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Stock assessment of the Tigertooth croaker, *Otolithes ruber* (Bloch & Schneider, 1801) from the commercial prawn trawl fishery by-catch in coastal Kenya

Fatuma A. Mzingirwa[1]*, Jane M. Nyamora[1], Johnstone O. Omukoto[1], Paul Tuda[2,3]

[1] Kenya Marine and Fisheries
Research Institute (KMFRI),
PO Box 81651-80100, Mombasa,
Kenya

[2] Leibniz Centre for Tropical
Marine Research (ZMT),
Fahrenheitstr. 6, 28359 Bremen,
Germany

[3] Heidelberg Center for Environment
(HCE), Heidelberg University,
Im Neuenheimer Feld 229, 69120
Heidelberg

* Corresponding author:
fmzingirwa@gmail.com

Abstract

Commercial bottom prawn trawling has been reported to generate a higher proportion of by-catch of up to 70% in Kenya. The Tigertooth croaker, *Otolithes ruber* is one of the species caught in large quantities as commercial by-catch and also by artisanal fishers. This has led to growing concern that the species could be at risk of over-exploitation. The purpose of this study was to carry out a stock assessment of *O. ruber*. Stock assessment parameters were estimated using ELEFAN with the generic algorithm as included in the R package TropFishR. The length-converted catch curve and the length-based yield per recruit model were employed. The exploitation rate (F/Z = 0.71) indicates that the stock is overfished based on the length-converted catch curve. The current fishing mortality (F = 2.3) based on the catch curve is larger than the reference level (= 1.1) based on the yield per recruit analysis and also indicates that the stock is overfished (= 2.09). To reverse the current trend of exploitation, improved management of the stock is required, which should include further studies on other by-catch species and the generation of data to capture the whole fishery for a better estimation of stock status.

Keywords: *Otolithes ruber*, data-limited, Malindi-Ungwana bay, Kenya, exploitation

Introduction

The Tigertooth croaker, *Otolithes ruber* (Bloch & Schneider, 1801), is a demersal fish species belonging to the family Sciaenidae and is widely distributed throughout the Indian Ocean along the east coast of Africa and the west Pacific ocean (Brash and Fennessy, 2005; Froese and Pauly, 2019). They inhabit warmer (26 °C – 29 °C) marine and brackish waters and are found over sandy and muddy substrates and river mouths at depths of 10 – 40 m (Eskandari *et al*., 2012; Farkhondeh *et al*., 2018). Previous studies have reported on some aspects of the biology of *O.ruber*, reporting a maximum and common length of 90 cm and 40 cm (TL), respectively (Froese and Pauly, 2019; Sousa and Dias, 1981). Length at first maturity of *O. ruber* was estimated to range from about 22 cm to 40 cm (TL) (Fennessy, 2000). Studies by Eskandari *et al*. (2012), from the Northwest Persian Gulf in the south of Iran, reported a size at maturity range of between 30 to 40 cm (TL). In both India and South Africa, the species has been reported to mature at a comparatively smaller size, ranging between 22-24 cm (Brash and Fennessy, 2005). Mature females have been found to occur throughout the year, suggesting prolonged and continuous spawning activity (Santhoshkumar *et al*., 2017; Velip and Rivonker, 2018). *O. ruber* are mainly carnivores with adults feeding on fishes, prawns and other invertebrates (Froese and Pauly, 2019).

In most of the southwest Indian ocean countries, for example, South Africa, Mozambique and Tanzania, *O.ruber* is caught as by-catch from Panaeid prawn

trawlers (Fennessy, 2000; Schultz, 1992). In addition, the fish is also targeted by recreational hook and line fishers in South Africa and by gillnet and beach seine artisanal fishers in Mozambique and Tanzania (Olbers and Fennessy, 2007). Similarly, in Kenya, *O. ruber* is mainly caught as by-catch on prawn trawlers (Munga *et al.*, 2014), and by artisanal fishers using gillnets, prawn seines and handlines (Mwatha, 2002; Omukoto *et al.*, 2017).

It is well known that *O. ruber* is caught in large numbers, but since it is rarely studied, very little is known about the status of the species. This raises the question of whether the stock is being overexploited or being sustainably fished. Studies by Olbers and Fennessy (2007) have shown that though the species is not a principal target for most fisheries, the vast quantities of small individuals discarded due to its low economic value makes it particularly vulnerable to overexploitation. Similar observations have been found off Malindi-Ungwana Bay in Kenya where juveniles of *O. ruber*, *Johnius sp.* (both Sciaenidae), and *Pomadasys sp.* made up to 25 % of the by-catch by mass (Munga *et al.*, 2014). This implies that the local artisanal fisheries, which rely on the resource as a source of livelihood, are impacted.

Information on the status of exploited fish stocks is vital for making fisheries management decisions (Melnychuk *et al.*, 2017). Traditionally, such information is derived from stock assessment models, which are often data-intensive and complex, rendering them unsuitable for data-limited fisheries (Prince and Hordyk, 2019; Wang *et al.*, 2020). Even in the presence of a routine data collection system, often there is a lack of long time-series data, and often, the data is aggregated, limiting the use of stock assessment models (Chrysafi and Kuparinen, 2015). Over the past decade, a number of data-limited assessment methods (DLMs) have been developed to assess data-limited stock status (Dowling *et al.*, 2019). Given that for most data-limited fisheries length-frequency data from commercial catches tend to be the primary data type available, most of the DLMs are length-based, which has made it possible to assess the population parameters of exploited fish stocks in tropical waters (Chong *et al.*, 2019; Rudd and Thorson, 2017).

The present study is the first attempt to assess the stock status of *O.ruber*, a by-catch species from the prawn trawl fishery in Malindi-Ungwana Bay. Most studies have predominantly focused on the assessment of

target and commercially important species, but the assessment of by-catch species is mostly ignored, and as a result, very little is known about their status (Cook and Heath, 2018). In this study, we explore the use of the most widely used non-parametric length based approach, the Electronic Length Frequency Analysis (ELEFAN) (Pauly, 1987; Pauly and David, 1981), to estimate growth and mortality parameters of *O. ruber* to provide management advice for their sustainable exploitation in the fishery.

Materials and methods
Study area
The prawn trawling fishery in Kenya is carried out in Malindi-Ungwana Bay, between latitudes 3°30'S and 2°30'S and longitudes 40°00'N and 41°00'N (Fig. 1). The area is considered one of the most productive fishing grounds along the coast due to its wide continental shelf (extending between 15 and 60 km offshore) relative to other parts of the Kenyan coastline. In addition, the bay is influenced by the inflow of the rivers Tana and Sabaki, which carry sediments resulting in a vast stretch of sandy beaches and dunes made up of terrigenous sediments. The bay is shallow with a mean depth of 12 m during high spring tide at 1.5 nm and 18.0 m at 6.0 nm offshore, respectively. The depth increases rapidly to 100 m after 7 nm and generally decreases northwards. Due to its bathymetry, environmental characteristics and topography, Malindi-Ungwana Bay has the highest concentrations of shallow water prawns on the Kenyan coast with several semi-industrial prawns trawling in the area.

The bay is influenced by two dominant offshore current regimes: the Northeast Monsoon (NEM) and the Southeast Monsoon (SEM). During the SEM, which occurs between April and October, the current circulation is dominated by the northward flow of the East African Coastal Current (EACC). During this season, the bay also receives the most substantial river discharge from the rivers Tana and Sabaki (Kitheka *et al.*, 2005). During the NEM, between November and March, the northward-flowing EACC meets the southward flowing Somali Current to form the Equatorial Counter Current, which flows away from the coast of   the Indian Ocean (Jacobs et al., 2020). During the NEM, the ocean waters in nearshore areas have higher salinities than during the SEM due to low precipitation and reduced river discharge compared to the SEM period. Prawn fishing and production are higher during the SEM.

Sampling

Length data for *O. ruber* was collected by trained scientific observers on-board 3 shallow water (5 – 40 m) prawn trawlers during the trawling season of April - October for 2016, 2017 and 2018. Data collection fol-

information which entails start and end time of haul, positions, depth, target catch, by-catch, discards, catch composition, mitigation measures and environmental interactions (TEDs, PETs, large by-catch, e.g. sharks and fate of these species). The sampling protocols used
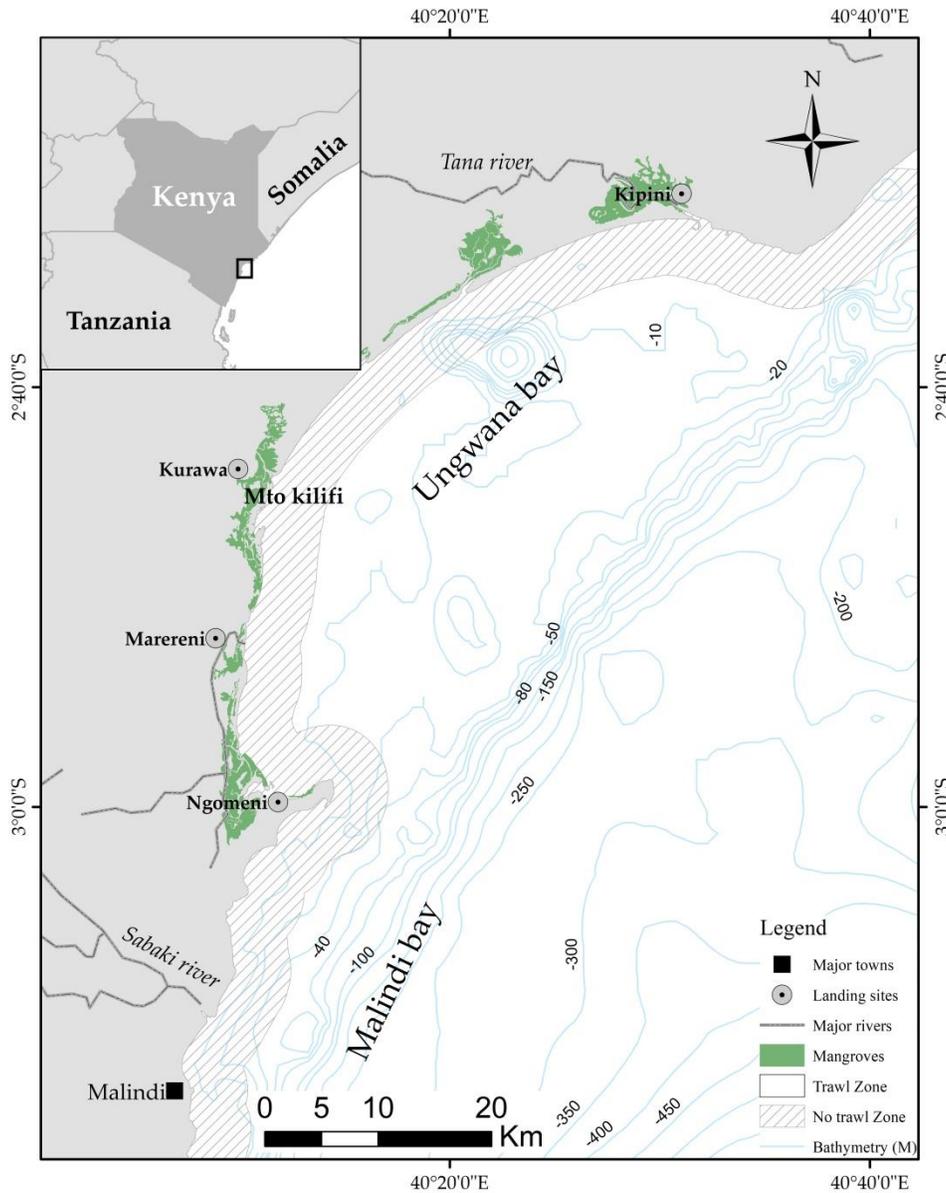
Figure 1. Map of Kenya (inset) and the Kenyan coastline showing the location of Malindi and Ungwana Bays and the Sabaki and Tana rivers.

lowed documented trip instructions and designated sampling protocols adopted from the Southwest Indian Ocean Fisheries Project (SWIOFP) Observer Program Data Collection Guide, 2012. Specifically, the trip instructions included: Capturing vessel and trip information, recording of the gear characteristics, collecting and recording the catch and fishing effort

for catch composition determination was as follows: First, large-sized fish samples were stored before being processed and the catch divided virtually into random sample portions of 30% to a maximum of 20 kg from the catch (1 portion). Samples were then sorted to species/family level, total weight and numbers for each species/family observed in the sample was recorded,

and individual total length was measured to the nearest mm using a standard measuring board.

This data collection was part of the annual observer deployment programme that commenced in 2016 to contribute to fisheries management of panaeid prawns and associated by-catch.

Data Analysis

Length frequency catch data (LFCD) of *O.ruber* from 2016 to 2018 was pooled and converted to quarterly catches with the assumption that the samples were representative of the total catch of the month (Abobi *et al.*, 2019). The ShinyTropFish (version 0.9.1) based on the TropFishR package (version 1.7.0; Mildenberger *et al.*, 2017) was used to assess the status of the species by estimating the growth and mortality parameters from modal progression and catch curve analysis using the ELEFAN_GA function (Taylor and Mildenberger, 2017).

To generate a confidence interval around the estimated growth parameters, the updated version of the TropFishR with bootstrap functionality was used to fit the growth curve to the length-frequency catch data (LFCD) (Pauly, 1987; Pauly and David, 1981; Schwamborn *et al.*, 2019).

Estimation of Growth Parameters

The Von Bertalanffy's growth parameters (VBGP) (von Bertalanffy, 1938), that is, asymptotic length (L∞) and growth constant (K), were estimated using the length-frequency catch data (LFCD) in TropFish. This was done by applying the seasonalised von Bertalanffy's growth function (VBGF) to the length-frequency catch data (LFCD) (Somers, 1988).

An updated version of the Electronic Length frequency Analysis (ELEFAN) (Pauly, 1987; Pauly and David, 1981; Schwamborn *et al.*, 2019) was used to fit the growth curve to the length-frequency catch data (LFCD). For optimum search and improvement in the accuracy of the growth parameters L∞ and K estimation, the LFCD was binned according to the maximum body length observed for the fish species (Wang *et al.*, 2020).

$$\text{Optimum bin size (OBS)} = 0.23 * Lmax^{0.6}$$

An initial seed value of L∞ was estimated based on the mean of the 1 % of the largest observed individual in the sample (Lmax) following the formula by Pauly (1984):

$$\text{where } L\infty = Lmax\, /0.95$$

The growth performance index (Φ') (Pauly, 1984), was used to compare growth parameters.

The estimated potential longevity t_{max} of *O.ruber* was computed from the formula (Pauly, 1980; Taylor, 1958):

$$t_{max} = 3/K$$

Mortality Parameters

The instantaneous total mortality rate (Z) was computed from the LFCD based on the linearized length-converted catch curve (LCC) (Pauly, 1983).

Given the importance yet difficulty in reliably estimating the natural mortality (M) (Jørgensen and Holt, 2013), an updated version of the Pauly (1980) growth-based method was applied (Then *et al.*, 2015):

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

This approach is preferred over other empirical formula used to estimate natural mortality (M) given that it resulted in better prediction power from meta-analyses of more than 200 fish species of different life histories (Then *et al.*, 2014). The rates of fishing mortality (F) and exploitation rates (E) were calculated based on the relationship:

$$F = Z - M \text{ and } E = \frac{F}{Z}$$

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

Probability of capture

The probability of capture was estimated based on the ascending left arm of the length-converted catch curve (Pauly and Munro, 1984). Primarily, the method entails the backward extrapolation of the right, descending left arm of the catch curve in each length class. The probability of capture is obtained by dividing, for each length-class, the numbers caught (N) by the numbers available (N/P), resulting in a curve from which the length at first capture Lc can be estimated (Pauly, 1987).

Yield per recruit

The length-based yield per recruit model (YPR) by Thompson and Bell (1934) was used to evaluate the exploitation levels of O.ruber, which would result in optimum yield. With the growth parameters as the
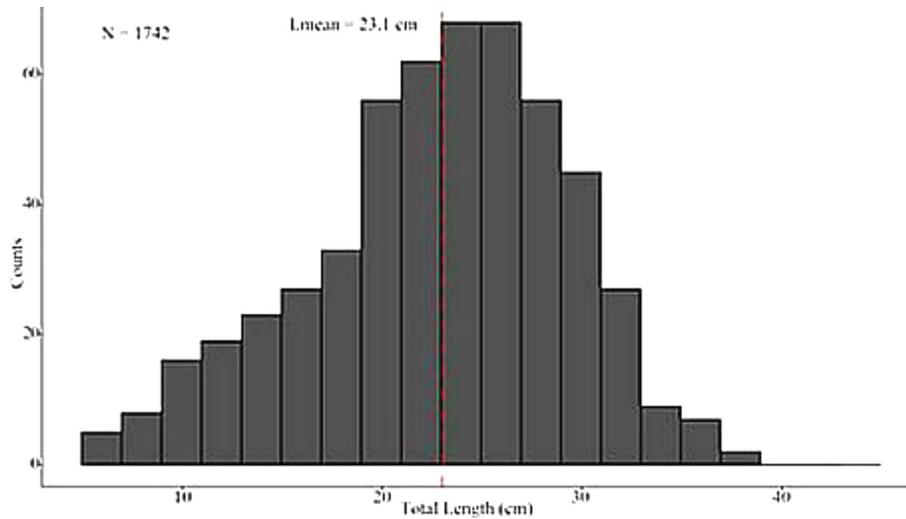
Figure 2. Length frequencies of *O. ruber* collected from commercial prawn trawlers as by-catch samples from Malindi-Ungwana Bay, 2016-2018.

input, the reference levels F_{max} (the fishing mortality, which produces the highest yield per recruit), $F_{0.5}$ (the fishing mortality that results in a 50 % reduction of the biomass compared to the unexploited population), and $F_{0.1}$ (the fishing mortality that corresponds to 10 % of the slope of the yield per recruit curve at the origin) were estimated. The impacts of varying fishing mortality and selectivity (Lc/ L∞) were assessed using the yield isopleths diagramme.

Results
Size distributions of the stock
The length frequency distribution of the 1742 individuals of *O. ruber* revealed a unimodal distribution and was negatively skewed (Fig. 2). The total length (TL) ranged between 5 and 38.4 cm, with a mean size of 23.1 cm (Fig. 2). The majority of the *O.ruber* individuals caught (53.1 %) had a TL larger than the mean size. The mean size of the individuals caught was generally lower in 2016 (22.04 ± 7.6 cm) and 2017 (22.9 ± 5.5 cm) compared to 2018 (24.4 ± 4.9 cm; Table 1).

The results of the Kruskal-Wallis rank-sum test revealed that there was a significant difference between the mean length across the years (chi-squared = 10.123,

df = 2, p-value = 0.006337). A pairwise comparisons using the Wilcoxon rank-sum test showed that the mean length in 2018 was significantly different (p < 0.05) from the year 2016 and 2017 (Table 2).

Estimation of growth parameters
The length frequency (LFQ) data spans 3 years (2016, 2017, 2018) and comprises of 1742 length measurements, which are aggregated over 9 sampling times (Fig. 3). The figure shows the raw LFQ data (Fig. 3a) and after restructuring with a moving average of 5 (Fig. 3b).

The analysis of the pooled length-frequency data of the *O.ruber* gave an initial L∞ value of 39.2 cm estimated from the mean of the 1 % largest fish in the sample (Table 3). Using L∞ = 39.2 cm as a seed value and an MA of 5, the ELEFAN_GA routine in TropFishR yielded L∞ estimates of 41.7 cm and a K of 0.70 yr⁻¹ (Fig. 3c). The bootstrapped ELEFAN routine in TropFishR yielded L∞ estimates of 41. 7 cm, (CI=33.1- 44.6 cm) and a K of 0.79 yr⁻¹ (CI = 0.23-0.89).

The value of mode of the distribution (maximum density result after 500 resamples = 0.79) was slightly higher than the GA estimate (Appendix, Figure A).

Table 1. Summary statistics of the size distribution of the *Otolithes ruber* in the commercial prawn by-catch sample.

Year	N	Min (cm)	Max (cm)	Mean size (cm) ± SD
2016	526	5.0	38.4	22.0 ± 7.6
2017	630	10.0	34.0	22.9 ± 5.5
2018	586	9.0	36.0	24.4 ± 4.9

Table 2. Pairwise comparisons of the mean length between the years in *Otolithes ruber* using Wilcoxon rank-sum test.

	2016	2017
2017	0.435	
2018	0.013	0.013
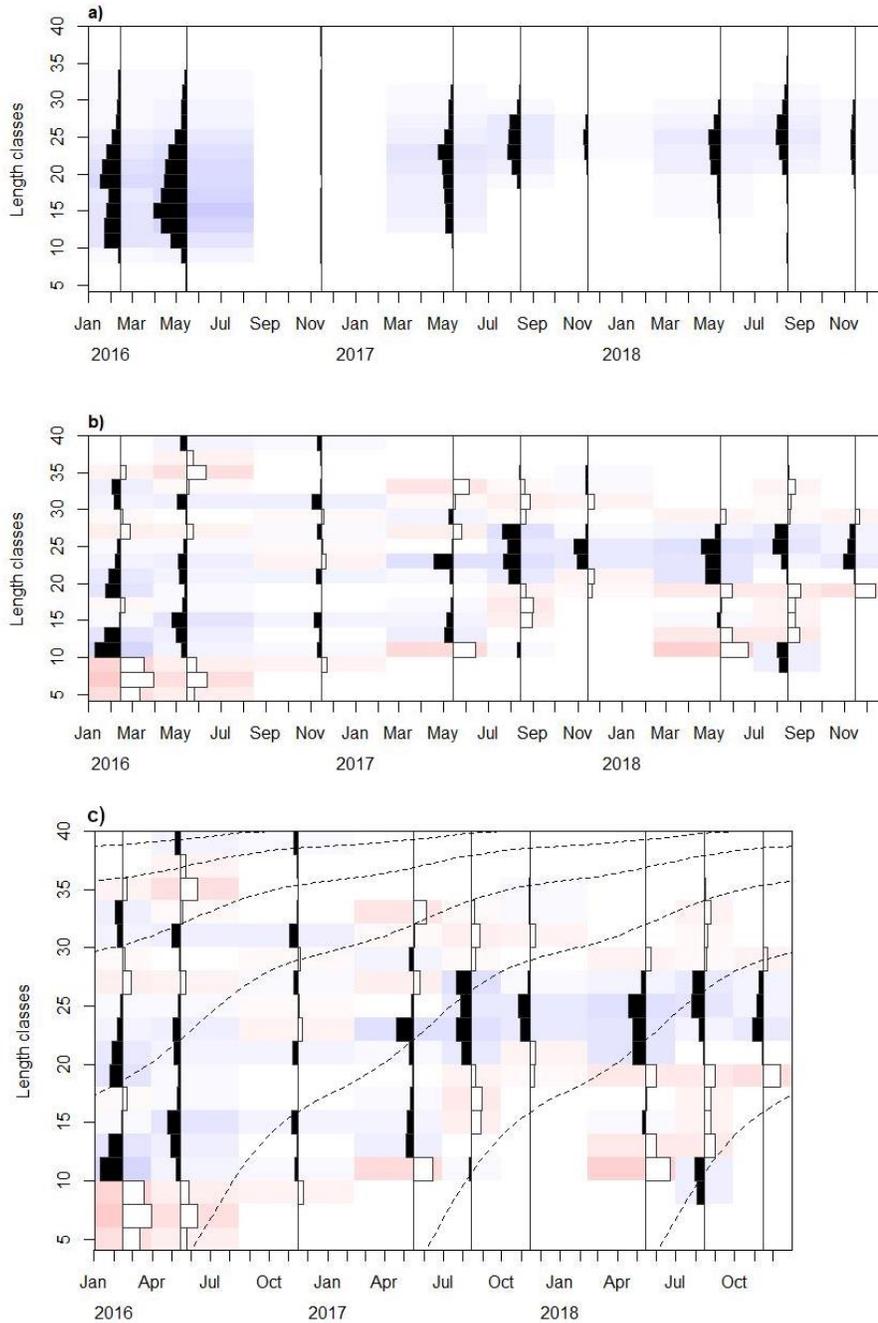
Figure 3. Raw (a) restructured (b) length frequency data of *O. ruber* from Malindi-Ungwana Bay, 2016-2018; (c) restructured length-frequency distribution with superimposed growth curves of *O. ruber* obtained through the ELEFAN_GA function (with the settings MA = 5, Linf = 41.7, K = 0.79, C = 0.43).

Table 3. Comparison of growth parameters of *Otolithes ruber* in this study with those from other studies.

Study	Methods	L∞ (cm)	K (year⁻¹)	Φ'	Reference
FishLife	Aggregated	43.9	0.38	2.86	(Thorson *et al.*, 2017)
This study	Length- based	41.7	0.70	3.087	
KwaZulu-Natal, South Africa	Age-based	41.9	0.31	2.74	(Brash and Fennessy, 2007)
KwaZulu-Natal, South Africa	Length-based	51.1	0.6	3.19	(Fennessy, 2000)
Kuwait	Length- based	59.0	0.39	3.13	(Almatar, 1993)
Sofala Bank, Mozambique	Length- based	42.9	0.14	2.42	Gislason (1985)
San Miguel Bay, Philippines	Length- based	29.5	0.455	2.60	Navaluna (1982)

The growth performance index (Φ') and the longevity (tmax) estimated for *O.ruber* was 3.087 and 4.28 years, respectively.

Mortality and selectivity

The instantaneous total mortality (Z) of *O.ruber* derived from the computed VBGP values was 3.23 (Fig. 4), with natural mortality of 0.931 estimated by the Then *et al*. (2015) approach. The estimated instantaneous rate of fishing mortality (F) was 2.30 per year, with an exploitation ratio of 0.71 (Table 4) which suggests that the *O.ruber* stock in Malindi-Ungwana Bay could be overexploited (E > 0.5). Applying the bootstrap routine resulted in a comparatively lower Z estimate of 1.02 for the maximum density value but with a wide confidence interval (Z = 0.57-3.69). With this procedure, the estimated range of the exploitation rate also varied widely (E = 0.28-0.70) (Appendix, Table A). With the above values, the backward projection of the descending arm of the catch curve resulted in a mean size at first capture (Lc) of 23.8 cm, assuming a trawl-like gear selectivity (Fig. 5).

Recruitment and yield per recruit

Given the growth parameters, the LFQ data can be extrapolated backwards onto the time axis to indicate the relative recruitment pattern (Fig. 6). The pattern exhibited by the size distribution of the *O.ruber*
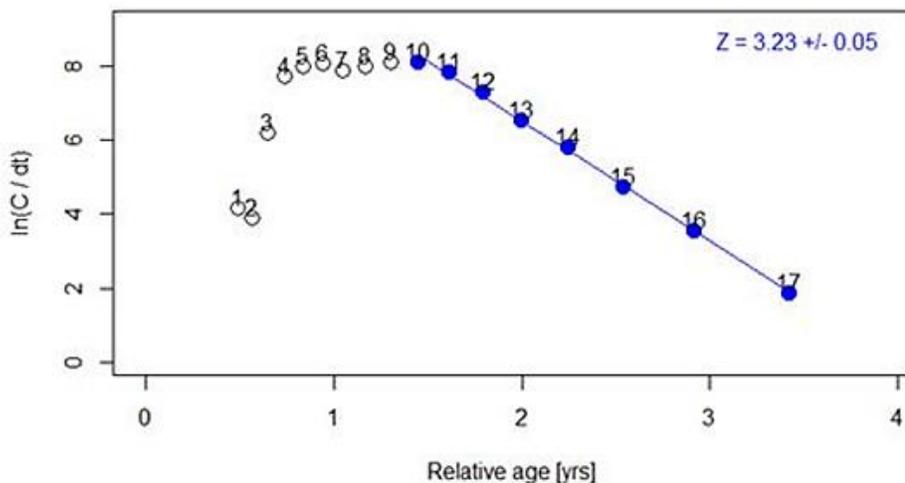
Figure 4. Length converted catch curve showing total mortality (Z) of *O.ruber* in the prawn trawl fishery.

Table 4. Computed mortality, exploitation rates and the selectivity of *Otolithes ruber*.

Z	M	F	E	L50	L75
3.23	0.931	2.302	0.71	23.8 cm	25.3 cm

indicated two unequal recruitment pulses with the major peak occurring during the eighth month (Fig. 6).

The estimation of the biological references are presented in Table 5 and Fig. 7. The optimal exploitation and fishing rate E_{max} (0.542) and F_{max} (2.32) values were well below the actual values of the current exploitation of 0.7 and fishing mortality of 2.3 year^{-1}, respectively

and is an indication that the species appears to be overexploited.

The yield and biomass per recruit isopleth diagrammes are represented in Figs. 8 and 9, respectively. The solid black lines are the isopleths indicating different areas of the same yield and biomass, with the dotted lines indicating the current fishing mortality
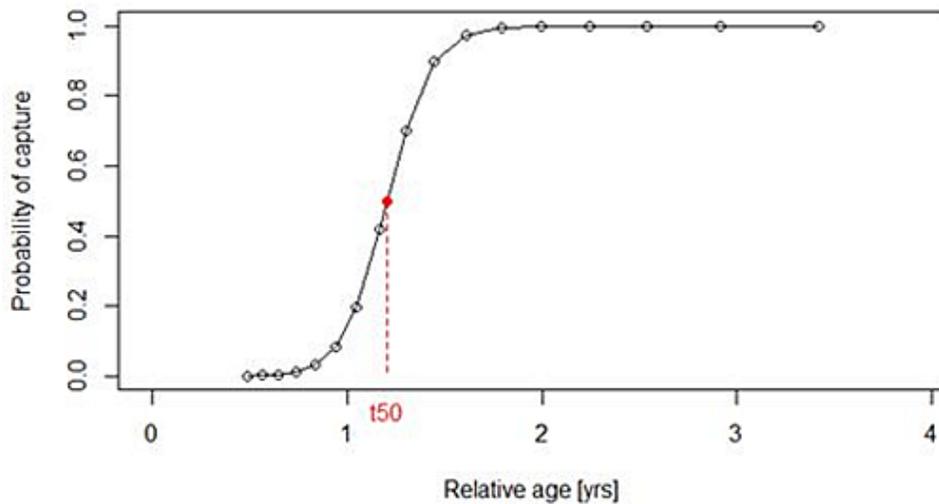
Figure 5. Probability of capture of *O.ruber* as estimated from the backward extrapolation of the descending arm of the catch curve. The dotted line indicates the relative age corresponding to the size at first capture (L50 = 23.8 cm).
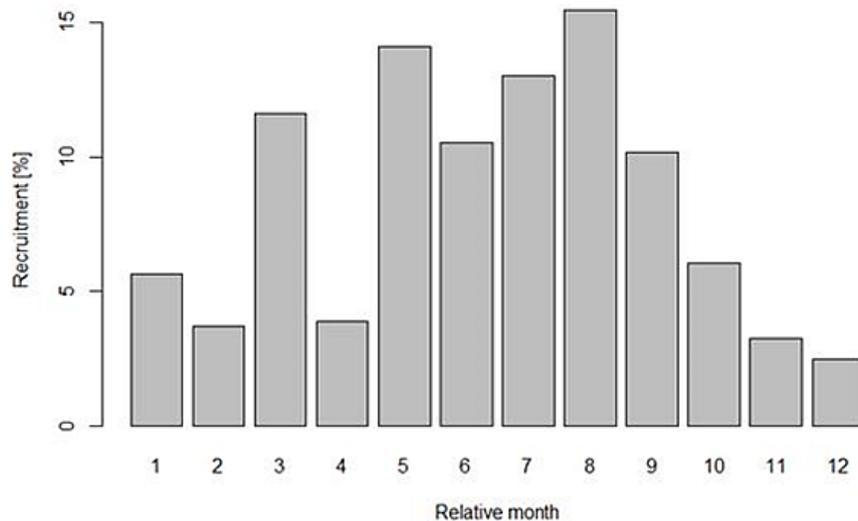
Figure 6. Recruitment pattern of *O. ruber* of the Malind-Ungwana Bay estimated from the restructured length–frequency data onto an arbitrary 1-year timescale. The species exhibits two peaks of unequal magnitude.

Table 5. The estimated biological reference levels from the length-based yield per recruit model (Thompson and Bell, 1934).

F01	Fmax	F05	E01	Emax	E05
1.102	3.306	0.918	0.542	0.78	0.497
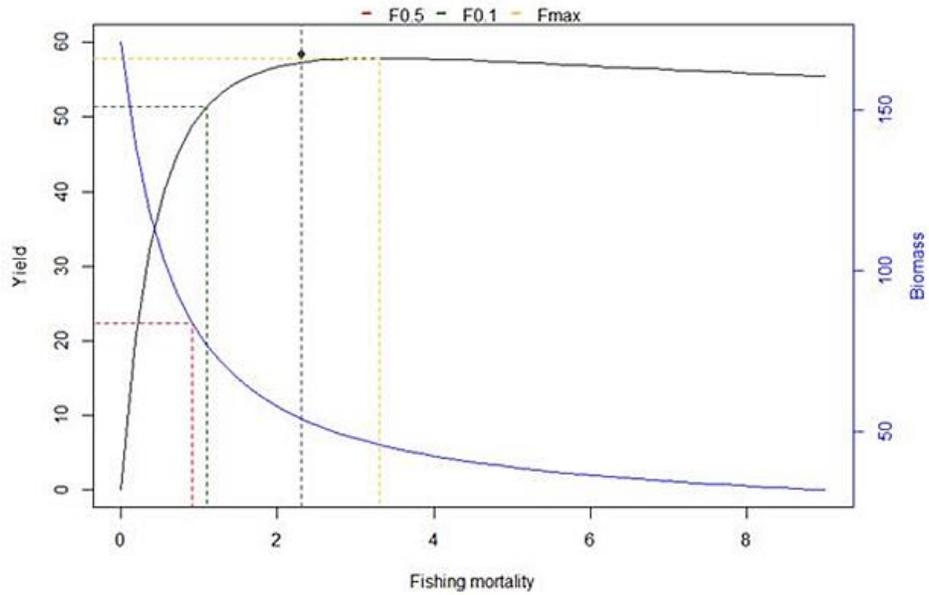
Figure 7. Relative yield per recruit curve for *O.ruber* indicating the yield and biomass per recruit for a range of fishing mortality values, respectively. The dashed lines show the reference levels F0.1, F0.5, Fmax and the current fishing mortality based on the catch curve analysis.
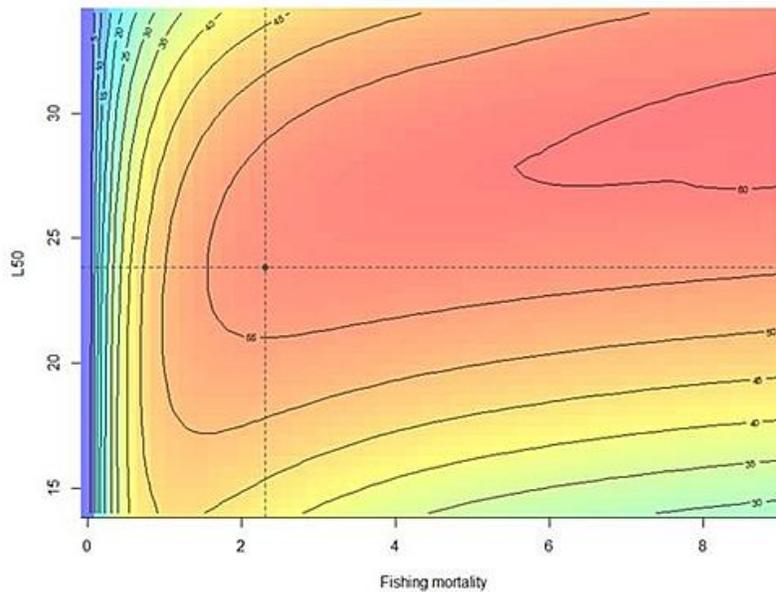
Figure 8. Isopleth diagrammes of the relative yield per recruit as a function of relative size at first capture (Lc/Linf) and fishing mortality for *O. ruber*. The solid black lines are the isopleths indicating different areas of the same yield, while the dashed line indicates the current fishing mortality and selectivity based on the catch curve analysis.
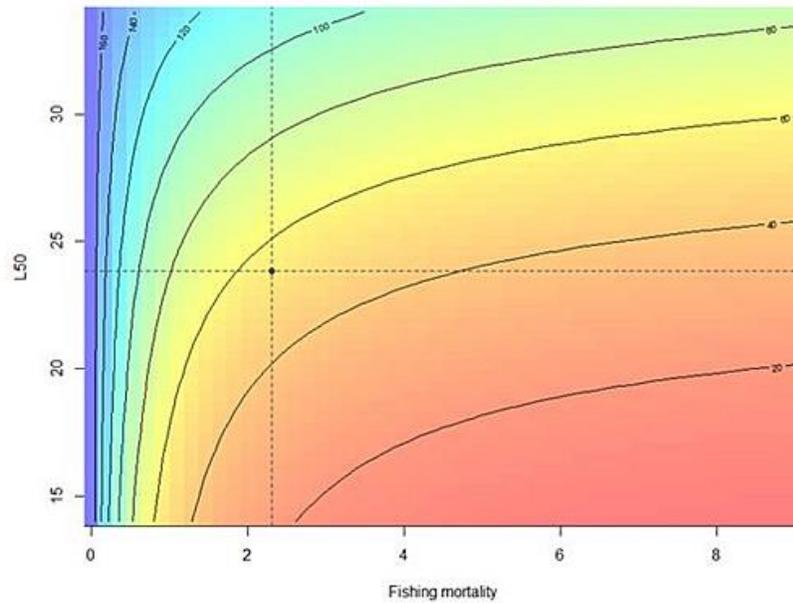
Figure 9. The biomass per recruit isopleth graph as a function of the fishing mortality and the relative size at first capture (L50). The black solid lines are the isopleths indicating different areas of the same biomass, and the dashed line indicates the current fishing mortality and selectivity based on the catch curve analysis.

and selectivity based on the catch curve analysis. The ratio between the Lc and the L∞ represents different scenarios typical to changes in mesh size. At the fishing effort and selectivity found in this study, *O.ruber* stocks are mostly exploited at a smaller size and at a much higher fishing effort. The Lc/L∞ ratio for the fishery was estimated at Lc/L∞ = 0.57.

Discussion

O. ruber commonly occurs as by-catch in prawn trawl fisheries in the western Indian Ocean region and many tropical fisheries of the world (Fennessy, 2000; Munga *et al.*, 2014; Olbers and Fennessy, 2007). on the east African coast, the contribution of *O. ruber* to the overall by-catch landed is substantial (Munga *et al.*, 2014). Nevertheless, their commercial importance is low compared to other demersal species of comparable size. Studies from the region suggest that industrial fleets discard a high proportion of *O. ruber*, the majority being juveniles, (< 20 cm) (Mwatha, 2002; Olbers and Fennessy, 2007). Moreover, relatively little is known regarding their status, and that of other by-catch species, which compromises the management and sustainability of these fisheries. One of the primary goals of fisheries management is to conserve sufficient reproductive potential in stock to allow sustainable exploitation, which requires knowledge of the species' life history (Komoroske and Lewison, 2015). However, the challenge of inadequate data (type, amount and quality)

limits the proper assessment and management of these fisheries (Dowling *et al.*, 2008).

This study is the first attempt on the Kenyan coast to assess the status of *O. ruber,* from Malindi-Ungwana Bay, making use of the length-frequency data from catch obtained from non-selective prawn trawl fishing nets. Validation of stock status from length-at-age data provides a more precise and unbiased estimate compared to length-frequency analysis, which strongly affects sample bias. The application of both methods offers the most robust results (Pauly, 1987). Nevertheless, given the cost implications of sampling and the difficulty in the ageing of tropical fish from otoliths, the length-based approaches have become more popular for tropical data-limited fisheries, where length-frequency data is easily collected.

In the absence of time series data on catch or catch-at-age data, the non-parametric ELEFAN routine in TropFishR (Mildenberger *et al.*, 2017) was used to estimate the growth parameters of *O. ruber* based on 1742 length measurements over the period from February 15, 2016, to November 15, 2018. The sample size (n = >1500) and the period over which the sample was collected (> 6 consecutive months) met the requirements for the appropriate sample size for assessing length data for growth studies (Hoenig *et al.*, 1987; Pauly, 1987). Besides, the graphical representation of both the raw and restructured length-frequency data

revealed clearly defined modal groups with shifts in the modal length over time, a criterion for assessing the suitability of length-frequency data for the estimation of growth parameters (Wolff, 1989).

The size distribution of the caught individuals from this study demonstrates that *O. ruber* is being caught at relatively larger sizes with more than 53.1 % larger than the mean size at maturity (23.8 cm). Other studies on *O. ruber* have reported the length at first maturity (L50) as 22.6 cm (Froese and Pauly, 2019) and ranging from 22.1 cm in the Arabian Gulf (Lee and Al-Baz, 1989) and between 22-24 cm and 23.8 cm in India and South Africa, respectively (Brash and Fennessy, 2005). Thus, using an approximate value of 23 cm as the length at maturity, which compares to the length at first capture obtained in this study (Lc = 23.8 cm), it is clear that the current exploitation of *O. ruber* with regards to size is slightly above the size at first capture and size at maturity, but falls short of the optimum target (% mature fish in catch = 100%) (Froese, 2004). According to Munga *et al.* (2014), the average sizes of the individuals caught in trawl by-catches was significantly smaller than in artisanal catches. Nevertheless, both fisheries operate within the same area but with the artisanal fleets operating less than 3 nm from shore. The difference in sizes of individuals caught is attributed to the selectivity of the trawl nets, which retain much smaller individuals than those regularly caught by artisanal fishing gears due to the smaller mesh size (mesh size of trawl gear; 45-70 mm). The maximum reported size of *O.ruber* in this study (Lmax 38.4 cm) is much smaller than individuals observed in the northern waters of the Persian Gulf, which reported much higher estimates (Lmax = 67.57 cm; Eskandari *et al.*, 2012).

Table 3 compares the growth parameters obtained in this study with those obtained from other studies. The results indicate that the values of L∞ compare well with estimates from Mozambique and South Africa, although not with the estimates of K, which is more than double that obtained in these studies (Brash and Fennessy, 2007; Gislason, 1985). The potential longevity of *O. ruber* was estimated at 4.3 years, which indicates that the species is short-lived. In contrast, the estimated longevity of the species varied widely from other studies (Brash and Fennessy, 2005), which indicated that *O. ruber* and most species of family Sciaenidae are generally slow-growing and long-lived (mean K = 0.32 ± 0.05).

Munro and Pauly (1983) proposed the phi prime (φ) as a suitable indicator for interspecific comparison of growth performance of different species of fish stocks given that the index is more or less constant for a family or similar taxa. The estimated phi prime with current estimates of K and L∞ is 3.08, which compares well with the estimates from Kuwait (φ = 3.19) and South Africa (φ = 3.13) and is within the range of estimates reported in the FishBase (φ = 2.41-3.39) (Froese and Pauly, 2019). The differences in the φ index can be attributed to the differences in the estimation of growth parameters related to the bias in the size distribution of the specimens analyzed here due to the absence of juveniles and larger individuals (Lmax = 90 cm), which may have been missed.

Based on estimated growth parameters, two dependent stock status indicators were estimated employing the length-converted catch curve and the length-based yield per recruit model. The estimated natural mortality (M) was 0.931 year^{-1} leading to fishing mortality of 2.302 year^{-1} and an exploitation rate (F/Z) of 0.71 for the fully exploited part of the stock, indicating that *O. ruber* in the Malindi-Ungwana Bay stock is experiencing excessive fishing pressure (E > 0.5). However, the confidence interval estimated from the bootstrapping routine of the TropFishR gives a wide range of estimates for both the growth parameters and the exploitation rate (E = 0.28-0.70). The wide range of confidence interval around the exploitation rate may be due to the biased sample from the commercial trawl fishery. According to Beare *et al.* (2005), data from commercial sources are likely to be biased due to levels of misreporting and discarding and lack spatial detail, which can result in biased estimates of growth parameters. The estimate of fishing mortality in the current study(F = 2.3) based on the catch curve is larger than the reference level (= 1.1) based on the yield per recruit analysis, further strengthening the evidence of overexploitation (= 2.09). Similar results have been reported in Mozambique and the Philippines, where *O. ruber* has been overfished by the prawn trawlers (Brash and Fennessy 2005). Also, the estimated Z/K ratio (Z/K = 4.6) is high, further highlighting that the population of *O. ruber* is mortality-dominated (Z/K>2) and is experiencing excessive fishing pressure (Etim *et al.*, 1999).

Pauly and Soriano (1986) proposed an extension to the length structured yield per recruit model applied to tropical fisheries for species associated with high M/K values and E> 0.5. Based on the Lc/ L∞ ratio (a proxy for mesh size) and fishing effort, four quadrants are proposed, each with distinct properties. Under the

current fishing scenario, the estimate of Lc/ L∞ of 0.57 and an exploitation rate (E) of 0.71 falls within quadrant D (Pauly and Soriano, 1986). The implication is that small fish are caught at a higher fishing effort requiring a reduction in effort and an increase in mesh size as a management intervention. The recruitment pattern of the *O. ruber* conforms to the general pattern exhibited by most tropical fish species, which have double recruitment pulses (Pauly, 1982). The recruitment pattern was estimated by the backward extrapolation of the LFQ data onto the time axis to indicate the relative recruitment pattern (Fig. 7). However, the pattern can not be interpreted in absolute terms as information about the length at age 0 is lacking and cannot be estimated from length frequency data alone (Pauly, 1987). Nevertheless, based on the length-frequency data used (Appendix, Table B), the observed peak for smaller sized individuals is between the fifth and seventh months, with the possibility that the young join the adults as recruits in the eighth month. The bimodal peak observed for *O. ruber* in this study is consistent with the results reported for the species in the northwest Arabian Gulf (Mohamed *et al.*, 2002). Thus, a better understanding of the recruitment pattern of the *O.ruber* is critical in formulating better management practices such as in the determination of the seasonal closure for prawn trawling, which is currently from November to March annually (Munga *et al.*, 2016). However, to infer an informed management recommendation, there is a need to augment the current studies with biological, catch and effort data and biomass estimates to capture the variability and changes in population structure. Comparison of biomass and catch-based methods will give a true picture of the fishery, as some studies have reported significantly different results when the two methods were employed (Branch *et al.*, 2011).

Management implications

O. ruber constitutes the highest by-catch species in the commercial prawn trawl fishery in Malindi- Ungwana Bay in Kenya, and is also common among artisanal landings. Previous studies have documented resource-use conflict between the artisanal fishers and the trawlers arising from resource-use overlap, which resulted in the trawling ban in 2006 (Munga *et al.*, 2012). Among the critical issues highlighted included the infringement of the trawlers into the artisanal fishers fishing zones and the incidental capture and discarding of the fisher's target species, of which *O. ruber* is a crucial component. Thus, the Prawn Fisheries Management Plan (PFMP-2010) was instituted

to guide fisheries management decision and reduce conflict with artisanal fishers (Thoya *et al.*, 2019). The management plan is due for a review, but the lack of routine monitoring and appropriate data makes it challenging to assess the effectiveness of the management plan. This study highlights the importance of describing and assessing by-catch in specific fisheries to determine whether there are problems in the fishery (Kennelly, 1995; Munga *et al.*, 2012).

This study has assessed the stocks of *O.ruber,* a common by-catch species in the Malindi-Ungwana Bay prawn fishery, and has found that the stocks are being over-exploited (based on a data-limited situation). This calls for stringent measures for the management of the Malindi-Ungwana Bay fishery. However, for practical management recommendations, there is a need for further studies on other by-catch species, and complement these with independent surveys. The current sample is biased towards specific sizes, which might be an artefact of the spatial preference by the commercial prawn trawl. It is suggested that data from the artisanal fishery is included in future assessments to capture the whole fishery for a better estimation of the stocks. Further attempts should be made towards the collection of biological data to provide improved estimates of the reference points, which can be used to complement the current study and thereby contribute to more informed decision making. These efforts should be complemented by the ongoing seasonal closure and gear adjustments to reduce by-catch and juvenile capture.

Conclusions

Given the fact that *O. ruber* is the highest by-catch species in catches of the commercial prawn trawlers in Malindi-Ungwana Bay, it can be expected that their stocks could be at risk. This study has proven that the stocks of *O.ruber* are being overexploited. Further studies are, however, required across all gears and methods, for comparison. It is strongly recommended that stocks of *O.ruber* need proper management to ensure sustainable exploitation and to avoid collapse.

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Appendices

Table A. Pooled length frequency of *Otolithes ruber* from 2016 to 2018 (constant interval of 2 cm).

ML	2016					2017						2018				
	Jun	Jul	Aug	Sep	Oct	May	Jun	Jul	Aug	Sep	Oct	May	Jun	Jul	Sep	Oct
5		1														
7																
9		1		1	1									3		
11	15	28		3	5	5			1				1	3		
13	27	15		29	5	25							4	1		
15	20	10	2	32	7	24	1		2				10	2		
17	24	15	2	24	4	27	3		5				18	5		
19	11	26	10	16		10	15	1	11	2	4	1	19	6		2
21	7	21	13	15	2	16	27	10	23	13	6	7	36	24	4	16
23	6	11	8	10	1	18	39	11	34	21	19	9	27	27	13	19
25	2	9	6	5	3	12	20	6	27	24	26	20	21	32	20	26
27	4	2	5	5	3	4	15	1	28	24	14	19	8	21	38	22
29	11	2	1	2	2	2	8	2	7	10		13	1	6	25	14
31	11	4	1	3	3	2	4		5	4	2	5		7	12	4
33	6					3	2		1	3	1			3	5	1
35	1						1		1		1			2	1	
37			1		1									3		
39			1		1											

Table B. Growth parameter estimates resulting from the bootstrapping routine of the TropFishR indicating the confidence interval.

Species	Parameter	Mod	Lower	Upper
Otolithes ruber	$L\infty$	41.7	33.1	44.6
	K	0.79	0.23	0.89
	t_{anchor}	0.43	0.12	0.87
	C	0.54	0.19	0.88
	t_s	0.68	0.17	0.86
	Φ	3.14	2.39	3.25
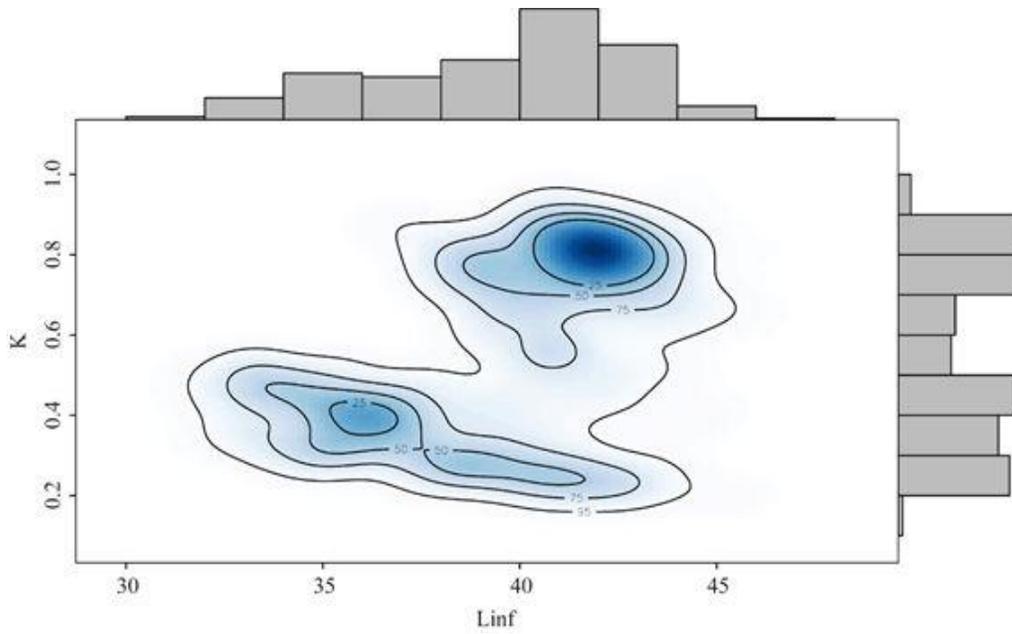
Appendix, Figure A. Scatter histogram of bootstrapped ELFFAN for *O. ruber* using TropFishR. The points represent the individual combinations of L_∞ and K estimates, while the contours represent the density of the combinations.
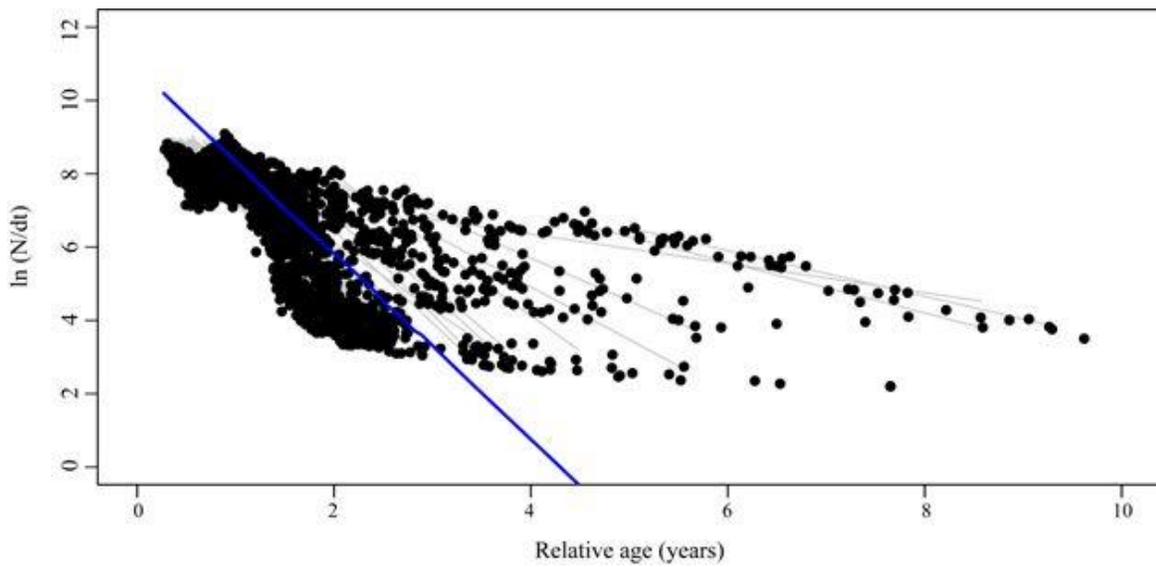
Appendix, Figure B. The bootstrapped linearized length-converted catch curve based on pooled length frequency catch data for *O. ruber.*