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Commission des Thons de l'Ocean Indien
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EXPLORATORY ASSESSMENT OF GROWTH, MATURITY AND LENGTH-BASED SPAWNING POTENTIAL RATIO (LB-SPR) OF PRIORITY SHARK SPECIES FROM KENYA'S INDUSTRIAL LONGLINE FISHERY

BENEDICT K. KIILU, BERNERD FULANDA, EDWARD KIMANI, GLADYS OKEMWA, ZACHARY OGARI, KELVIN WACHIRA AND ELIZABETH MUENI

Purpose, expectation and action intended (select one or more and include corresponding text)

1. Require strong precautionary measures *C. longimanus* and *C. falciformis*
2. Institutionalize continuous observer coverage with standardized recording of species identity, length, sex, hook position, gear configuration, soak time, and release condition.

Discussions (for information and open discussion):

[The paper is to inform meeting members that…, as set out in Section X]

This paper is to inform members that CPCs can contribute meaningfully to regional and global shark conservation by applying integrated, data-limited methods to generate actionable evidence. The challenge has always been in translating findings into policy and practice: e.g. using the data limited methods to regulate fishing mortality, protect critical habitats, and ensure that management frameworks are responsive to the biological realities of species-specific vulnerability. This is well set out in the Methodology and Results sections (Sections 2 and 3)

Feedback (to collect input and suggestions)

[The paper is to request review and comments on…, as set out in Section X]

The paper is to request review and comments on integration of various data limited methods to inform decision making processes.

Conclusion (to record a concluded position or summary)

[The paper is to seek confirmation that…, as set out in Section X]

The paper is to seek confirmation that datasets – including species-specific length compositions, maturity schedules, sex-ratio information, standardized CPUE, spatial distribution data, and vulnerability estimates – are particularly valuable because regional stock assessments depend heavily on fisheries-dependent information, and their contribution can strengthen precautionary measures across the Western Indian Ocean

Recommendation (to ask the meeting to endorse a recommendation)

[The paper is to seek endorsement on…, as set out in Section X]

Develop measures to reduce any further exposure of *Isurus oxyrinchus* fishing mortality increases

Decisions (to request formal approval of actions)

[The paper is to seek approval on…, as set out in Section X]

Institutionalization of continuous observer coverage with standardized recording of species identity, length, sex, hook position, gear configuration, soak time, and release condition, among other parameters

Abstract

Sustainable management of pelagic sharks in the Western Indian Ocean requires robust data on demographic structure and stock status. This study provides an integrated assessment of four key species namely Blue shark (*Prionace glauca*), Oceanic whitetip shark (*Carcharhinus longimanus*), Shortfin mako shark (*Isurus oxyrinchus*), and Silky shark (*Carcharhinus falciformis*) utilizing catch data to evaluate population resilience.

We developed sex-specific maturity ogives to determine length-at-50% maturity (L_{50}), revealing distinct sexual dimorphism across all focal species. Subsequent Length-Based Spawning Potential Ratio (LB-SPR) modeling was applied to length-frequency distributions to estimate current stock status relative to unfished levels.

Results indicate varying levels of exploitation, with notably low SPR values observed for the Silky shark (SPR = 0.09) and Oceanic whitetip shark (SPR = 0.07), suggesting significant recruitment overfishing and a critical need for enhanced conservation measures. Conversely, the Blue shark exhibited a relatively higher SPR (0.41), while the Shortfin mako shark showed moderate status (SPR = 0.34).

These findings highlight the utility of length-based metrics in data-limited contexts to inform IOTC management strategies, emphasizing that species-specific and sex-disaggregated approaches are essential for mitigating further declines in pelagic shark populations within the region.

Key words: Data-limited fisheries, Sharks, VBGF, LBSPR, Length-frequency analysis, sex ratios, Kenya EEZ

Exploratory assessment of growth, maturity and Length-Based Spawning Potential Ratio (LB-SPR) of priority shark species from Kenya's industrial longline fishery

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Abstract

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1. Introduction

Elasmobranchs (sharks and rays; subclass *Elasmobranchii* within class *Chondrichthyes*) include apex predators, mesopredators and benthic consumers that can influence marine food webs and community structure. Many species have slow growth, late maturity, long reproductive cycles and low fecundity, traits that increase their sensitivity to fishing mortality and prolong recovery after depletion (Musick, 1999; Stevens et al., 2000; Dulvy et al., 2014). Global assessments indicate substantial declines in many oceanic and coastal populations, with more than one-third of assessed species threatened with extinction (Dulvy et al., 2021; Pacoureau et al., 2021).

Reconstructed catch data suggest that reported and estimated shark and ray landings in Kenya declined from approximately 3,100 metric tonnes in the late 1970s to less than 750 metric tonnes by 2020 (Sea Around Us, 2023; Kiilu, 2016; Murage et al., 2020). Because landings are also affected by fishing effort, reporting practices, fleet composition and management measures, this decline should not be interpreted as a direct abundance trend without supporting effort-standardized data. Changes in catch composition toward smaller sharks, batoids and juvenile cohorts may nevertheless be consistent with demographic change and warrant species-level assessment (Jabado, 2018; Kaunda-Arara et al., 2022).

Kenya's marine elasmobranch harvest is characterized by three distinct fishery sectors. The nearshore artisanal fishery operates within shallow coastal habitats using monofilament and multifilament gillnets, handlines, bottom longlines and ringnets, and these operations overlap extensively with sensitive coastal nursery grounds, mangrove estuaries and coral reef ecosystems (Fulanda et al., 2011; Munga et al., 2014). The semi-industrial prawn-trawl fishery operates primarily on demersal grounds such as Malindi-Ungwana Bay, where non-selective bottom trawling generates substantial incidental bycatch of juvenile sharks, rays, guitarfishes and sawfishes (Kaunda-Arara et al., 2022). The industrial offshore pelagic longline fishery operates beyond 12 nautical miles into the EEZ, targeting pelagic tunas and billfishes while intercepting oceanic sharks as high-value target catch or secondary bycatch (Gilman et al., 2008; Clarke et al., 2013).

A fundamental challenge in evaluating and managing elasmobranch stocks within developing coastal nations like Kenya is the prevalence of data-limited conditions. Historical catch statistics routinely aggregate landings into generic categories such as "sharks" or "rays," masking species-specific population collapses and preventing conventional age-structured stock assessments (Cavanagh et al., 2003; Ricard et al., 2012). To overcome these data constraints, length-based analytical models such as the von Bertalanffy Growth Function (VBGF), Electronic Length Frequency Analysis (ELEFAN), and the Length-Based Spawning Potential Ratio (LBSPR) offer

robust frameworks for evaluating demographic structure, growth dynamics, mortality rates, and remaining reproductive capacity (Cortés, 2000; Hordyk et al., 2015; Froese et al., 2018). Furthermore, integrating semi-quantitative risk frameworks like Productivity and Susceptibility Analysis (PSA) allows researchers to contextualize species vulnerability against gear-specific exposure (Hobday et al., 2011; Patrick et al., 2010).

Despite increasing international mandates, including regional management regulations under the Indian Ocean Tuna Commission (IOTC), listing under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), and Kenya's National Plan of Action for Sharks (NPOA-Sharks 2023), empirical data on species-level growth parameters, demographic truncation, and spawning potential remain sparse across Kenya's marine sectors (FAO, 2000; IOTC, 2023; Kiilu et al., 2019).

This study evaluates the growth trajectories, size composition, mortality rates, and spawning potential ratios of 4 prioritized shark and ray species across Kenya's industrial longline fisheries using extensive length-frequency datasets collected between 2016 and 2025.

Specifically, this study aims to: determine species-specific size structures, sex ratios and juvenile proportions across offshore pelagic sharks to identify evidence of growth and recruitment overfishing; estimate key growth parameters (L_∞ and K) and mortality parameters (M, F, Z and E) using length-converted algorithms; quantify stock depletion and remaining reproductive output using LBSPR modelling to establish biological reference points across data-limited elasmobranch taxa; and provide an empirical basis for prioritizing species-specific conservation interventions, spatial nursery protections and gear modifications within national and Western Indian Ocean management frameworks.

2. Materials and Methods

2.1. Study area and geographic extent

This study was conducted within Kenya's Exclusive Economic Zone (EEZ), a maritime jurisdiction covering approximately 230,000 km² and extending up to 200 nautical miles offshore. Geographically, the EEZ extends from 4°54′1.2″ S at the southern limit to 1°39′14.7″ S at the northern boundary, and longitudinally from 39°13′16.7″ E to 44°35′10″ E (Kenya Fisheries Service, 2023).

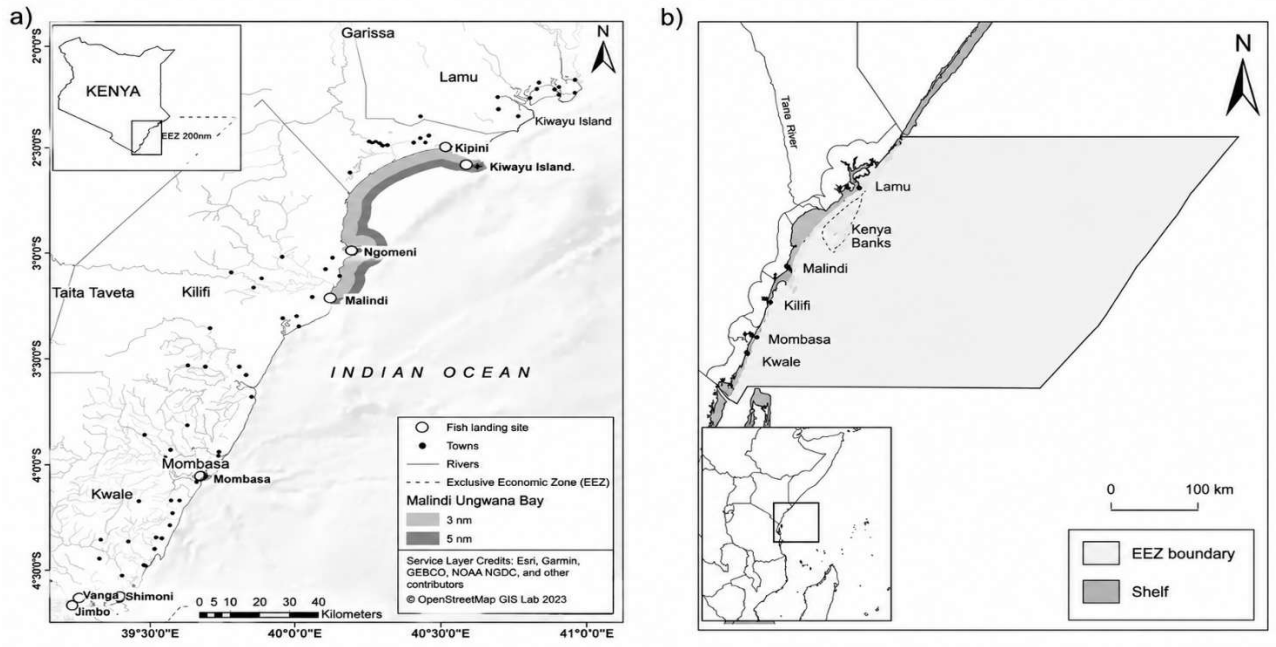

Figure 1. Study area showing Kenya's coastal fishery areas, the Exclusive Economic Zone and continental shelf waters to the 200-m isobath.

The oceanographic conditions within the Kenyan EEZ are strongly governed by the monsoon wind system. The Northeast Monsoon occurs from October to March and is characterized by warmer waters, weaker upwelling and reduced productivity, while the Southeast Monsoon occurs from April to September, enhancing coastal upwelling and primary productivity and influencing pelagic predator distribution and fishing-effort intensity (McClanahan, 1988; Schott et al., 2009). Transitional periods, locally known as *Matlai*, occur in March–April and October–November and are marked by variable winds and shifts in species composition (Munga et al., 2014).

2.2. Data sources, preparation and standardization

The research focused on the industrial pelagic longline fishery, which operates in deep offshore waters beyond 12 nautical miles, targeting tuna and tuna-like species while taking pelagic sharks as bycatch (Gilman et al., 2008; Clarke et al., 2013).

Industrial longline fishery data were compiled from onboard observers, vessel logbooks, and KeFS/ IOTC monitoring records detailing spatial coordinates, hook depths, soak times, and shark bycatch metrics (IOTC, 2023).

Historical landings were assembled as two complementary series covering 1950–2020: Sea Around Us reconstructed landings for 1950–2014 and official statistics and FAO datasets for 2000–2020, with the aim of accounting for underreporting (Sea Around Us, 2023; FAO, 2000).

Lengths were standardized by using fork length, with occasional inter-metric conversions based on published species- or genus-level relationships (Compagno, 2005; Cortés, 2000). Length-frequency

data were then grouped into species-specific size bins after screening for transcription errors, duplicate entries and outliers against reference maximum sizes.

2.3. Growth and mortality estimation framework

The study utilized growth estimation via the von Bertalanffy Growth Function (VBGF) and Length-Based Spawning Potential Ratio (LBSPR) modelling. Species-specific von Bertalanffy growth parameters (L_∞ and K) were estimated from length-frequency data using ELEFAN, with the software version, optimization routine, bin widths, temporal aggregation and bootstrap procedure stated for reproducibility (Pauly & Morgan, 1987; Gayanilo et al., 2005). Total mortality (Z) was estimated from length-converted catch curves only for datasets that met the method's assumptions (Pauly, 1983). Natural mortality (M) was estimated using empirical estimators such as Pauly's temperature-dependent formula and Jensen's k-based method (Pauly, 1980; Jensen, 1996), and fishing mortality was calculated as $F = Z - M$. Negative or biologically implausible estimates were screened using predefined criteria (Ricker, 1975).

LBSPR analyses were conducted separately for each species fork length for pelagic sharks, and species-specific length-class intervals. Model inputs comprised asymptotic length (L_∞), the natural-mortality-to-growth ratio (M/K), length at 50% maturity (L_{50}) and the selectivity parameters estimated from the retained length-frequency data (Hordyk et al., 2015). Input values and sample sizes were reported by species, and maturity values were expressed in the same length metric as the observations (Stevens et al., 2000; Clarke et al., 2018). Model outputs included relative fishing mortality (F/M) and spawning potential ratio (SPR). Because estimates are conditional on equilibrium, life-history and selectivity assumptions, these were interpreted as fishery-dependent indicators rather than direct estimates of absolute abundance or stock size (Prince et al., 2015). Species with limited length coverage or small samples were treated as exploratory, and conclusions were evaluated alongside observed size structure, maturity composition and the consistency of alternative biological inputs. Limit and target reference points were defined before classifying results, and sensitivity to plausible maturity, growth and selectivity values was considered where alternative inputs were available (Cortés, 2000).

Juvenile status was defined by comparing each observation with a species-specific length at 50% maturity expressed in the same metric as the measured length. Where published maturity differed by sex, region or length type, sex-specific values or documented conversion equations were applied (Nakano & Stevens, 2008; Rigby et al., 2019). All maturity sources, conversions and uncertainty ranges were tabulated, and sensitivity analyses were used where more than one credible threshold was available.

3. Results

3.1. Population Growth, Size Structure and Demographic Patterns

The evaluation of the industrial longline fishery highlighted four priority oceanic species: the Blue shark (*Prionace glauca*), Silky shark (*Carcharhinus falciformis*), Oceanic whitetip shark (*Carcharhinus longimanus*), and Shortfin mako (*Isurus oxyrinchus*). These species dominated longline catches and therefore provided consistent focal points for demographic assessment across all analyses (Nakano & Stevens, 2008; Clarke et al., 2018).

As a result, the assessment of dataset adequacy revealed considerable variation among the selected elasmobranch species in terms of sample size, temporal coverage, and suitability for length-based stock assessment analyses. While some species possessed sufficient data to support robust analyses such as LBSPR, growth estimation (VBGF/ELEFAN), mortality estimation, recruitment pattern analysis, and sex ratio determination, other species were represented by relatively small sample sizes that limited the application of one or more analytical approaches (Pauly, 1983; Ricker, 1975). The suitability of each dataset for the planned stock assessment methods is summarized in Table 1.

Table 1. Assessment of the suitability of available datasets for length-based stock assessment analyses of selected elasmobranch species.

Fishery	Species	Data source	Records (n)	Sex data available	Temporal coverage	LBSPR	VBGF/ ELEFAN	Mortality (Z)	Sex ratio	Recruitment pattern	Overall assessment
Industrial longline	*Prionace glauca*	Industrial longline observer data (2016–2025)	498	Yes	Multi-year	Suitable	Conditionally suitable	Suitable	Suitable	Conditionally suitable	Good candidate
Industrial longline	*Isurus oxyrinchus*	Industrial longline observer data (2016–2025)	150	Yes	Multi-year	Exploratory	Exploratory	Exploratory	Limited	Exploratory	Limited analyses only
Industrial longline	*Carcharhinus longimanus*	Industrial longline observer data (2016–2025)	305	Yes	Multi-year	Limited	Conditionally suitable	Conditionally suitable	Suitable	Conditionally suitable	Moderate
Industrial longline	*Carcharhinus falciformis*	Industrial longline observer data (2016–2025)	141	Yes	Multi-year	Exploratory	Exploratory	Exploratory	Limited	Exploratory	Limited analyses only

Legend:

1. Excellent: Dataset exceeds recommended requirements for robust analysis.
2. Suitable: Dataset meets or satisfies the recommended data requirements. Robust analysis can be performed.
3. Conditionally suitable: Dataset satisfies the minimum but not the preferred data requirements. Analysis can be performed, but estimates should be interpreted cautiously
4. Limited applicability: Dataset contains sufficient information only for preliminary or descriptive analyses but is inadequate for robust parameter estimation. Only descriptive statistics or exploratory analyses are appropriate.
5. Exploratory: Dataset does not meet the preferred requirements for robust quantitative inference but contains sufficient information to generate indicative estimates; results are interpreted cautiously and are not used independently for definitive stock-status classification.

As shown in Table 1, *Prionace glauca* had the most comprehensive dataset and was suitable for all planned length-based stock assessment analyses (Fulanda et al., 2011; Kaunda-Arara et al., 2022). In contrast, *Isurus oxyrinchus* were represented by relatively small sample sizes, limiting the application of growth and mortality estimators (Stevens et al., 2000; Cortés, 2000).

Nonetheless, differences in sample size among analyses resulted from method-specific data screening, and sample sizes comprised records satisfying the measurement, biological-variable and quality-control requirements of the respective analysis (Pauly & Morgan, 1987; Ricker, 1975). In cases where the sample sizes were below the preferred threshold for robust model application, some species were analyzed for exploratory assessments to provide indicative estimates. In such circumstances, results were interpreted cautiously and were not used independently to make definitive conclusions regarding stock status (Prince et al., 2015; Hordyk et al., 2015).

3.2. Length-Frequency Data as the Analytical Foundation

The length-frequency distributions of the four pelagic shark species sampled from the industrial longline fishery revealed distinct demographic structures relative to published maturity thresholds (Table 2).

The Blue Shark (*Prionace glauca*, n = 423) ranged 54.0–330.0 cm FL, with a modal peak around 230.0 cm FL. The maturity threshold (L50 = 200.0 cm FL) was well to the left of the dominant mode, resulting in only 20.6% juveniles (Nakano & Stevens, 2008; Jolly et al., 2013; Cortés et al., 2010). This confirms that the longline fishery primarily interacts with adult cohorts.

The Shortfin Mako (*Isurus oxyrinchus*, n = 78) spanned 103.0–295.0 cm FL, with a modal peak near 180.0 cm FL. Relative to the maturity threshold (L50 = 210.0 cm FL), 71.8% of individuals were juveniles (Stevens et al., 2000; Rigby et al., 2019). This wide, multimodal footprint indicates exploitation of both immature and mature cohorts, with a high dependency on subadult biomass.

The Oceanic Whitetip (*Carcharhinus longimanus*, n = 241) ranged 74.0–274.0 cm FL, with a modal peak around 160.0 cm FL. The maturity threshold (L50 = 130.0 cm FL) was exceeded by most individuals, yielding 27.0% juveniles (Clarke et al., 2018; Rigby et al., 2019). This pattern reflects a mixed harvest but still shows truncation at larger sizes, with few individuals above 210.0 cm FL.

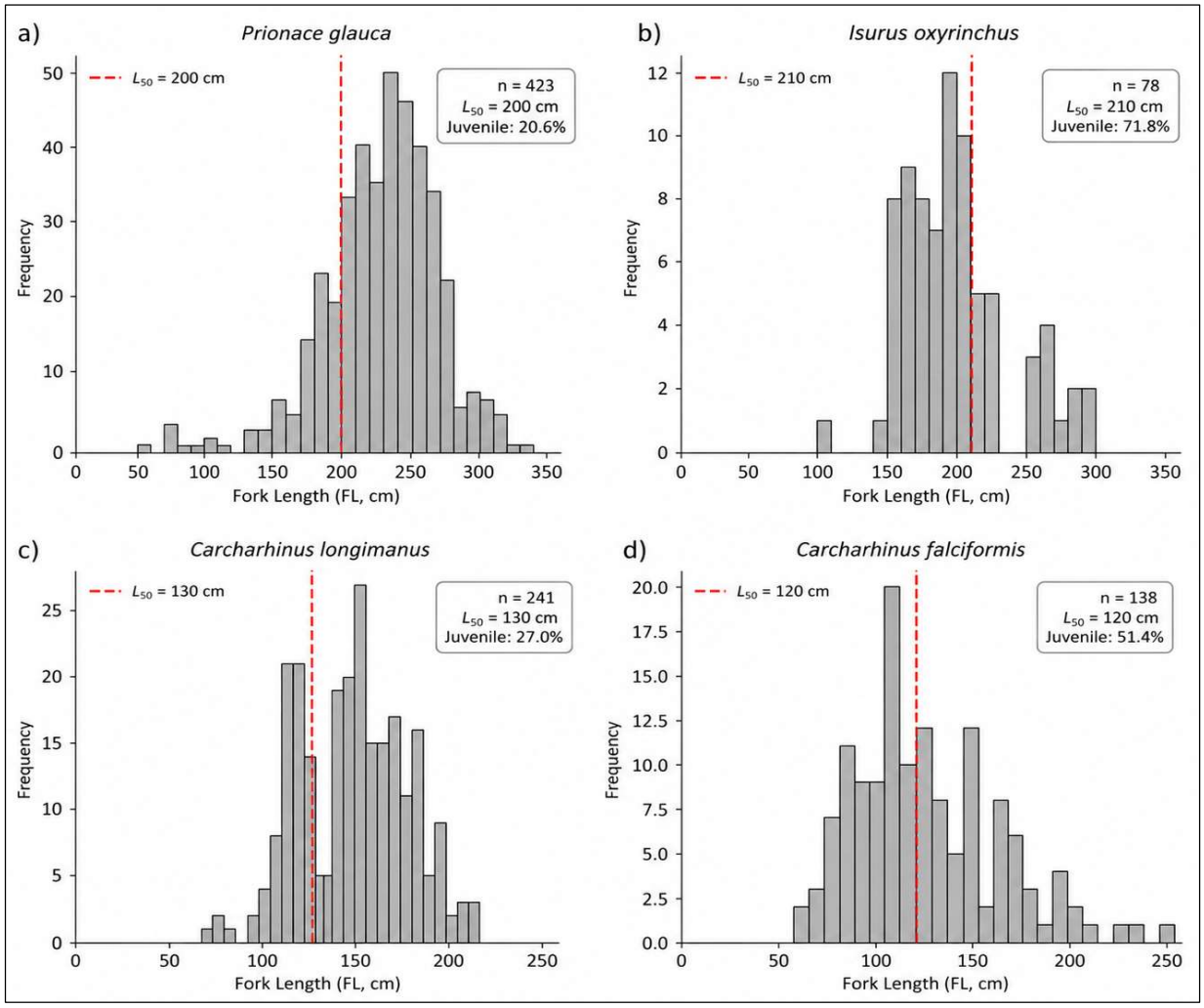

Figure 2. Fork-length frequency distributions of four pelagic shark species sampled from the industrial longline fishery, showing maturity thresholds (L_{50}) and juvenile proportions. Juveniles were operationally defined as individuals below the species-specific L_{50}.

The Silky Shark (*Carcharhinus falciformis*, n = 138) ranged 60.0–250.0 cm FL, with a modal peak near 140.0 cm FL. The maturity threshold (L50 = 120.0 cm FL) was exceeded by some individuals, but juveniles still comprised 51.4% of the catch (Clarke et al., 2018; Cortés et al., 2010). The distribution was left-skewed, indicating heavy reliance on immature cohorts and a risk of growth overfishing.

Figure 2 demonstrates that pelagic sharks in the industrial longline fishery show species-specific contrasts in demographic structure. Blue Sharks are predominantly mature, Oceanic Whitetips show mixed age composition, while Shortfin Makos and Silky Sharks are heavily juvenile-dominated. These patterns highlight the selective pressures of longline fisheries: adult exploitation in some species, but significant juvenile interception in others, raising conservation

concerns for populations with slower growth and late maturity (Dulvy et al., 2014; Pacoureau et al., 2021).

The contrasting size-frequency profiles between pelagic sharks underscore the role of gear selectivity and habitat overlap in shaping demographic vulnerability. Longline fisheries, operating offshore, interacted mainly with adult cohorts of species such as the Blue Shark, thereby presenting a comparatively lower risk of recruitment overfishing. These findings highlight the need for differentiated management strategies that account for the ecological setting and life-history traits of species exploited by longline fishing gear (Prince et al., 2015; Hordyk et al., 2015).

3.3. Length Based Spawning Potential Ratio (LB-SPR)

The species-specific stock indicators derived from Table 1 reveal marked contrasts among the four pelagic shark species assessed, reflecting differences in mean size, maturity thresholds, fishing mortality, and spawning potential ratio (SPR). Overall, *Prionace glauca* and, to a lesser extent, *Isurus oxyrinchus* retained comparatively higher reproductive potential, whereas *Carcharhinus falciformis* and *Carcharhinus longimanus* exhibited strong evidence of recruitment overfishing and reduced reproductive capacity.

For the Blue Shark (*Prionace glauca*), the mean observed length was 226.2 cm, exceeding the estimated length at 50% maturity (L50 = 200 cm). The fishing mortality relative to natural mortality was moderate (F/M = 2.33), while the SPR was 40.8%. This value is above the commonly applied limit reference point (LRP) of 30–40% used in many data-limited elasmobranch assessments to infer reproductive sustainability (Cortés, 2000). These indicators suggest that *P. glauca* currently maintains a relatively healthy reproductive status in the assessed fishery, although continued monitoring remains warranted due to its frequent interaction with pelagic longline fleets (Nakano & Stevens, 2008).

The Shortfin Mako (*Isurus oxyrinchus*) had a mean length of 220.1 cm, which was below the reported length at 50% maturity (L50 = 270 cm). The estimated fishing mortality ratio (F/M) was 1.55, while the spawning potential ratio (SPR) was 21.2%. This SPR value was above the limit reference point (LRP of 20%) but below the target sustainability range of 20–30%, indicating that the stock was near the lower boundary of the reference range. Given the species' slow growth, late maturity, and high vulnerability to fishing pressure, the observed SPR should be interpreted cautiously and considered alongside broader evidence of population declines in heavily exploited oceanic shark fisheries (Stevens et al., 2000; Rigby et al., 2019).

In contrast, the Silky Shark (*Carcharhinus falciformis*) showed clear evidence of overexploitation. The mean length was 125.9 cm, substantially below the estimated maturity threshold (L50 = 210 cm). Fishing pressure was high, as indicated by an F/M ratio of 2.29, and the resulting SPR was only

6.7%. This low SPR indicates depleted spawning potential consistent with high fishing pressure which may substantially reduce the reproductive output of the population. These findings are consistent with previous assessments identifying *C. falciformis* as highly vulnerable to pelagic longline exploitation because of its life-history characteristics and frequent capture in tropical tuna-associated fisheries (Cortés et al., 2010; Clarke et al., 2018).

The Oceanic Whitetip Shark (*Carcharhinus longimanus*) also showed a critical stock-status signal. The mean length was 150.1 cm, below the estimated L50 of 180 cm. The estimated fishing mortality ratio was the highest among the assessed species (F/M = 3.97). This elevated fishing pressure resulted in an SPR of 7.2%, indicating severe depletion of spawning capacity. The combination of high fishing mortality and very low SPR suggests that the reproductive potential of *C. longimanus* has been substantially compromised. This result is consistent with global assessments that report major population declines and classify the species as highly threatened due to intensive fishing pressure in oceanic longline fisheries (Clarke et al., 2018; Rigby et al., 2019).

Table 2. Length-based spawning potential ratio (LBSPR) analyses for four pelagic shark species (Prionace glauca, Isurus oxyrinchus, Carcharhinus falciformis and Carcharhinus longimanus).

Species	**Sample Size (n)**	**Mean Length (cm)**	**L∞ (cm)**	**M/K**	**L_{50} (cm)**	**F/M**	**Estimated SPR (%)**	**Stock Status**
Prionace glauca	498	226.2	380	1.35	200	2.33	40.8%	Above LRP
Isurus oxyrinchus	150	220.1	400	1	270	1.55	21.2%	Above LRP
Carcharhinus longimanus	305	150.1	300	1	180	3.97	7.2%	Below LRP (Overfished)
Carcharhinus falciformis	141	125.9	330	1	210	2.29	6.7%	Below LRP (Overfished)

The results in Table 2 demonstrate contrasting stock-status patterns among pelagic sharks interacting with the industrial longline fishery. *Prionace glauca* showed the most favourable indicators, with a mean size above L50 and an SPR exceeding the lower sustainability reference range. *Isurus oxyrinchus* showed an intermediate condition, with SPR near the sustainability boundary, suggesting that its current status is sensitive to any increase in fishing mortality. In contrast, *Carcharhinus falciformis* and *Carcharhinus longimanus* exhibited critically low SPR values below 10%, indicating severe reproductive depletion and likely recruitment overfishing.

The combination of low SPR, elevated F/M ratios, and high proportions of immature individuals in the catch highlights the vulnerability of pelagic sharks to industrial longline fisheries, consistent with global conservation assessments that identify silky sharks and oceanic whitetip sharks as threatened by overexploitation, particularly in tuna and billfish longline fisheries (Clarke et al., 2018; IUCN, 2022). Accordingly, *C. falciformis* and *C. longimanus* should be considered priority species for management intervention, while *I. oxyrinchus* requires precautionary monitoring due to its borderline status and inherently low productivity.

3.4. Population and Growth Dynamics

The gender compositions and corresponding chi-square (χ^2) goodness-of-fit assessments for the four pelagic elasmobranch species sampled within the offshore fishery reveal distinct structural trends in their population demographics (Table 4). The analysis tested the null hypothesis of a balanced 1:1 sex ratio (H_o: Females = Males), which serves as an important metric for tracking potential spatial segregation, mating aggregations, or gear-selectivity biases in pelagic environments (Wearmouth & Sims, 2008; Cortés, 2000).

Table 4. Chi-square (χ^2) goodness-of-fit analysis of sex ratios for four pelagic shark species (Prionace glauca, Carcharhinus falciformis, Carcharhinus longimanus and Isurus oxyrinchus). The null hypothesis was a 1:1 female-to-male sex ratio.

Species Name	Females (F)	Males (M)	Ratio (F:M)	χ^2 Stat	p-value	Result
Prionace glauca	296	165	1.79:1	37.23	< 0.0001	Highly Significant
Carcharhinus falciformis	68	49	1.39:1	3.09	0.079	Not Significant
Carcharhinus longimanus	129	121	1.07:1	0.26	0.6129	Not Significant
Isurus oxyrinchus	47	56	0.84:1	0.79	0.3752	Not Significant

The Blue Shark (*Prionace glauca*) showed a significant female-biased sampled sex ratio of 1.79:1 ($\chi^2 = 37.23$, $p < 0.0001$). Sexual segregation is documented in pelagic sharks and may contribute to spatially or seasonally biased catches (Nakano & Stevens, 2008). However, the observed ratio could also reflect gear selectivity, sampling coverage or differential availability of the sexes. Without spatially and temporally stratified analyses, the data do not establish that the fishery overlapped a female migration corridor or foraging hotspot.

The Silky Shark (*Carcharhinus falciformis*) showed a moderate skew favoring females (1.39:1). However, this imbalance remains statistically non-significant at the traditional $\alpha = 0.05$ baseline ($\chi^2 = 3.09$, $p = 0.079$).

The sampled sex ratios of the Oceanic Whitetip Shark (*C. longimanus*; 1.07:1) and Shortfin Mako Shark (*Isurus oxyrinchus*; 0.84:1) did not differ significantly from 1:1. These results indicate that the study did not detect a departure from parity in the sampled catches; they do not demonstrate homogeneous distributions, equal vulnerability to longline gear or absence of spatial segregation. Resolving those mechanisms would require sex-specific spatial, temporal and gear-selectivity analyses (Rigby et al., 2019).

A further analysis of maturity ogives for *P. glauca* revealed a pronounced horizontal shift between the sexes (Figure 3). Females seemed to transition rapidly to maturity, with a calculated L50 centering near 80 cm while males exhibited a more gradual inflection curve that approaches 50% maturity at a significantly larger length of approximately 103 cm. This pronounced divergence underscores the species' specialized reproductive allocation strategies and suggests that juvenile males remain vulnerable to selective fishing pressure for a longer duration before participating in the spawning biomass (Hazco et al., 2010; Nakano & Stevens, 2008).

For *C. longimanus*, the fitted maturity ogives indicated that females reached 50% maturity at approximately 90 cm and males at approximately 110 cm. These values are approximate visual estimates and should be replaced by model-derived L50 estimates. Before interpretation, the recorded length metric and units, female and male coding, and the scale used in the logistic model should be verified. The final results should report the number of females and males included, the estimated L50 for each sex with 95% confidence intervals, and a measure of ogive slope or L95–L50. Given that these apparent maturity lengths are low for Oceanic Whitetip Shark, their biological plausibility should be evaluated against the verified measurement protocol and the size range represented in the sample (Clarke et al., 2018).

For *I. oxyrinchus*, the sex-specific ogives in Figure 4 yielded apparent maturity transitions at lengths substantially below the pooled L50 values used elsewhere in the manuscript. These estimates were therefore not interpreted as biologically reliable. The discrepancy indicates a likely inconsistency in the length metric or units, sex labels, maturity coding or fitted model specification. Pending verification of those inputs, the analysis should report the sex-specific sample sizes and model-derived L50 estimates with 95% confidence intervals and the fitted slope or L95–L50 interval, and should not use the current ogive estimates for juvenile classification or LBSPR parameterization (Stevens et al., 2000; Rigby et al., 2019).

The maturity ogives for *C. falciformis* show a slightly different dynamic, where both sexes scale into larger absolute size ranges before attaining maturity. Females achieve 50% maturity at approximately 103 cm, maintaining a clear lead over the male cohort, which does not attain a matching maturity probability until reaching approximately 120 cm. The broader horizontal spread of the data points along both curves reflects a more protracted transition phase into functional reproductive maturity for this circumtropical carcharhinid (Cortés, 2010; Clarke et al., 2018).

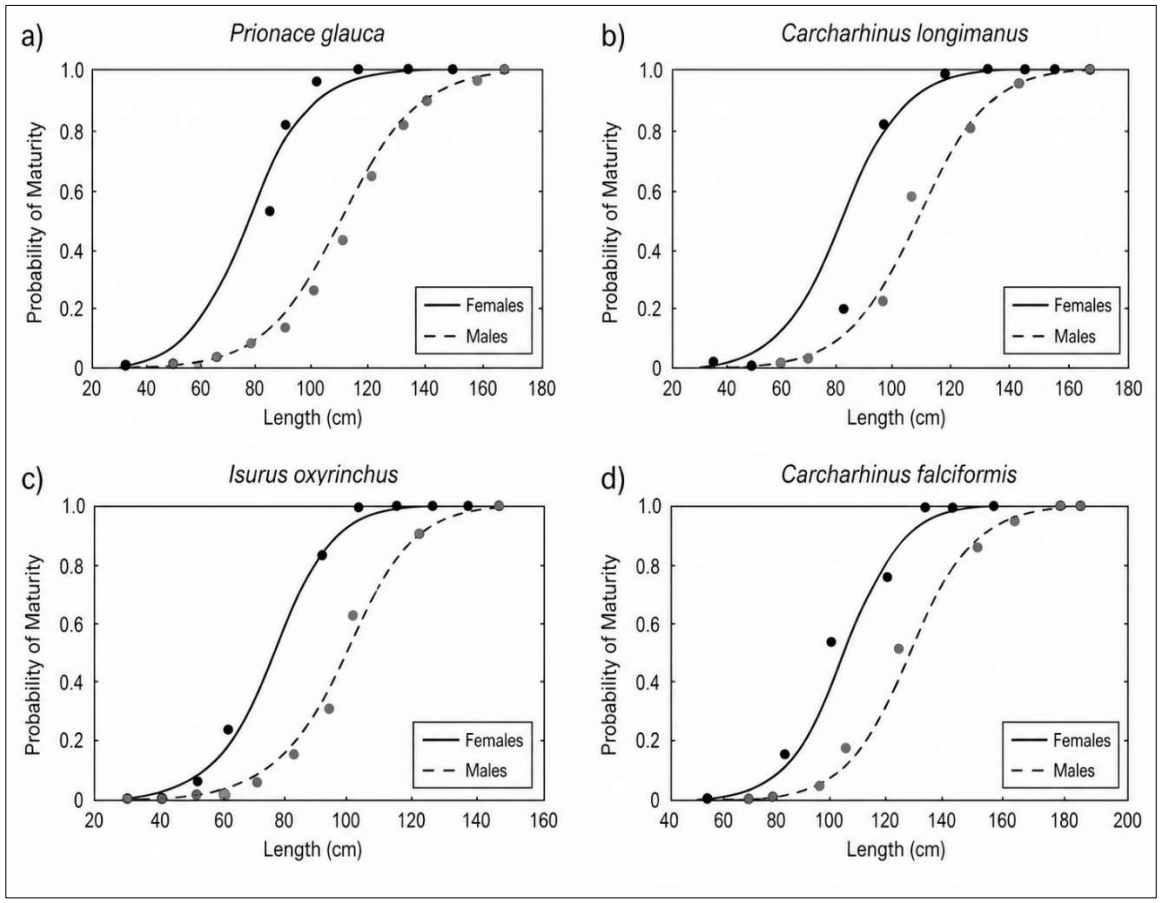

Figure 4. Sex-specific maturity ogives for four pelagic shark species (Prionace glauca, Carcharhinus longimanus, Isurus oxyrinchus and Carcharhinus falciformis). Curves show the probability of maturity as a function of length, with females (red) and males (blue) fitted separately.

4. Discussion

The present study has provided an integrated assessment of the population structure and exploitation status of elasmobranchs interacting with Kenya's industrial pelagic longline fisheries. The study was motivated by the persistent challenge of assessing sharks and rays in data-limited fisheries, where conventional age-structured assessments are constrained by limited biological sampling, incomplete catch histories, inconsistent effort information and inadequate time-series data (Cavanagh et al., 2003; Dulvy et al., 2014).

To address these constraints, the study combined length-frequency analysis, Von Bertalanffy Growth Function (VBGF) and Electronic Length Frequency Analysis (ELEFAN), mortality estimation, recruitment reconstruction, sex-ratio analysis, and Length-Based Spawning Potential Ratio (LBSPR). This integrated framework allowed the biological characteristics of individual species to be considered alongside their exposure and susceptibility to specific fishing pressures (Hordyk et al., 2015; Prince et al., 2015).

Overall, the results demonstrate that elasmobranch exploitation in Kenya is not characterized by a uniform stock response to fishing impacts. Rather, substantial differences occur between offshore pelagic sharks, and among species exposed to different fishing operations (Fulanda et al., 2011; Kaunda-Arara et al., 2022).

4.1. Length-Frequency Structure as Evidence of Demographic Pressure

The length-frequency analyses provided some of the clearest evidence of differential fishing effects among fisheries.

The offshore longline fishery produced species-specific size structures. Blue Sharks were predominantly represented by individuals above the selected maturity threshold, whereas Shortfin Makos and Silky Sharks had substantial juvenile representation (Nakano & Stevens, 2008; Clarke et al., 2018). However, juvenile dominance alone was not equated automatically with recruitment overfishing. A juvenile-dominated sample can arise from genuine nursery-ground sampling, spatial segregation, gear selectivity or seasonal aggregation (Wearmouth & Sims, 2008). The stronger inference emerges when juvenile dominance is combined with low SPR, high F/M, high vulnerability and evidence of fishing exposure (Prince et al., 2015; Hordyk et al., 2015).

Juvenile-dominated samples do not necessarily imply reproductive depletion. Species-specific recruitment ecology, maturity schedules, selectivity and life-history characteristics must therefore be considered (Stevens et al., 2000; Cortés, 2010).

4.2. Interpretation of Length-Based Spawning Potential Ratio (LBSPR) Outputs

The implementation of Length-Based Spawning Potential Ratio (LBSPR) modeling provided an essential quantitative framework for evaluating spawning biomass depletion across Kenya's data-limited elasmobranch stocks. By integrating length-frequency distributions with fundamental life-history parameters (M/k, L_{50}, L_{95}, and L_{∞}), LBSPR estimates the proportion of unfished spawning potential remaining under current exploitation regimes (SPR) alongside relative fishing mortality (F/M) (Hordyk et al., 2015; Prince et al., 2015). Because LBSPR operates under steady-state equilibrium assumptions, these outputs represent model-based proxies of population health rather than direct measurements of absolute spawning biomass (Mildenberger et al., 2017). The analytical validity of these estimates depends on sampling representativeness, gear selectivity dynamics, and parameter reliability (Pons et al., 2018).

4.3. Pelagic assemblages and oceanic stock status

The pelagic shark community exhibited distinct, species-specific responses to industrial longline exploitation. Blue Shark (*Prionace glauca*) displayed the most favorable reproductive status among pelagic species (SPR = 40.8, Lmean = 226.2 relative to L50 = 200.0 cm). This SPR exceeds the

standard target reference point (40%), reflecting the species' higher intrinsic growth rate (r), earlier maturity, and higher fecundity relative to other carcharhinids (Cortés, 2000). However, an elevated relative fishing mortality (F/M = 2.33) indicates that extraction rates substantially exceed natural mortality. Consequently, this favorable SPR reflects biological resilience rather than an absence of exploitation pressure, aligning with Indian Ocean Tuna Commission (IOTC) assessments that highlight stock sensitivity to catch reporting gaps and selectivity shifts (Coelho et al., 2018; IOTC, 2017).

Shortfin Mako (*Isurus oxyrinchus*) yielded an intermediate SPR of 21.2%, with mean length falling below the size-at-maturity threshold (Lmean < L50). This places the stock directly adjacent to the 20% Limit Reference Point (LRP), signaling severe spawning potential reduction. Given its low biological rebound potential and high longline susceptibility, this result aligns with IOTC Ecological Risk Assessments categorizing Shortfin Mako among the most threatened pelagic species (IOTC, 2018). This status reinforces the precautionary management mandates established under IOTC Resolution 25/09, which requires the mandatory live-release of makos and establishes binding pathways to constrain overall fleet mortality (IOTC, 2025).

Silky Shark (*Carcharhinus falciformis*) and Oceanic Whitetip Shark (*Carcharhinus longimanus*) exhibited very low estimated spawning potential, with SPR values well below commonly used limit reference levels and excessive fishing rates (F/M > 2.00). The low SPR estimated for *C. falciformis* is consistent with regional Indian Ocean assessments reporting overfishing concerns for silky shark (IOTC, 2022). For *C. longimanus*, the very low estimated SPR is consistent with severe demographic pressure, but it should be interpreted as a length-based indicator rather than a precise measure of absolute spawning biomass. These findings support strict precautionary management, including compliance with RFMO retention prohibitions and relevant international trade controls under CITES Appendix II (Dulvy et al., 2021).

Pelagic species such as *C. falciformis* and *C. longimanus* demonstrated low SPR and elevated F/M in longline datasets, consistent with their high vulnerability scores and global evidence of decline in oceanic sharks (Dulvy et al., 2021).

LBSPR modeling extracted valuable information from length composition, allowing estimation of spawning potential ratios and relative fishing mortality without reliance on age-structured datasets. Because LBSPR was specifically designed for small-scale and data-poor fisheries, its application was particularly appropriate in the Kenyan context (Hordyk et al., 2015).

Growth analysis using the Von Bertalanffy Growth Function (VBGF) and ELEFAN provided essential biological context by supplying life-history parameters that explained demographic differences among species. These parameters linked exploitation outcomes to intrinsic biological traits such as

growth rate, asymptotic size, and age at maturity, thereby strengthening interpretation of vulnerability patterns (Pauly & Morgan, 1987).

5.0. Limitations of the Study

Despite the strengths of the integrated framework, several limitations constrain the strength of inference and must be acknowledged to contextualize the findings.

All principal datasets were fisheries-dependent, meaning that samples reflected fishing behaviour rather than random sampling of the population. Fishing location, gear type, fisher behaviour, vessel characteristics, seasonality, and market conditions all influenced observed length compositions and catch rates.

Observer coverage was incomplete across vessels, years, seasons, and fishing grounds. This limitation is particularly problematic for rare species or those with strong seasonal movements, as their vulnerability may be underestimated or overlooked. Similar challenges have been documented in other Western Indian Ocean fisheries, where uneven sampling has constrained the reliability of elasmobranch assessments (Clarke et al., 2018).

Length-based methods such as LBSPR are sensitive to the quality of growth, maturity, and selectivity parameters. Violations of the assumption that sampled length compositions represent the exploited population can bias outputs. This is especially critical where maturity parameters were derived from external populations, as life-history traits may vary geographically (Hordyk et al., 2015; Simpfendorfer et al., 2011).

6.0. Management implications and recommendations

The industrial longline management should be species-specific. The pelagic results indicate that *C. longimanus* and *C. falciformis* require strong precautionary measures, while *Isurus oxyrinchus* shows intermediate resilience but should not be exposed to further mortality increases. These recommendations align with current Indian Ocean Tuna Commission (IOTC) measures, which emphasize species-level reporting and live-release protocols for makos (IOTC, 2023).

The decade-long observer dataset highlights the value of standardized fisheries-dependent monitoring. The IOTC member states should institutionalize continuous observer coverage with standardized recording of species identity, length, sex, hook position, gear configuration, soak time, and release condition. This would strengthen both national assessments and Kenya's contributions to IOTC scientific processes, echoing best practices in other regions (Clarke et al., 2018).

The significance of these findings extends beyond Kenya because many focal pelagic sharks are highly migratory and cannot be managed effectively through national measures alone. The industrial longline fishery operates within the broader Western Indian Ocean tuna ecosystem, where sharks routinely cross EEZ boundaries and move between national waters and the high seas. National catch reductions may therefore have limited effect if fishing mortality is displaced geographically. Regional cooperation through IOTC is essential (IOTC, 2023).

The Indian Ocean already provides examples of how data-limited approaches can support regional decision-making. Preliminary silky shark assessments have combined catch reconstruction, CPUE standardization, and data-limited modelling to provide management advice despite uncertainty (IOTC, 2023). Similarly, blue shark assessments have demonstrated the value of integrating longline CPUE, catch histories, and biological information (Clarke et al., 2018). Kenya's results contribute to these regional efforts by providing species-specific length compositions, maturity schedules, sex-ratio information, standardized CPUE, spatial distribution data, and vulnerability estimates. These datasets are particularly valuable because regional stock assessments depend heavily on fisheries-dependent information, and Kenya's contributions can strengthen precautionary measures across the Western Indian Ocean.

7.0. Conclusion

Within the industrial pelagic longline fishery, four species dominated catches and provided the clearest insights into oceanic stock status. Blue Shark (*Prionace glauca*) exhibited comparatively favorable indicators, with mean size above the maturity threshold and an SPR of 40.8%. Despite elevated fishing mortality (F/M = 2.33), this species' faster growth and higher fecundity confer resilience, though continued monitoring is essential to ensure sustainability.

Shortfin Mako (*Isurus oxyrinchus*) showed intermediate resilience, with an SPR of 21.2% close to the lower reference boundary. Its slow growth and late maturity highlight the need for precautionary management, as even modest increases in fishing mortality could push the stock into severe depletion.

In contrast, Silky Shark (*Carcharhinus falciformis*) and Oceanic Whitetip Shark (*Carcharhinus longimanus*) exhibited critically low SPR values (6.7% and 7.2%, respectively) and high relative fishing mortality (F/M > 2.0). These results confirm severe reproductive depletion and align with global assessments identifying both species as highly threatened by longline exploitation (Clarke et al., 2018; Dulvy et al., 2021).

Taken together, the integrated synthesis of LBSPR, growth estimation, mortality analysis, sex-ratio assessment, and CPUE provides a coherent evidence framework for prioritizing management. The convergence of multiple indicators on depletion for *C. falciformis*, and *C. longimanus* underscores

the urgent need for precautionary action. *I. oxyrinchus* warrants close monitoring due to its borderline status, while *P. glauca* remains comparatively resilient but vulnerable to sustained fishing pressure.

The principal contribution of this study is not a single estimate of stock status but a multidimensional framework for identifying management priorities under uncertainty. This approach is directly aligned with the precautionary objectives of the FAO IPOA-Sharks (FAO, 2000) and the emerging regional management framework under IOTC, which emphasize species-specific monitoring, improved reporting, and proactive conservation of vulnerable stocks (IOTC, 2023).

Ultimately, Kenya can contribute meaningfully to regional and global shark conservation by applying integrated, data-limited methods to generate actionable evidence. The challenge now lies in translating these findings into policy and practice: reducing fishing mortality, protecting critical habitats, and ensuring that management frameworks are responsive to the biological realities of species-specific vulnerability.

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