Original Article

Comparative assessment of the impacts of artisanal trolling and industrial longlining on yellowfin tuna exploited off the Kenyan coast

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Abstract
The Indian Ocean yellowfin tuna stock has been classified as overfished and remains subject to overfishing by industrial and artisanal fleets despite the implementation of catch reduction measures to rebuild the stocks. This study assessed the impacts of artisanal trolling and industrial pelagic longlining on the population structure of yellowfin tuna exploited in Kenyan waters. Catch data including fork length, sex and gonad maturity were examined for the two fisheries between April 2019 and April 2021. Selection patterns were then compared using eight length-based indicators and a suite of indicator ratios. Results showed that artisanal trolling caught individuals with smaller fork length, ranging from 32–177 cm with a mean of 76 ± 0.5 cm and a mode of 71 cm. The industrial fishery caught significantly larger individuals ($p > 0.05$) ranging from 52 – 204 cm with a mean of 137 ± 0.7 cm and a mode of 160 cm. Length at first capture (L_c) for artisanal trolling was estimated at 36 cm and 80 cm for the industrial fishery. Statistical tests further revealed significant differences in length distribution and selectivity curves. It was clear that the fisheries consistently captured distinct components of the yellowfin tuna population structure. The industrial fishery was dominated by mature individuals above length at 50 % maturity (>100 cm, L_{50}) constituting 90 % of the sampled catch of which 56 % were large mega-spawners above the optimum length (> L_{opt} + 10%). On the other hand, 92 % the artisanal trolling fishery constituted small individuals below L_{50} and no mega-spawners. Overall, the average monthly sex ratio was skewed to males (F:M ratio = 1: 1.14). Deviations from the expected 1:1 sex-ratio were not significant; however, industrial longline catches were skewed towards large males, and artisanal trolling catches towards small females. The study illustrates application of widely used length-based approaches to derive insights on fishery interactions in data limited scenarios.

Keywords: tuna fisheries, selectivity, length-based indicators, western Indian Ocean

Introduction
Yellowfin tuna support numerous small-scale and highly valuable industrial fisheries worldwide and is ranked among the most valued and sought-after commercial species (Miyake *et al.*, 2010). Yellowfin tuna rank as the second most important commercial tuna species harvested worldwide after Skipjack (Galland *et al.*, 2016). The species is highly migratory, inhabiting the tropical and subtropical seas. Due to adaptation to subsurface feeding they occur in waters of up to 250 meters depth within coastal, neritic and oceanic waters (Schaefer and Fuller, 2002). The most recent regional assessment has classified the Indian Ocean (IO) yellowfin tuna stock as overfished (Fu *et al.*, 2021). Despite the overfished state, the stock remains subject to overfishing due to increasing fishing effort by industrial and artisanal fleets (Fu *et al.*, 2021). Catches of yellowfin tuna in the region have consequently continued to increase from 402,913 mt in 2015 to 432,623 mt in 2019, averaging at 434,568 mt annually (Fu *et al.*, 2021). Industrial longline catches of yellowfin tuna in the IO region average 73,240 mt, annually representing about 17 % of the total annual catch (ISSF, 2019). The proportion of yellowfin tuna caught by artisanal

fleets has also increased from 30 % in the 2000s to 50 % in more recent years (Lecomte *et al.*, 2017).

Kenya lies within the rich tuna belt in the western Indian Ocean (WIO), which is mainly exploited by foreign industrial fishing vessels. Kenya's artisanal tuna fleet consists of an estimated 600 fishers using 414 vessels and diverse gear types including longlines, trolling lines, handlines, multifilament and monofilament nets (Ndegwa *et al.*, 2020). The fleet landed an estimated to 2,740 tons of tuna in 2019 (Ndegwa *et al.* 2020). Handlines, longlines and trolling lines are selective passive gears which consist of a mainline that is attached with baited hooks. Deployment strategies for these gear types are adjusted by changing the fishing depth, bait type and even construction materials to target specific species (Watson and Kerstetter, 2006). Artisanal trolling in Kenya involves use of monofilament lines which are hooked with artificial lures or natural baits. The lines are towed and hauled using a pole along the water surface. The fishers use mechanized fibreglass vessels which enable them to travel far distances in search of tuna. Reliable estimates of yellowfin tuna catches by the artisanal fishery are however lacking due to the strong seasonality and migratory nature of the fishery. Kenya's industrial longline fishery operates within the Exclusive Economic Zone (EEZ) (Ontomwa *et al.*, 2021). Industrial longline fishing uses multiple branch lines which are deployed at varying depths. In 2020, three industrial longline vessels were licensed to fish in Kenya's EEZ landing approximately 670 metric tonnes of assorted species of which approximately 132 mt (20 %) constituted yellowfin tuna (Government of Kenya, 2021).

Interactions between artisanal and industrial fisheries can arise when the same species are targeted, and such overlaps can cumulatively influence overall fishery performance (Powelle and Leslie, 2020). Studies on fishery interactions are important in understanding sources of fishing mortality and impacts of fished populations to inform the development of sustainable management strategies. There are some assessments characterizing interactions in tuna fisheries (Hampton *et al.*, 1996; Leroy *et al.*, 2016). Information on tuna fishery interactions is limited in the WIO region, and particularly Kenya. Use of length-based indicators to assess data-poor fisheries has become popular, as they are reported to perform as well as catch-based models (Kell *et al.*, 2022). This is more so because length composition data is easy to obtain and hence the most frequently collected data parameter among data-poor fisheries. Thus, this study applies a suite of length-based methods to derive insights on the impacts of artisanal trolling and industrial longlining on yellowfin tuna exploited off the Kenya coast

Materials and methods

Study Area

Monitoring of artisanal trolling catches was conducted at three selected fish landing sites along the Kenyan coast: Watamu, Amu and Kiwayu Island (Fig. 1). The fishing grounds within these sites are characterized by patchy and fringing reefs with high coral diversity, seagrass beds and extensive mangrove forests (Fulanda *et al.*, 2009). The continental shelf extends 15 - 60 km and covers an estimated area of 35,300 km^2. Kiwayu Island is located north-east of Amu town and borders the 250 km^2 Kiunga Marine National Reserve (KMNR).

Catch characterization

Publicly available data on yellowfin tuna landings across the WIO region for the years 1979 to 2020 was obtained from the IOTC website (www.iotc.org) to assess regional trends in annual yellowfin tuna catches by sector (industrial vs artisanal). For the more localized comparative assessment, yellowfin tuna caught off the Kenya coast by artisanal trolling lines were monitored monthly for four days at the three study sites between July 2020 and April 2021 for a duration of 10 months. Timing of sampling dates was informed by alerts sent by representatives of the beach management units on the presence of yellowfin tuna in landings at each site. All landed yellowfin tuna caught by artisanal trolling were sampled. Yellowfin tuna data collected by scientific observers from the Kenya Marine and Fisheries Research Institute deployed onboard industrial longline vessels between April 2019 and June 2020 was extracted. The observers collected catch data following the observer sampling protocol for longline fishing (Groeneveld and Heinecken, 2010). A simple random sampling protocol was employed in which fish were randomly sampled after an entire line hauling period. A total of 56 hauls (representing one haul per day) were sampled, and each haul contained between 1,950 and 2,720 hooks. Biometric measurements recorded included fork length (FL), measured to the nearest 0.1 cm on a measuring board and individual fish weight measured to the nearest 0.1 kg using an electronic weighing scale. Gonads from a sample of the measured fish were then visually examined to determine the sex of each fish.

Data processing and analysis

Length distribution and sex ratio

Length frequency histograms for the two fisheries were compared using a length interval of 10 cm. The Kolmogorov–Smirnov two-sample test was then applied to determine whether the length frequency distribution significantly differed between the fisheries. Sex ratio was calculated as the proportion of females to males (F:M), and the differences in sex ratio between the two fisheries was assessed using Chi-square test ($\chi 2$).

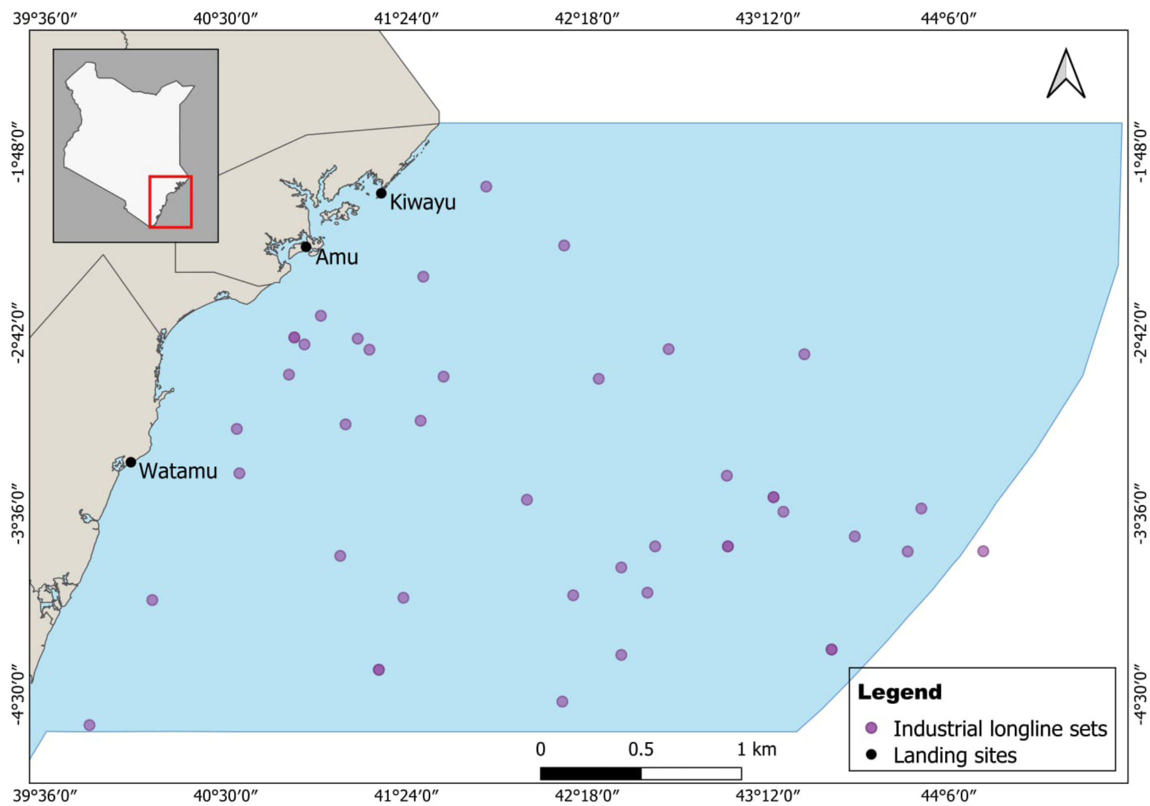

Figure 1. Map showing the artisanal fishery landing sites at Watamu, Amu and Kiwayu along the Kenyan coast, and industrial longline sets where yellowfin tuna were caught off Kenya's EEZ between April 2019 and April 2021.

Length indicators and indicator ratios

Length at first capture was estimated as the length of 50 % (SL_{50}) and 95 % (SL_{95}) of the fish retained by the two fisheries (trolling and pelagic longlining). The analysis was conducted on the online platform available at http://barefootecologist.com.au/. Each measured individual was classified as immature, maturing, mature or as a mega-spawner as defined by Froese (2004). Immature fish were classified as those below the reported size at first maturity (L_m), maturing as those between L_m and the length at which 50 % of fish were sexually mature (L_{50}), mature fish as those above L_{50}, and mega-spawners as fish larger than the optimum length (L_{opt}) plus 10 %. Optimal length is defined by Froese and Binohlan (2000) as the length when total biomass of a year-class reaches a maximum value. Classification of maturity status was based on length thresholds reported by Creech and Gunasekera (2020) as follows: immature (<76 cm), maturing (76-100cm), mature (>100 cm) and mega-spawners (≥143 cm). Length-based indicators by Froese (2004), and Cope and Punt (2009) were calculated for the two fisheries as: (i) percentage of mature fish in catch, with 100 % as target; (ii) percent of specimens with optimum length in catch, with 100 % as target; and (iii) percentage of 'mega-spawners' in catch, with target of 30-40 %. Life history parameters and length thresholds for life stages of yellowfin tuna are shown in Table 1. Length ratios defined in ICES (2015) were then calculated for each fishery and then for the pooled data and the derived ratios were compared against expected values as shown in Table 2. A traffic lights table was then generated assigning a colour code of either red or green to the derived ratios, with red reflecting a dangerous condition and green reflecting satisfactory conditions.

Table 1. Life history parameters and length thresholds for life stages of yellowfin tuna.

Parameter	Value	Source
L_∞	195 cm	Kimakwa *et al.* (2021)
L_{max}	165 cm	Creech and Gunasekra (2020)
L_{50}	100 cm	IOTC (2017)
L_{95}	121 cm	Creech and Gunasekra (2020)
L_{mat}	76 cm	Binohlan and Froese (2009)
K	0.44	Kimakwa *et al.* (2021)
M	0.59	Kimakwa *et al.* (2021)
M/K	1.37	calculated
L_{opt}	130	Froese and Binohlan (2000)

Results

Long-term temporal trends of yellowfin tuna landings catch estimates reported by IOTC indicated a general increasing trend in yellowfin tuna landings from the 1980s, peaking in 2004 followed by a decline until 2009 and a subsequent increase (Fig. 2). Over the last five years (up to 2020), industrial fleets accounted for 59 % of the yellowfin tuna landings in the region. Industrial longlines and artisanal trolling lines in the region altogether contributed about 32,000 mt (9 %) of yellowfin tuna landings annually.

Length distribution, sex ratio and maturity composition

Length distribution - Overall, a total of 3,138 yellowfin tuna individuals were sampled over the study period. A total of 916 and 1,076 tuna individuals were visually examined for sex ratio and maturity in the artisanal trolling and industrial longline fishery, respectively. Analysis of the length composition showed that the overall fork length distribution ranged from 32 - 204 cm (Fig. 3). Yellowfin tuna caught by the industrial longline fishery ranged from 52 - 204 cm with modal fork length of 160 cm, while that for the artisanal trolling fishery ranged from 32 - 177 cm with modal fork length of 71 cm. The Kolmogorov-Smirnov test revealed significant differences in length distributions and selectivity curves between the two fisheries ($D = 0.821 > 0.05$, at 0.05 CI).

The average monthly sex ratio was skewed to males (F:M ratio = 1: 1.14). Monthly variations in the sex ratio were observed in both fisheries; however, results of the Chi-square test showed no significant differences

Table 2. Comparison of monthly sex ratios (F: M) of *Thunnus albacares* catches in the artisanal trolling and industrial longline fishery occurring in Kenyan waters during March 2020 to April 2021.

Fishery	Month	Female	Male	F : M ratio		Chi-square	p-value
Artisanal trolling line	August	78	76	1	0.97	0.504	p=0.478
	September	73	71	1	0.97	0.462	p=0.497
	October	22	9	1	0.41	2.084	p=0.149
	November	59	32	1	0.54	1.890	p=0.169
	December	36	27	1	0.75	0.044	p=0.834
	January	73	70	1	0.96	0.392	p=0.531
	February	58	32	1	0.55	1.699	p=0.192
	March	64	57	1	0.89	0.106	p=0.745
	April	35	29	1	0.83	0.0028	p=0.958
	July	18	16	1	0.89	0.0286	p=0.867
Industrial longline	April	63	76	1	1.21	2.412	p=0.1204
	May	80	214	1	2.68	3.351	p=0.067
	June	38	69	1	1.82	0.0037	p=0.952
	August	63	59	1	0.94	6.712	P=0.500
	September	63	140	1	2.22	0.775	p=0.379
	October	80	139	1	1.74	0.120	p=0.913
	December	13	13	1	1.00	1.11	p=0.292

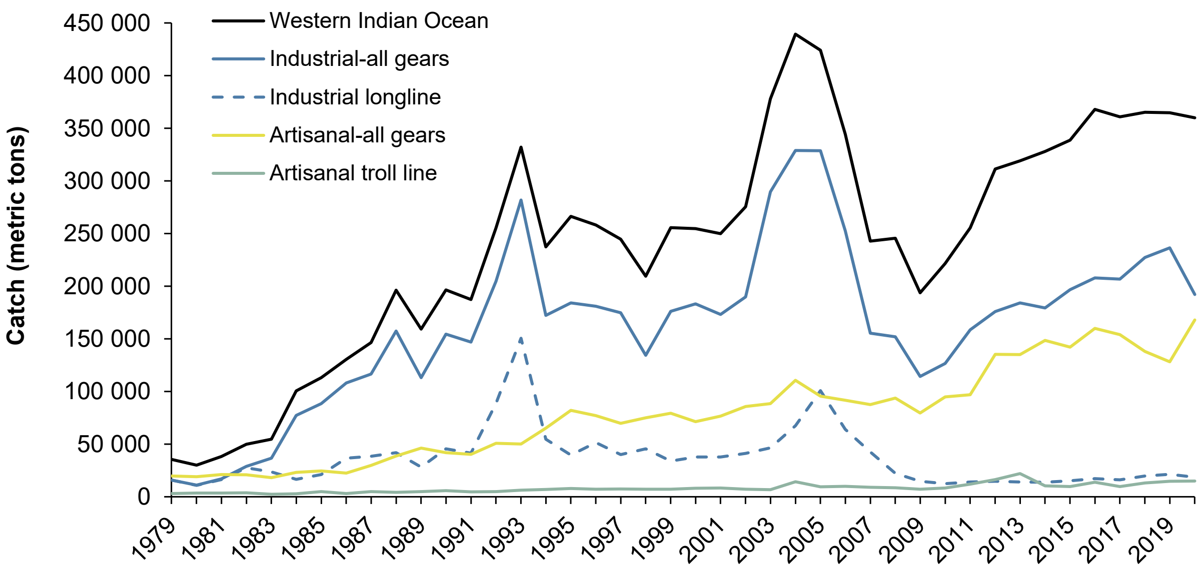

Figure 2. Annual time series of yellowfin tuna catches (mt) caught by the industrial and artisanal fleets within the western Indian Ocean region from 1979 to 2020 (Source: IOTC).

(Table 3). By fishery, the average monthly sex ratio was 1: 0.78 for the artisanal trolling fishery and 1: 1.66 for the industrial longline fishery. This indicates that yellowfin catches by the artisanal trolling fishery are skewed to females, while industrial pelagic longline fishery catches are skewed to males. Mature individuals (>100 cm) of yellowfin tuna constituted 90 % of the industrial longline, of which 56 % were mega-spawners, while 92 % of the yellowfin tuna targeted by artisanal trolling was immature with no mega-spawners (Fig. 3). The selectivity curves revealed the catch of fish was below the size at maturity for artisanal trolling while the industrial longline selected fish above size at maturity (Fig. 4). It was also apparent that both fisheries consistently caught a higher proportion of the dominant life phases across months demonstrating high selectivity as the proportions did not vary significantly between months (Fig. 5).

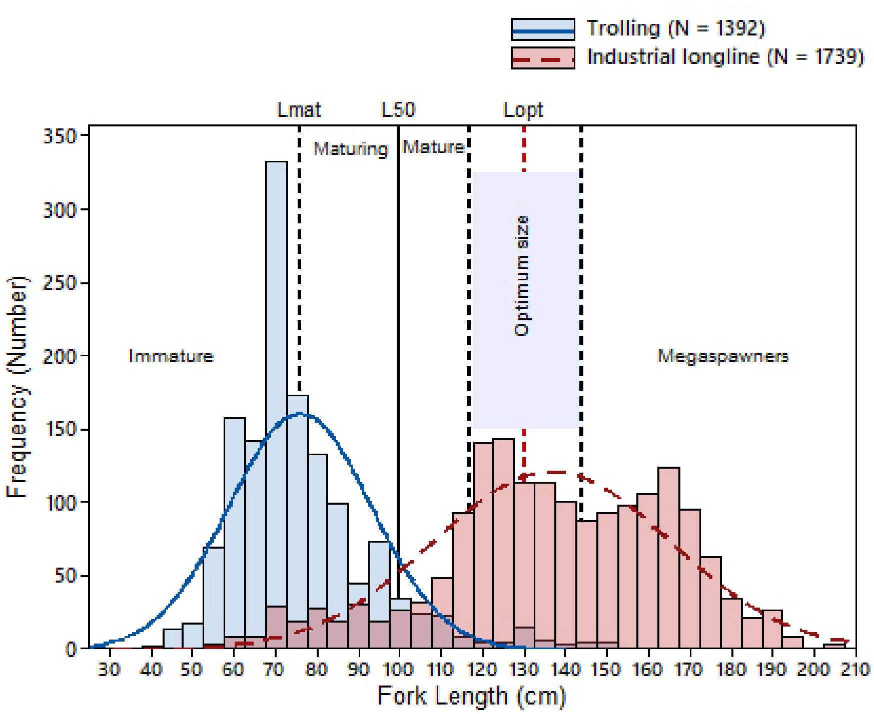

Figure 3. Length frequency distribution for yellowfin tuna caught by the artisanal trolling and industrial longline fishery off the Kenyan coast between April 2019 and April 2021.

Table 3. Summary of length-based indicators used in the assessment and the derived estimates.

Source	Indicators	Calculation	Reference point	Artisanal trolling	Industrial longline
ICES (2015)	L_c	Length at first capture (50% of the overall mode)	L_{mat}	36 cm	80 cm
	$L_{25\%}$	25th percentile of length distribution	L_{mat}	65 cm	114 cm
	L_{maxy}	Length class with maximum biomass in catch	$L_{opt} = \frac{3}{3+\frac{M}{k}} \times L_{inf}$	71 cm	165 cm
	$L_{95\%}$	95th percentile of length distribution	L_{inf}	73 cm	187 cm
	L_{mean}	Mean length of individuals > Lc	$L_{opt} = \frac{3}{3+\frac{M}{k}} \times L_{inf}$	93 cm	140 cm
	$L_{max5\%}$	Mean length of largest 5%	L_{inf}	127 cm	187 cm
Froese (2004)	P_{mat}	Percentage of mature fish above L_{50}	L_{50}	0.07	0.90
	P_{opt}	Percentage of fish at optimum length	L_{opt}	0.03	0.38
	P_{mega}	Percentage of mega-spawners	0.3 – 0.4	0.01	0.43

Length indicators and indicator ratios

Length at first capture of 50 % (SL_{50}) and 95% (SL_{95}) was estimated to be 63 cm (95 % CI, 61 – 64 cm) and 69 cm (95 % CI, 67 – 71 cm) respectively for artisanal trolling. For the industrial longline SL_{50} and SL_{95} was 138 cm (95 % CI, 127 – 148 cm) and 191 cm (95 % CI, 176 – 204 cm), respectively. The findings showed that the two fisheries predominantly captured different life phases of yellowfin tuna (Table 4). The summary of the generated length indicator ratios for the two fisheries shows that ratios for artisanal trolling were all below expected values indicating poor conservation outcomes due to the high proportion of immature sizes (Fig. 5). On the other hand, the ratios for the industrial longline fishery were all above expected values. Ratios for the pooled dataset showed an overall poor conservation outcome with immature and mega-spawners remaining below expected values.

Discussion

This study applied length-based metrics to compare the impacts of artisanal trolling and industrial longlining on yellowfin tuna exploited off the Kenya coast. The study derived insights on interactions between

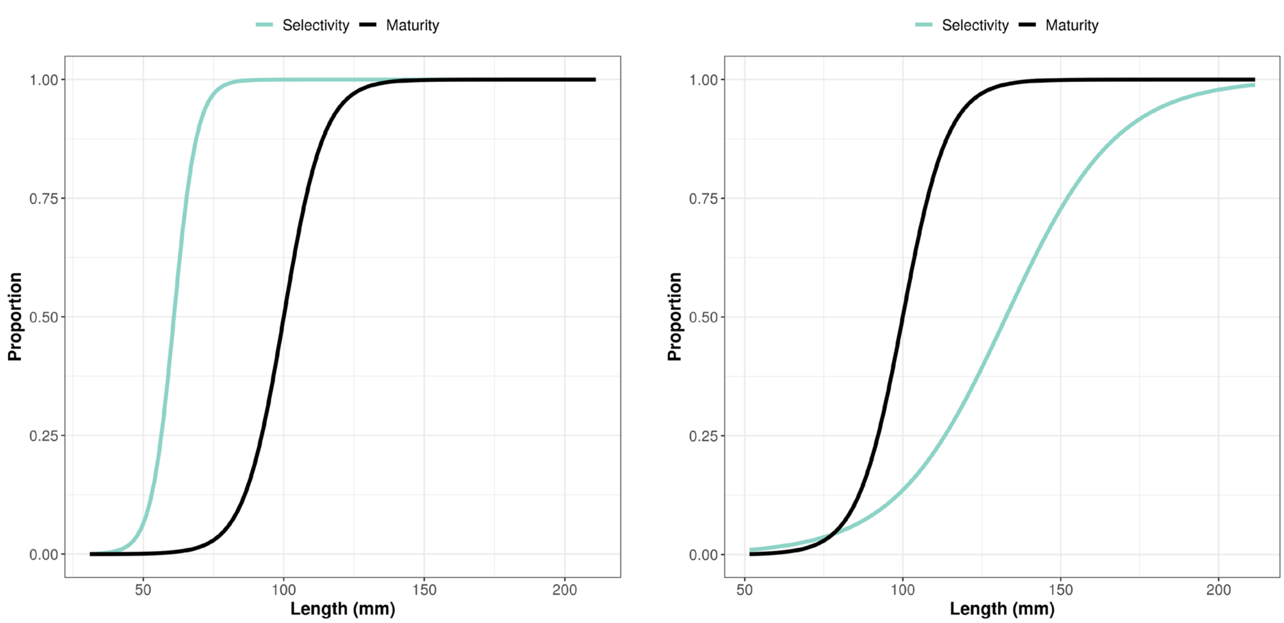

Figure 4. Selectivity and maturity curves for yellowfin tuna caught by a) artisanal trolling and b) industrial longline off the Kenyan coast between April 2019 and April 2021.

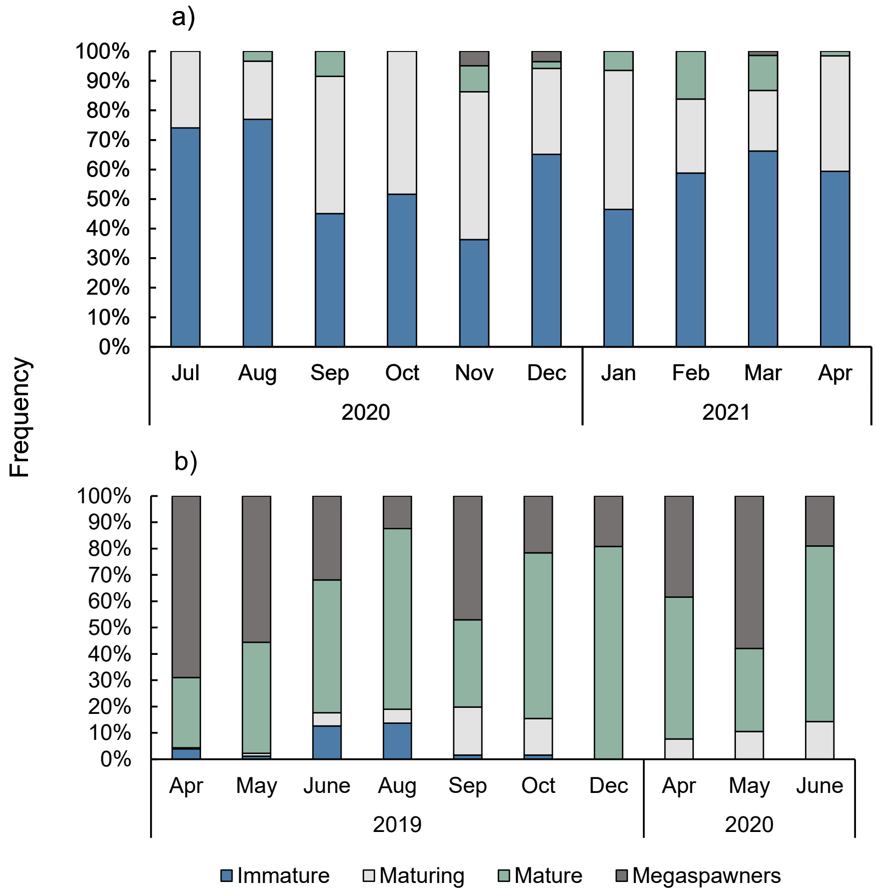

Figure 5. Monthly variation in the proportion of immature and mature yellowfin in the sampled catches caught by a) artisanal trolling and b) industrial pelagic longline off the Kenyan coast. Maturity length thresholds used: immature (<76 cm), maturing (76-100cm), mature (>100 cm) and mega-spawners (≥143 cm).

industrial and artisanal tuna fisheries in the WIO region. The observed fork length ranges for artisanal trolling (32 cm – 177 cm) were within reported ranges for the Indian Ocean region of 30 – 180 cm (IOTC, 2017). A maximum length of 204 cm recorded for the industrial longline fishery was much higher than the reported range for the region, but falls within the maximum reported length of 239 cm (Froese and Pauly, 2022).

Artisanal trolling mainly caught immature and maturing fish below the size at 50 % maturity (100 cm) while the industrial longline mainly caught mature fish. The high capture of juvenile yellowfin tuna in artisanal fishing gears has been reported within the Indian Ocean region (GTA, 2021). Juveniles mainly occur in surface waters and migrate to deeper depths as they mature. Thus, juvenile and immature sizes of yellow fin tuna will more likely be caught in artisanal fishing

Table 4. Summary of the indicator ratios for the traffic lights system. Cells shaded green are above the expected value and those shaded in red are below expected values.

Management outcome	Indicator ratio	Expected value	Artisanal trolling	Industrial longline
Conservation of immature fish	L_c / L_{mat}	> 1	0.47	1.05
	$L_{25\%} / L_{mat}$	> 1	0.86	1.50
Conservation of mature individuals	$L_{max5\%} / L_{inf}$	> 0.8	0.65	0.95
	P_{mega}	≥ 0.3	0.01	0.43
Optimal yield	L_{mean} / L_{opt}	≈ 1	0.48	0.72
MSY	$L_{mean} / L_{F=M}$	≥ 1	0.87	1.10

gears. In contrast, industrial longline fishery preferentially targets larger individuals of yellowfin tuna which are found in deeper offshore waters indicating more of a logistic curve. Therefore, the selection curve for the artisanal fishery is more likely to be dome shaped while that of the industrial fishery will approach a logistic curve.

The spatial distribution of immature and mature phases of yellowfin tuna is reported to be influenced by various environmental conditions that affect the horizontal distribution and vertical partitioning of yellowfin tuna life stages by size or sex. These environmental conditions include depth of deployment and type of bait used (Løkkeborg and Bjordal, 1992, Ingólfsson *et al.*, 2017 Eighani *et al.*, 2019). Juvenile yellowfin tuna are also known to be attracted to floating objects which act as fish aggregating devices (FADs) (Girard *et al.*, 2004; Dagorn *et al*., 2013; Scutt Phillips *et al*., 2017). Artisanal fishers are known to fish around natural floating objects to enhance fishing efficiency. Thus, the strong association of yellowfin tuna juveniles with FADs makes them highly vulnerable to capture by trolling lines and other surface associated fishing gears.

The observed skew in sex ratio to males for the industrial longline fishery corresponds with Zhu *et al.* (2008) who reported an increasing abundance of males with size. The observed skew to males could also be a general reflection of the population dynamics of yellowfin tuna, as older females have been reported to have a higher natural mortality than males (Fu *et al.*, 2018). The skew to females observed in the artisanal trolling catches could be an artefact of spawning patterns, as a high abundance of yellowfin tuna females have been reported to aggregate in coastal areas to spawn during the northeast monsoon season (Zudaire, 2013), which coincides with the peak in artisanal fishing effort. However, a more intense sampling regime may further ascertain this hypothesis.

The study reveals that the two fisheries impact on different but critical life phases of the yellowfin tuna population. The observed differences in length distributions and selectivity curves may be influenced by the availability and catchability in the two regions and the gears. This however remains to be tested. Selective removal of these life phases can result in truncation of the affected size classes (Berkeley *et al.*, 2004; Hsieh *et al.*, 2010), and alter related demographic processes such as maturation and sex ratios (Kendall *et al.*, 2012). Extrapolation of the findings to the yellowfin tuna stock will require some weighting of the two fisheries based the fishing mortality contributed by each fishery across the region. However, the available catch estimates reported to IOTC for both the industrial and artisanal sectors are known to be under-estimated due to under-reporting and illegal fishing (Le Manach *et al.* 2012, 2015). It is important to note that the length-based assessment methods utilized in this study are most appropriate when applied in the context of a full stock. This study has applied the methods in a novel manner to derive insights on interactions between industrial and artisanal tuna fisheries and impacts on yellowfin tuna population structure. These findings highlight issues of conservation concern with regards to overharvesting of immature yellowfin tuna by artisanal fleets, and the need for localized measures within national jurisdictions to control high fishing mortality of immature fish and mega-spawners. Future assessments should integrate stock-wide data as well as the full spectrum of fishing gear types for a more comprehensive understanding of fishery interactions on the yellowfin tuna stock within the WIO region.

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