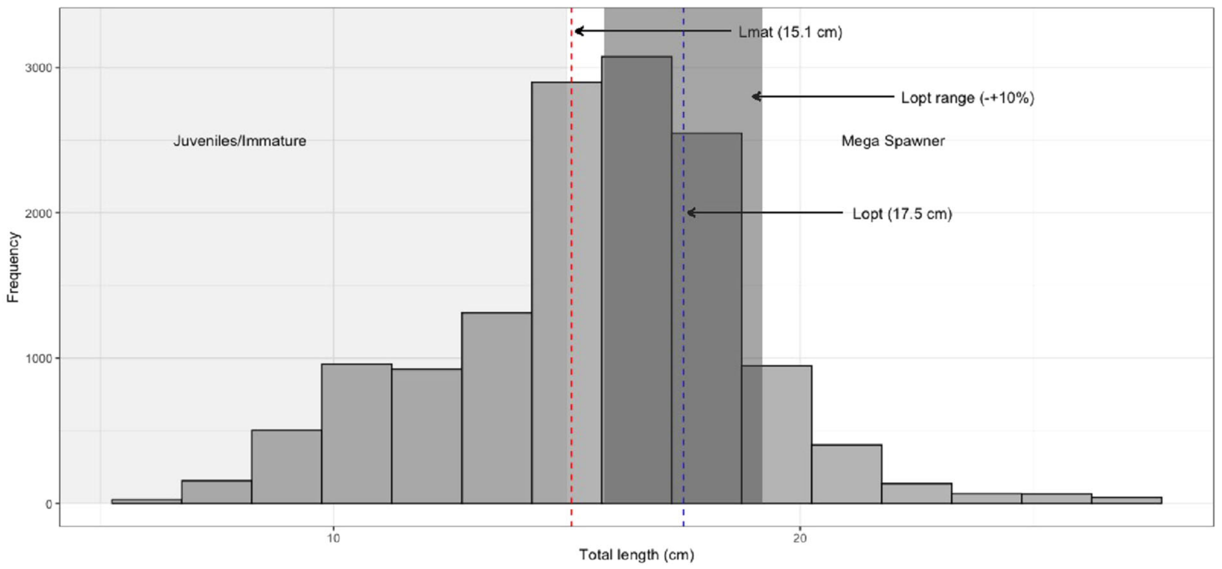

FIGURE 2 | The length-frequency distribution of all fish with Froese's indicators. The red dotted line represents the size at maturity (L_{mat}), and the blue dotted line represents the length at which maximum yield can be obtained (L_{opt}). The shaded light grey area represents the immature individuals, and the dark grey area represents the range of the optimally sized fish, those between 0.9 and 1.10 of optimal length (L_{opt}). Fish to the right of the dark grey shaded area represent the mega-spawners.

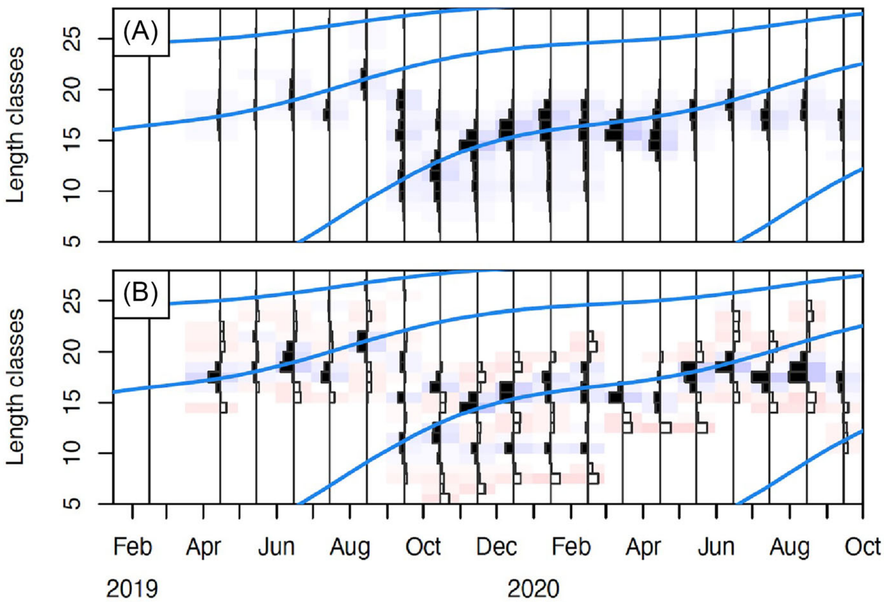

FIGURE 3 | Length-frequency data of *Decapterus macarellus* collected from Tanga and Bagamoyo with overlaid von Bertalanffy growth function (VBGF) curves fitted by ELEFAN with genetic algorithm. Ideally, the growth curves overlay with length bins with a high count or high positive value (blue shading) for raw (A) and restructured (B) data, respectively.

TABLE 2 | Estimated von Bertalanffy growth parameters (L_∞, K and t_{anchor}) and the growth performance index of *Decapterus macarellus* (Φ').

L_∞ (cm)	K (year^{-1})	t_{anchor}	Φ'	R_n
31.9	0.74	0.177	2.88	0.30

Note: t_{anchor} is defined in the unit interval (i.e., range from 0 to 1) due to the yearly repeating pattern of the growth curves, and R_n value is the goodness of fit of model estimation.

TABLE 3 | Estimated mortality, selectivity and biological reference points of *Decapterus macarellus*.

Parameters	Estimates
Total mortality (Z)	3.63 year^{-1}
Natural mortality (M)	1.06 year^{-1}
Current fishing mortality (F_{curr})	2.57 year^{-1}
The ratio of fishing mortality to natural mortality (F/M)	2.43
Length at first capture (L_{c50})	13.6 cm
Length a first maturity (L_{mat})	15.1 cm
Fishing mortality rate that achieves maximum yield per recruit ($F_{\max}$)	1.73 year^{-1}
The fishing mortality rate at which the slope of the yield-per-recruit curve is only one-tenth the slope of the curve at its origin ($F_{0.1}$)	0.84 year^{-1}
Fishing mortality that results in a 50% reduction of the biomass ($F_{0.5}$)	0.61 year^{-1}
Exploitation rate (E)	0.71
Spawning potential ratio (SPR)	0.11

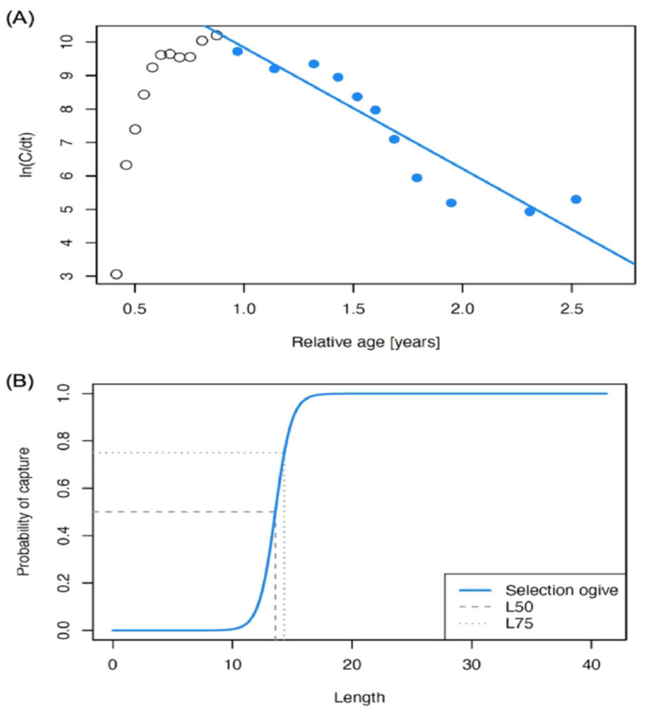

FIGURE 4 | Logarithm of catch per length interval against relative age (A) and estimated logistic gear selectivity curve as the probability of capture (B) for the *Decapterus macarellus*. The blue dots in (A) correspond to values used in the regression analysis (blue line) of the catch curve for the estimation of total mortality (Z), which corresponds to the slope of the displayed regression line.

4.2 | Length-Based Indicators

Among the three indicators, P_{mega} is the most sensitive to L_∞ biases, showing the highest sensitivity. A 20% increase in L_∞ reduced P_{mega} by 25%, while a 20% decrease increased it by 30%. However, L_{mat} biases had minimal effects on all indicators.

4.3 | Length-Based Spawning Potential Ratio

SPR and F/M ratio were highly sensitive to M/K biases. A 20% increase in M/K reduced SPR by 15% and increased F/M by 18%. Conversely, a 20% decrease increased SPR by 20% and reduced F/M by 17%. On the other hand, L_{mat} had minor effects on SPR and F/M.

4.4 | Length-Based Reference Point

P_{obj} was moderately sensitive to L_∞ and M/K biases. A 10% increase in M/K reduced P_{obj} by 10%, whereas a 20% decrease increased it by 15%. SB showed minimal sensitivity to L_{mat} but was moderately affected by L_∞ (Table S1)

4.5 | Robustness of Methodologies

4.5.1 | Length-Based Indicators

LBI was relatively robust for P_{mat} and P_{opt}, which showed minimal sensitivity to parameter biases. This indicates that these indicators are less prone to fluctuations in input parameters like L_∞ and M/K. P_{mega}, however, was highly sensitive to changes in L_∞, suggesting that LBI's effectiveness largely depends on accurate L_∞ estimates.

4.5.2 | Length-Based SPR

LBSPR demonstrated consistent sensitivity patterns, with SPR being more sensitive to M/K ratio than L_∞. The F/M was also predictable across different scenarios. High sensitivity to M/K indicates that LBSPR results can vary significantly if growth-related parameters are misestimated. Generally, LBSPR is moderately robust but demands precise growth parameter estimation to ensure reliability.

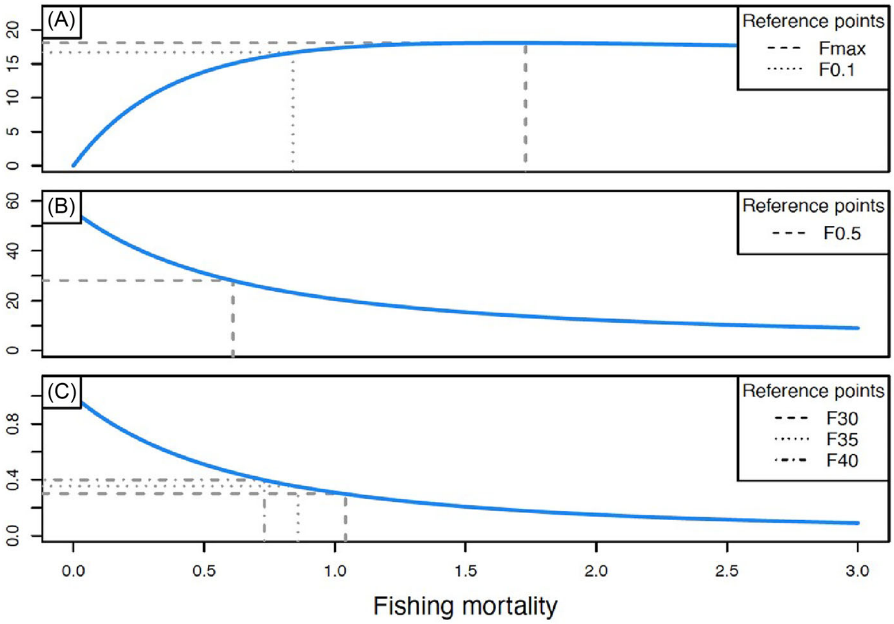

FIGURE 5 | Yield per recruit (A), biomass per recruit (B) and spawning potential ratio (C) for a range of fishing mortality rates (*x*-axis). The grey dashed lines indicate various reference points: F_{max} = fishing mortality (F) leading to the maximum yield per recruit; $F_{0.1}$ = fishing mortality that corresponds to 10% of the slope of the yield per recruit curve at the origin; $F_{0.5}$ = fishing mortality that results in a 50% reduction of the biomass. F_{30}, F_{35} and F_{40} correspond to F that leads to an SPR of 30%, 35% and 40%, respectively.

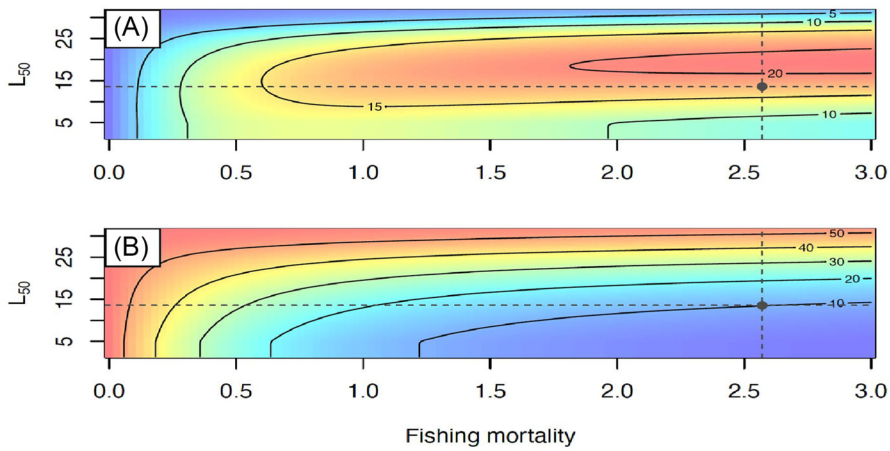

FIGURE 6 | Yield (A) and biomass (B) per recruit for a range of fishing mortality rates and gear selectivity combinations. Red colour indicates high, whereas blue indicates low yield and biomass. Gear selectivity is defined by the length at 50% selectivity (L_{50}). The black dot indicates current yield and biomass per recruit.

4.5.3 | Length-Based RPs

The LBRP showed moderate sensitivity overall. SB and P_{obj} were less sensitive to biases, making this methodology relatively stable across scenarios. However, its reliance on multiple indicators (i.e., P_{mat}, P_{opt} and P_{mega}) integrates some variability from LBI.

4.5.4 | Electronic Length Frequency Analysis

The primary outputs (L_∞ and K) are essential for downstream calculations, showing moderate sensitivity to biases. On the other hand, given that ELEFAN-derived parameters directly influence LBI, LBSPR and LBRP, its robustness impacts the reliability of all methods. This methodology is foundational, but its sensitivity means its outputs must be treated cautiously. In general, the LBRP emerges as the most robust methodology among those analysed.

5 | Discussion

Fisheries assessment in developing countries often grapples with logistical constraints, including the lack of long-term data (Fujita 2021). Data-limited assessment methods can partly address this issue by providing insights into fish stock status when used alongside precautionary harvest control rules (Jardim, Azevedo, and Brites 2015; Scarcella et al. 2023). Assessing small pelagic stocks like *D. macarellus* poses an additional layer of complexity due to their short lifespan, population variability and limited data availability (Fréon et al. 2005; Hilborn et al. 2022). This study applied data-limited stock assessment methods to better understand the status of *D. macarellus* in Tanzanian coastal waters.

At a fundamental level, the objective of fisheries management is to ensure that the fish are mature and harvested at their optimal size (Froese 2004). Our analysis revealed a concerning discrepancy between the proportion of targeted individuals and the optimal lengths for harvest. Although over 80% of the caught individuals were mature, only 30% and 43% fell within the optimal length (P_{mat} and P_{opt}, respectively), with a critically low proportion (9%) of mega-spawners (P_{mega}), significantly indicating the stock's resilience (Froese 2004; Babcock, Tew, and Burns-perez 2018). The inclusion of 30%–40% of the mega-spawners in the catch represents a healthy age structure and is desirable, but when it declines to less than 20%, it raises concerns.

Given the difficulty in translating Froese (2004) indicators into practicable management advice, Cope and Punt (2009) developed the decision tree to evaluate Froese indicators (P_{mat}, P_{opt} and P_{mega}) and to provide advice concerning fishing mortality (F) and SB. Our results, indicating a P_{obj} value of less than 1, are indicative of an unsustainable fishery under the current pattern of selectivity (Cope and Punt 2009; Babcock et al. 2013) with the SB falling below the TRP = 0.4 SB.

Estimates of the mortality reveal that fishing mortality (2.57 year^{-1}) is largely responsible for the overall mortality due to the high exploitation rate ($F/M > 1$). According to Gulland (1971), the optimum yield is achieved when $F = M$ (i.e., $E_{opt} = 0.5$). The higher fishing mortality rate observed in this study can be attributed to increased fishing pressure on small pelagic species in Tanzanian coastal waters following a significant increase in the number of ring nets in recent years (Sekadende et al. 2020). The relative yield and biomass per recruit (Y/R and B/R) in the present study indicate that the current fishing effort (F_{curr}) is by far higher than all BRPs, including the $F_{\max}$, $F_{0.1}$ and $F_{0.5}$. Thus, a more appropriate BRP of $F_{0.1}$ would be needed to reduce the current fishing effort, which would increase both yield and biomass per recruit. This approach would result in more prudent and conservative levels of exploitation (Collie and Gislason 2011).

According to Hordyk et al. (2015) and Alam et al. (2022), an effort level of $F/M > 1$ would result in a sharp decline in SPR. The current SPR (SPR = 0.11) is below both the target and limit RP (0.3), indicating an unsustainable fishery. In this fishery, although it appears that the current size targets are not fully met, the main driver pushing the fishery to unsuitability lies in the effort expended, which takes advantage of the schooling behaviour of pelagic fish to make large catches using efficient gear such as ring nets in a relatively short time (Fréon et al. 2005).

Therefore, it is advised that the first management attempt should be geared at limiting the number of ring nets through licensing to minimize the F_{curr} level to $F_{0.1}$. Moreover, increase the ring net mesh sizes of fishers who target this species and other small pelagic to a bigger size (12 mm). In addition, given the nearshore tendencies of ring net fishing and the inability of most fishing vessels to travel far offshore, seasonal closures could offer an additional layer of protection. The implementation of these measures during the peak spawning months (August and September) would protect the spawners. However, this may prove difficult due to the dependence of coastal communities on the fishing industry. To protect juveniles and ensure the long-term viability of this stock, the ring net fishery should be conducted in near-deep waters (40–200 m) where schools of large *D. macarellus* and a few smaller individuals are found. Considering this circumstance, we emphasize once more that the relevant authority should control current fishing efforts by limiting the number of licenses that permit the use of ring nets but also facilitate these fishers with modernized vessels so that they can be capable of fishing in near-deep waters. This strategy will aid in reducing fishing pressure and minimizing the capture rate of both juveniles and mega-spawners, thereby promoting recruitment for stock sustainability.

Although the ring net is the primary fishing gear for catching *D. macarellus*, handlines are also used, albeit contributing only a small portion of the catch. This is because these gears do not chase fish like the ring net, making them less effective at catching fast-moving species like *D. macarellus*. Due to this, such gears often either do not capture this species at all or catch few individuals. Although sampling from all gear types that catch *D. macarellus* could provide more reliable estimates of some parameters, funding and logistical challenges, particularly in developing countries like Tanzania, made it unfeasible to sample from all gear types. Consequently, this study focused on sampling from the ring net, the primary gear for this fishery. On the other hand, although the number of ring nets in Tanzania is not higher compared to handlines and other gears, they are larger and typically catch more small pelagic fishes, including *D. macarellus* (Anderson and Samoilys 2016; Mwaipopo and Mahongo 2020). Therefore, this catch pattern could at least provide a sensible size composition of individuals from which some reliable stock assessment aspects can be inferred. Given the financial limitations of this study, focusing on the ring net was necessary to obtain a large size composition representation and abundant data, despite missing the full range of size composition.

Comparatively, the status of *D. macarellus* in other regions follows a similar pattern to that observed in this study, characterized by high fishing pressure and overexploitation. In Indonesia, *D. macarellus* is primarily caught using purse seine nets by both artisanal and semi-industrial fishers. According to Bintoro, Lelono, and Ningtyas (2020), who studied the biological aspects of this species in Prigi Waters, Indonesia, the growth rate was high (0.77 year^{-1}), with fishing mortality (F) at 2.71 year^{-1} surpassing natural mortality (M) at 0.28 year^{-1}. Additionally, the exploitation rate (E) estimated at 0.90 far exceeding the threshold value of 0.5 (Gulland 1971). This intense fishing pressure is further highlighted by Purwanto et al. (2022), who estimated the maximum sustainable yield (MSY) of *D. macarellus* in Eastern Indonesia at 69,900 t, captured by 805 purse seiners between 2005 and 2016. Persistent overfishing has led to the species being classified as overexploited, prompting a proposed rebuilding plan. This plan involves reducing catch levels to 80% of MSY and limiting the number of purse seiners to 427 to alleviate pressure and restore the stock to sustainable levels.

In contrast, Tanzania's *D. macarellus* fishery is entirely artisanal, relying on ring nets, with much of the fishing concentrated in nearshore waters (Clotilde and Christophe 2015). On the other hand, in Indonesia the species is targeted by both artisanal fishers and semi-industrial fishers using purse seine nets (Purwanto et al. 2021). Although both countries exhibit high fishing pressure, comparatively, the fishery in Indonesia is more under intense pressure that could be associated with advancement to semi-industrial fishing levels, fishing gear improvements, an increase in the number of purse seine nets and growing human population (Purwanto et al. 2022; Patikawa et al. 2018) compared to Tanzania.

In terms of management strategies, Tanzania and Indonesia adopt a group-level regulatory approach for small pelagics, rather than species-specific measures. However, the two countries differ in the regulations implemented and the data collection methods for updating management strategies. For instance, Tanzanian regulation declares the registration and licensing of vessels and fishers, with additional prohibition on ring net fishing is prohibited in waters less than 50 m deep to protect immature individuals (Clotilde and Christophe 2015). Conversely, Indonesia enforces similar licensing requirements but also employs a total allowable catch (TAC) system as part of its management framework (Retninoningtyas et al. 2024).

Furthermore, the methods for data collection also differ between the two countries. Tanzania relies on district officers who collect artisanal fishery data on a monthly basis. In contrast, Indonesia primarily uses vessel logbooks and occasionally deploys onboard observers. However, Indonesian regulations exclude vessels below five gross tonnage from mandatory reporting requirements (Ministerial Decree No. 48/2014), leaving a significant portion of fishing effort undocumented due to the high number of small-scale operators (Purwanto et al. 2022). Despite these differences, both countries face challenges in enforcing regulations, contributing to persistent high fishing pressure. In Tanzania, the open-access regime remains prevalent due to weak enforcement of access regulations, and fishing is concentrated in nearshore waters with limited offshore operations (Clotilde and Christophe 2015). Similarly, Indonesia struggles with limited capacity to monitor fisheries, enforce catch limits and regulate unlicensed vessels (Purwanto et al. 2022).

On the other hand, Cape Verde has extensively invested in the fishery of *D. macarellus* and small pelagics as a whole compared to Tanzania. In Cape Verde, the species is mainly caught using purse seine nets by both artisanal fishers who use outboard engine boats and industrial fishers operating vessels up to 17 m long (Vieira 2019; Da Cruz Delgado et al. 2024). Since 2008, fishing of *D. macarellus* in Cape Verde has been regulated by fishery policies (Republica de Cabo Verde 2009). Among the main management measures outlined in the management plan aimed at minimizing fishing pressure on this species were (i) restricting fishing effort through the implementation of no-fishing seasons or biological rest periods (BRPs) and (ii) imposing quotas on minimum landing sizes (MLS) (Republica de Cabo Verde 2021).

However, given that this species is targeted by both small-scale and industrial fishers, the measures initially implemented proved insufficient for its conservation (Da Cruz Delgado et al. 2024). Vieira (2019) reported an intensive harvesting rate of *D. macarellus* in Cape Verde waters, with natural mortality (M) at 0.28 year^{-1} and fishing mortality (F) at 2.31 year^{-1}, placing the stock at risk. These estimates were derived from catch data collected between 1989 and 2015, a period when landings peaked following the addition of 20 new semi-industrial purse seiners targeting small pelagics (Vieira 2019). To address this situation, fishery policy reforms were implemented in 2016, leading to adjustments in the measures already in place. These amendments included: (i) extending the BRPs by 1 month (i.e., from 2 months to 3), changing the no-fishing season from August to September pre-2016 to July-September post-2016 and (ii) increasing the MLS of *D. macarellus* from 18 cm fork length (pre-2016) to 20 cm fork length thereafter (Da Cruz Delgado et al. 2024). These reforms significantly reduced fishing pressure on *D. macarellus* in Cape Verde. Following these interventions, the species exhibited improved population metrics, with individuals reproducing at larger sizes (24.2 cm compared to 18.2 cm before policy interventions) and growing to larger mean sizes (29.07 ± 3.2 cm compared to 26.7 ± 2.8 cm pre-interventions) (Da Cruz Delgado et al. 2024).

Although *D. macarellus* fisheries in Cape Verde are exploited by both artisanal and industrial sectors, unlike Tanzania's fully artisanal fishery, the fishing pressure in Cape Verde is comparatively lower. This is attributed to species-specific management strategies, higher enforcement levels of existing regulations and timely fishery policy interventions, collectively enabling Cape Verde to implement effective measures and promote sustainable fishing (Da Cruz Delgado et al. 2024).

The sensitivity analysis revealed that the methodologies are robust but not immune to parameter biases. Key findings indicated that on ELEFAN Sensitivity, L_∞ had the most significant effect on exploitation rates and mortality parameters, emphasizing the importance of precise growth parameter estimation. Looking on LBI Sensitivity, P_{mega} was highly sensitive to L_∞, making it a crucial parameter for evaluating sustainable fishing practices. In contrast, L_{mat} biases were negligible. Evaluating the LBSPR Sensitivity, SPR and F/M were strongly affected by M/K, underscoring the need for accurate mortality and growth inputs; here L_{mat} had also minimal impacts. However, on LBRP Sensitivity, P_{obj} was moderately influenced by M/K and L_∞, suggesting that adjustments to these parameters could significantly alter management outcomes. These findings align with Cousido-Rocha et al. (2022), who noted similar patterns of sensitivity for LBI and LBSPR methods.

5.1 | Limitations and Scope of the Study

The decision to focus sampling efforts on the ring net, although practical, might have introduced some limitations. By not including samples from handlines, though landed with a very poor catch, the study may lead to biased estimates for parameters like size at first capture and length at first maturity. This is because the fish caught by different gear types may vary in size and maturity status. As a result, the data might not fully represent the population structure of *D. macarellus*. This limitation could partly explain the conflicting results observed in the present study, such as the size at first capture being slightly lower than the size at first maturity, despite a high proportion (over 80%) of mature individuals observed. Moreover, this study focused on the length-based stock assessment of *D. macarellus* from the Tanzanian coastal waters. The primary aim is to estimate key population parameters such as exploitation rate, fishing and natural mortality and SPR using LFQ. These metrics are critical for assessing the stock's status and providing recommendations for sustainable fishery management.

Another limitation of this study was the exclusion of environmental variables, such as water temperature, salinity and climate change impacts. These factors could influence fish growth and mortality rates. Owing to the lack of environmental data, the analysis is limited to biological factors, which may not fully capture the complexities of the stock's dynamics.

Given these limitations, the present study calls for future research to expand sampling efforts to include all relevant gear types and explore cost-effective data collection methods. These strategies can provide more comprehensive and unbiased data without significantly increasing costs. Moreover, future studies should incorporate environmental variables and socio-economic factors to provide a more inclusive understanding of stock dynamics and evaluate the feasibility and compliance of management recommendations.

5.2 | Conclusions

This study used multiple length-based data-limited approaches to assess the population status of *D. macarellus* in Tanzanian coastal waters. The sensitivity analysis demonstrates the robustness of the four data-limited methodologies and generally reveals that LBRP appears as the most robust methodology. The moderate sensitivity of its primary indicators (SB, P_{obj}) to biases and its integrative nature make it a reliable choice. However, its reliance on upstream methodologies (LBI and ELEFAN) suggests that ensuring precise estimates for L_∞, L_{mat} and M/K is crucial. The findings show that the species is under significant fishing pressure, the exploitation rate is well above optimal, and the SPR of 0.11 is extremely low. These findings point to a fishery that, if not properly managed, could quickly decline to a very low reproductive potential, threatening the species' long-term viability. Given these findings, immediate and adaptive management measures are needed to reduce fishing pressure and protect the *D. macarellus* stock. Failure to act could have disastrous consequences for the population and, as a result, for the communities, the livelihoods of which rely on it.

Author Contributions

Joseph Salawa Sululu: Conceptualization (equal); investigation (lead); funding acquisition (lead); writing–original draft preparation (lead); methodology (lead); data Curation (lead); resources (lead); formal analysis (equal); project administration (lead); writing–review and editing (equal); visualization (lead). **Blandina Robert Lugendo**: Supervision (lead); writing–review and editing (equal). **Paul Tuda**: Conceptualization (equal); software (lead); validation (lead); writing–review and editing (equal); formal analysis (equal). **Benaiah Lameck Benno**: Supervision (equal); writing–review and editing (equal).

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Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data that support the findings of this study are available from the corresponding author upon reasonable request.

Peer Review

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.