Biological Conservation 304 (2025) 111049

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

A megafauna in distress: Unsustainable exploitation of tiger sharks in the Arabian Sea and implications for conservation

Muralikrishna Gurugubelli [a], C. Abisha [a], T.A. Arundhathy [b], K. Ranjeet [c], Neelesh Dahanukar [d,*], Rajeev Raghavan [a,*]

[a] Department of Fisheries Resource Management, Kerala University of Fisheries and Ocean Studies (KUFOS), Kochi, India
[b] Department of Climate Variability and Aquatic Ecosystems, Kerala University of Fisheries and Ocean Studies (KUFOS), Kochi, India
[c] Department of Aquatic Environment Management, Kerala University of Fisheries and Ocean Studies (KUFOS), Kochi, India
[d] Department of Life Sciences, School of Natural Sciences, Shiv Nadar Institution of Eminence, Delhi, NCR, India

ARTICLE INFO

Keywords:
Elasmobranch
India
Oceanic shark
Overexploitation
Western Indian Ocean

ABSTRACT

Populations of the iconic tiger shark, *Galeocerdo cuvier*, are in a state of global decline, with the species assessed as 'Near Threatened' on the IUCN Red List. Despite this, there is a lack of fundamental information required for regional management, such as those on life history and ecology. We bridge this knowledge gap by generating the first information on the population dynamics of *G. cuvier* from the Arabian Sea – one of the world's most important shark fishing regions. Length-frequency data of 629 *G. cuvier* landed at Cochin (Southwest coast of India) over 16 months in 2023–2024, revealed the dominance of 180–240 cm length class, with the largest individual measuring 405 cm TL. The von Bertalanffy curve fitted to the length-frequency data revealed greater asymptotic length ($L_{\infty} = 490.55$ cm TL) and growth co-efficient ($K = 0.250$ y^{-1}) compared to populations from the Atlantic and Pacific. Estimates of fishing mortality ($F = 0.77$) and exploitation rate ($E = 0.71$) suggest that *G. cuvier* face high levels of fishing pressure. The length at first capture (L_C) indicates that close to 95 % of the catches are represented by immature individuals. In addition, young of the year *G. cuvier* (<150 cm TL) landed as 'bycatch' contributed to 23 % of the landings. To effectively mitigate these challenges, and secure the future of *G. cuvier* in the Arabian Sea, we propose the establishment of tiger shark conservation zones to help protect critical life-history stages, and implement size-based restrictions to reduce growth and recruitment overfishing.

1. Introduction

Chondrichthyan fishes – sharks, rays, guitarfishes and chimaeras are in a state of global crisis (Dulvy et al., 2021; Worm et al., 2024). Almost one-third of oceanic sharks and rays, two-thirds of coral-reef associated sharks and rays, and 62 % of guitar fishes are now threatened with extinction (Dulvy et al., 2021; Dulvy et al., 2014; Sherman et al., 2023a, 2023b). The global abundance of oceanic sharks and rays have declined by 71 % during the past five decades (Pacoureau et al., 2021), as a result of significant increase in fishing pressure to meet the demand for the meat and fin trade, as well as due to bycatch (Cardeñosa et al., 2022; Dulvy et al., 2021; Karnad et al., 2024; Worm et al., 2013). Fishing-induced mortality of sharks increased from around 76 to 80 million sharks between the years 2012 and 2019, of which ~25 million comprised threatened species (Worm et al., 2024).

The Tiger shark, *Galeocerdo cuvier*, a monotypic member of the family Galeocerdonidae, are large-bodied, apex predators distributed in tropical, sub-tropical and temperate oceans (Compagno, 1984; Ferreira et al., 2017; Randall, 1992), where they are exploited in commercial, recreational, and artisanal fisheries (Anderson and Ahmed, 1993; Ferreira and Simpfendorfer, 2019; Bègue et al., 2020). Tiger sharks are potentially keystone species, contributing to both ecosystem structuring and functioning (Balanin et al., 2023; Ferreira et al., 2017; Heithaus et al., 2008). Though they are frequently encountered in coastal regions, tiger sharks are highly mobile and capable of swimming great distances across oceanic waters including undertaking transoceanic migrations (Hammerschlag et al., 2012; Heithaus et al., 2007). The relatively fast growth rates (Emmons et al., 2021) and large litters (average litter size ranging from 30 to 50 pups) of tiger sharks are however compromised by their biennial (in some cases triennial) reproductive cycle (see Holland et al., 2019), making them particularly vulnerable to fishing pressure (Branstetter et al., 1987a, 1987b; Ferreira and Simpfendorfer, 2019).

* Corresponding authors.
E-mail addresses: neelesh.dahanukar@snu.edu.in (N. Dahanukar), rajeevraq@hotmail.com (R. Raghavan).

https://doi.org/10.1016/j.biocon.2025.111049
Received 20 November 2024; Received in revised form 21 February 2025; Accepted 23 February 2025
Available online 1 March 2025

Despite their iconic status, many important shark fisheries in which *G. cuvier* are exploited, remain poorly documented, with information on stock assessment, population structure and overall population trends lacking for much of the species' distribution (Ferreira and Simpfendorfer, 2019). Nevertheless, it is widely-recognized that tiger sharks are in a state of global decline (Brown and Roff, 2019; Ferreira and Simpfendorfer, 2019), and that the species may even have experienced high levels of historic fishing historically (Pirog et al., 2019). Local and regional declines have been particularly observed in eastern Australia including Queensland (Reid et al., 2011; Holmes et al., 2012; Roff et al., 2018; Brown and Roff, 2019; Manuzzi et al., 2022), and parts of the Atlantic (Baum et al., 2003; Myers et al., 2007). With a 30 % reduction of several local populations over the past three generations, *G. cuvier* is currently listed as 'Near Threatened' on the IUCN Red List (Ferreira and

Fig. 1. Tiger sharks, *Galeocerdo cuvier* caught from the Western Indian Ocean/Arabian Sea, and landed at Thoppumpady, Cochin, India.

Simpfendorfer, 2019), and the low genetic diversity and recent genetic bottlenecks indicate a vulnerable population sensitive to local and regional stressors (Pirog et al., 2019). An example of this is the Arabian Seas region (part of the Western Indian Ocean/WIO), where *G. cuvier* populations are estimated to have declined between 30 and 50 % in the last 50 years, and further declines predicted due to the continued demand from the shark-fin market (Ferreira and Simpfendorfer, 2019).

Fundamental information that forms the basis of management and conservation, such as those on biology, ecology, as well as size, trends and dynamics of each population are thus urgently required from various regions, where *G. cuvier* is known to be targeted in artisanal and commercial fisheries, as well as unintentionally caught (Ferreira and Simpfendorfer, 2019). Since the limited studies on age, growth and population dynamics of the species are largely restricted to the Pacific (Emmons et al., 2021; Holmes et al., 2015; Hung et al., 2024) and the Atlantic (Branstetter et al., 1987a, 1987b; Afonso et al., 2012), we aim to bridge the knowledge gap from other oceanic regions, especially in the global south where there is limited information on the biology and population dynamics (Dicken et al., 2017; Balanin et al., 2023; Vossgaetter et al., 2024). Towards this, we undertake a comprehensive assessment of the population dynamics of *G. cuvier* based on exploited catches landed in the Southwest coast of India, so as to understand age, growth and mortality parameters. To the best of our knowledge, this is the first attempt to understand the population dynamics of *G. cuvier* from anywhere in the Arabian Sea and adjacent waters – one of the world's most important shark fishing and trading regions (Jabado et al., 2018).

2. Materials and methods

2.1. Study area and the regional shark fisheries

The Western Indian Ocean (WIO) (30 million km^2; encompassing waters of 32 countries and territories) is not only one of the planet's most biodiverse oceanic regions, but also one of the most heavily impacted (Bullock et al., 2021). A total of 264 species of sharks and rays are known from the WIO, of which 43 % are threatened (Bullock et al., 2021). Some parts of the WIO are more significant for shark fisheries, such as the Arabian Sea which harbours 15 % of the described chondrichthyan species of the world, more than half of which are threatened (Jabado et al., 2018).

Sharks are a regular component in India's artisanal, small-scale and semi-industrial marine fisheries, where they are largely taken as bycatch, but also in targeted fisheries (Akhilesh et al., 2023). Much of the fishery occurs along the Southwest coast of the country, with Cochin fishing harbour (9.938°N & 76.261°E; on the outskirts of the city of Kochi/Cochin; Kerala State) (Fig. 1) being one of the most important landing sites, especially for *G. cuvier* (Bineesh et al., 2014; Rajkumar et al., 2021). Most sharks (>98 %) landed at Cochin are caught by the 'Thoothoor fishers', known for their deep-sea shark fishing skills (Parappurathu et al., 2020). These fishers utilize mechanized gillnetter-cum-liners, using gillnets to primarily catch rays, and longlines for sharks. Their catch encompasses a range of elasmobranchs from families Carcharhinidae, Alopiidae, Galeocerdonidae, Lamnidae, Dasyatidae, Echinorhinidae, Rhinochimaeridae, Stegostomatidae, Sphyrnidae, and Mobulidae, in addition to predatory teleost fishes such as tunas, seer fish, sailfish, and swordfish. *Galeocerdo cuvier* landed at Cochin originate from many parts of the WIO (off the western coast of India including from the seamounts, Laccadive archipelago, Oman, Maldives and Sri Lanka), where they are caught using mechanized gillnetter-cum-liners (Overall length/OAL between 10 and 20 m and operating at 200–500 m depths which sometimes increase up to depths >2000 m) in fishing operations that extend between 30 and 45 days.

2.2. Data acquisition

We studied exploited *Galeocerdo cuvier* samples ($N = 629$) landed at the Cochin fisheries harbour over a 16-month period from March 2023 to September 2024 (with breaks for three months coinciding with the annual fishing closure in the region, for protecting spawning populations of mostly marine fish species). Length data were collected at weekly intervals during the study period, which included 192 visits to the landing site. The total length (TL) was measured (using a 10 m measuring tape) from tip of the snout to the farthest point of upper caudal fin, and fork length (FL) from tip of the snout to the center of fork on the caudal fin. Sexes were separated based on the presence of clasper in males. Due to the practical difficulties in weighing individual fish in a busy commercial fish landing site, total weights (TW) of only those fish ($N = 16$) that were weighed by the fishers/harbour authorities as part of the auction process were noted.

2.3. Data analysis

We used TL for estimating growth and mortality-related parameters; however, to facilitate comparisons with previous studies that have used FL, we also provide the relationship between TL and FL determined using a linear regression, and the goodness of fit estimated using coefficient of determination. Data were converted to a length frequency table with 20 cm interval. Length structured population dynamics was estimated using FiSAT II Version 1.22 (Gayanilo et al., 2005). This approach was used instead of the more widely used mark-recapture and vertebral ageing methods because recapture studies are often limited by their small sample sizes, low recapture rates, and a lack of representation of the species' entire size range (Meyer et al., 2014), while vertebral columns are frequently unavailable for research because tiger shark samples are usually large and transported whole to the processing plants without being chopped at landing sites/fishing harbours (C. Abisha Pers. Observ.). Alternatively, length-based approach has been previously used to understand the population dynamics of elasmobranchs (see for example Xu et al., 2022; Nurdin and Kembaren, 2023; Kindong et al., 2022), including tiger sharks (De Crosta et al., 1984; Jatmiko and Nugroho, 2020; Hung et al., 2024).

The asymptotic length (L_∞) was estimated using Powell-Wetherall's Plot (Wetherall and Polovina, 1987) by selecting points using pseudo catch-curve. The ELEFAN I routine (Pauly, 1984) was used to estimate the growth constant (K) of Von Bertalanffy function. Estimates of L_∞ and K were used to estimate the growth performance index $\phi' = 2 \times \log L_\infty + \log K$ (Pauly, 1979). Hypothetical time at which the size at birth is zero (t_0) was estimated using the equation, $\log(-t_0) = -0.3922–0.2752 \log L_\infty - 1.038 \log K$ (Pauly, 1979). Potential longevity (t_{max}) was estimated using the formula $t_{max} = (3/K) - t_0$, by defining longevity, or life span, as the time required to attain 95 % of TL (Taylor, 1958).

Growth parameters were subsequently used to determine the recruitment pattern (Moreau and Cuende, 1991) by reconstructing the recruitment peaks to estimate the number of pulses per year, and quantifying the strength of each peak (Gayanilo et al., 2005). The total mortality (Z) for the population was calculated using the length-converted catch curve, while the natural mortality (M) was determined using six different estimators (Table 1) using the parameters L_∞, K, t_{max} and the average annual temperature of the area under study $T = 26$ °C (Rostek et al., 1997). Fishing mortality (F) was determined by subtracting natural mortality from total mortality ($F = Z - M$), and the exploitation rate (E) was calculated as the ratio of F/Z (Gulland, 1970). Average values of natural mortality, fishing mortality and exploitation were used for further analysis.

Length-structured virtual population analysis (VPA) was conducted to estimate survivors, natural mortality, and fishing mortality in each length-group. The length-weight relationship for the VPA analysis was obtained from Varghese et al., 2013. Yield-per-recruit (Y′/R) and biomass-per-recruit (B′/R) were estimated using Beverton and Holt (1957) yield-per-recruit analysis.

Table 1
Estimation of natural mortality rates (M, y^{-1}) using various approaches. The fishing mortality (F) is calculated from total mortality Z of 1.09 y^{-1} (F = Z – M), and the exploitation ratio (E) is calculated as F/Z.

Estimator	Reference	Mortality equations*	M	F	E
Pauly's M	Pauly (1980)	$M = e^{-0.0152-0.279\ lnL_\infty+0.6543lnK+0.463lnT}$	0.32	0.77	0.71
Frisk et al.	Frisk et al. (2001)	$M = e^{0.42lnK-0.83}$	0.24	0.85	0.78
Hoenig$_{nls}$	Then et al. (2015)	$M = 4.899t_{max}^{-0.916}$	0.52	0.57	0.53
Pauly$_{nls\text{-}T}$	Then et al. (2015)	$M = 4.118K^{0.73}L_\infty^{-0.333}$	0.19	0.90	0.83
Estimator T$_{max}$	Dureuil et al. (2021)	$M = e^{1.583-1.087\ lnt_{max}}$	0.34	0.75	0.69
Estimator P	Dureuil et al. (2021)	$M = -\ ln0.0178/t_{max}$	0.35	0.74	0.68
Average			0.33	0.76	0.70

* L_∞, asymptotic total length; K, growth constant; t_{max}, potential longevity; T, habitat temperature in °C.

3. Results

3.1. Length-frequency distribution, length-length relationship and sex ratio

The smallest and largest *Galeocerdo cuvier* encountered in the landings measured 75 cm and 405 cm TL (♀), and 85 cm and 365 cm TL (♂). For combined sexes, greatest frequency of individuals was recorded in the length classes of 180–200 cm TL ($N = 96$), followed by 200–220 cm ($N = 95$) and 220–240 cm TL ($N = 84$). Very few individuals were observed in the 60–80 cm ($N = 2$), 380–400 cm ($N = 3$) and 400–420 cm TL (N = 2) length classes. The frequency distribution of different length-classes across months indicated the occurrence of smaller individuals (<100 cm TL) between the months of March and June (Fig. 2). A linear relationship between the fork length and total length was also observed: $L_F = 0.8395\ L_T - 9.6454$ ($R^2 = 0.9912$; 95 % CI of slope: 0.8327–0.8466). Sex ratio was not significantly different from 1:1 (chi-square = 1.73, $P =$ 0.1882), with 331 females and 298 males. The month wise F:M ratio was also not significantly different from 1:1.

3.2. Growth and mortality

The largest individual landed during the study period was a female measuring 405 cm TL, and the calculated asymptotic length (L_∞) was 490.55 cm. The von Bertalanffy curve fitted to the length-frequency data

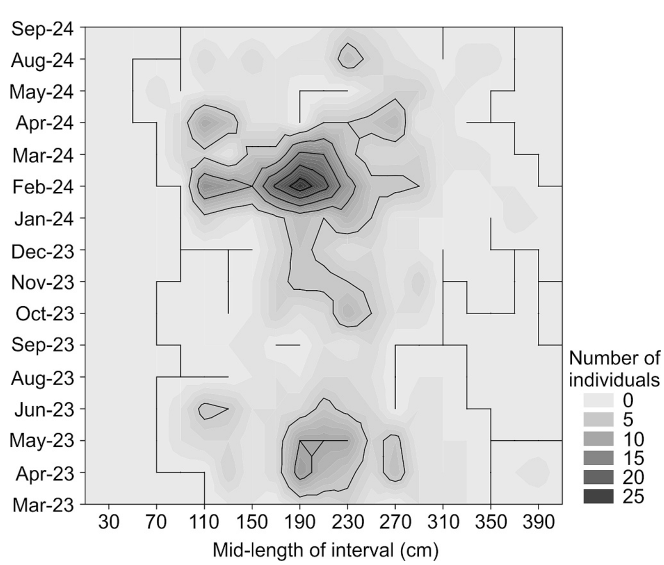

Fig. 2. Length frequency data of *Galeocerdo cuvier* based on exploited catches landed at Thoppumpady, Cochin, India and caught from the Western Indian Ocean/Arabian Sea.

(Fig. 3a) calculated the growth coefficient (K) at 0.250 y^{-1} and the growth performance index (ϕ) at 4.779. Recruitment analysis (Fig. 3b) indicated that the species has a single annual reproduction bout extending from June to August. Total mortality (Z) based on length converted catch-curve was 1.09 y^{-1} (95 % confidence interval: 0.97–1.21). Natural mortality coefficient (M) estimated using five different empirical formulas had a mean value of 0.33 y^{-1}, though the estimates ranged between 0.19 and 0.52 y^{-1} (Table 1).

3.3. Exploitation

Close to 98 % of the tiger sharks landed at Cochin were the targets of commercial fishery using baited longline, while the remaining 2 % were bycatch originating from gillnet and trawl fisheries. The relationship between length class and capture probability revealed that the length at first capture (L_C) was 171.58 cm TL. Virtual population analysis showed that the survival decreased rapidly with increase in the fishing pressure, starting from juveniles >110 cm TL (Fig. 3c). The yield-per-recruit and biomass-per-recruit analysis suggested that the current exploitation ratio (E) of 0.71 is greater than both the E_{50} (0.323) and E_{max} (0.551), indicating extremely high levels of overfishing (Fig. 3d).

4. Discussion

In India, the landings of elasmobranchs have declined over the last six decades, with many coastal species showing signs of overexploitation (Akhilesh et al., 2023). Despite this, there is a significant gap in research that informs conservation decision-making for elasmobranchs in the country (Gupta et al., 2022). One of the key areas where this gap is evident is the assessment of population status and dynamics (Akhilesh et al., 2023; Gupta et al., 2022) with limited information on many conservation-concern species including those that have been listed as Threatened, or Near Threatened on the IUCN Red List, an example of which is *G. cuvier*.

Galeocerdo cuvier grows to a maximum length of 740–750 cm TL (Ebert et al., 2013; Froese and Pauly, 2024; Vidthayanon, 2005), but individuals >500 cm TL are known to be rare (Ebert et al., 2013). A review of recent studies (since 2015) on *G. cuvier* reveals the absence of individuals >430 cm TL (Holmes et al., 2015; Jatmiko and Nugroho, 2020) and 360 cm FL (Emmons et al., 2021). The length of the largest individual encountered during our study (♀ 405 cm TL) is comparable to previous records of the species from the Arabian Sea (398 cm TL – Varghese et al., 2017, 411 cm TL – Shriram and Katkar, 2004, and 440 cm TL – Bineesh et al., 2014).

Our estimate of asymptotic length (L_∞) of *G. cuvier* (490 cm) is greater than those recorded previously using various approaches – 456 cm (length-based method; De Crosta et al., 1984), 406 cm (mark-recapture method; Meyer et al., 2014) and 440 cm (vertebral ageing; Branstetter et al., 1987a, 1987b) (Table 2). To the best of our

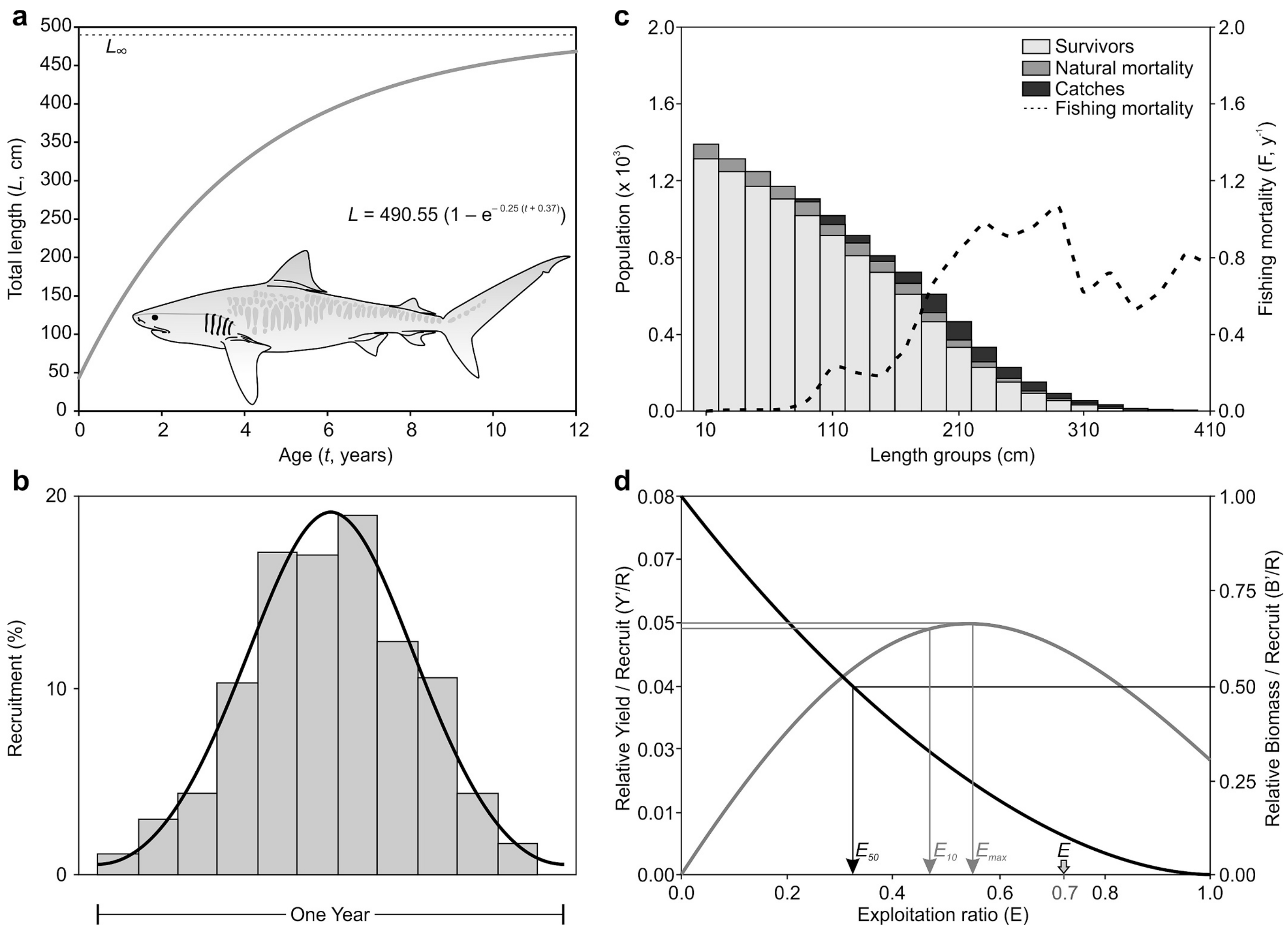

Fig. 3. Length-structured population dynamics of *Galeocerdo cuvier* based on exploited catches landed at Thoppumpady, Cochin, India and caught from the Western Indian Ocean/Arabian Sea. (a) von Bertalanffy growth curve, with asymptotic total length indicated using dashed line. (b) Computed recruitment pattern indicating single reproductive bout. (c) Virtual population analysis showing rapid decline in survivors with fishing mortality. (d) Relative yield per recruit and relative biomass per recruit analysis, with actual current exploitation (E = 0.71) is indicated using grey arrow.

Table 2
Comparison of growth and mortality parameters of *Galeocerdo cuvier* from various studies, employing different methods for studying growth dynamics.

Parameters*						Study area	Reference
L_∞	K	t_0	ϕ'	n	M		
Length-based							
490.6	0.250	−0.370	4.779	629	0.34	Arabian sea	Current study
456.3[a]	0.150	−1.270	4.495	204	0.20	Hawaii	De Crosta et al. (1984)
380.0	0.100	−0.860	4.160	696	0.12	West Nusa Tenggara	Jatmiko and Nugroho (2020)
433.0[b]	0.240	−0.570	4.653	283	0.33	Northwest Pacific Ocean	Hung et al. (2024)
Mark–recapture							
406.1	0.310	−0.758[h]	4.709	37	0.45	Hawaii	Meyer et al. (2014)
399.9[c]	0.178	−1.120	4.454	42	0.24	Western North Atlantic	Natanson et al. (1999)
324.3[d]	0.283	−0.190	4.474	217	0.38	Western North Atlantic	Kneebone et al. (2008)
Vertebral ageing							
440.0	0.107	−2.350	4.316	44	0.14	Western North Atlantic	Branstetter et al. (1987a, 1987b)
438.2[e]	0.070	−2.300	4.128	124	0.09	Western Australia	Emmons et al. (2021)
427.3[f]	0.102	−2.240	4.270	238	0.13	Western North Atlantic	Kneebone et al. (2008)
403.6	0.080	−2.689[i]	4.115	202	0.10	East coast of Australia	Holmes et al. (2015)
401.2	0.255	−1.077	4.613	67	0.37	South Atlantic Ocean	Santana da Silva et al., 2024
388.0	0.184	−1.130	4.442	25	0.25	Gulf-of-Mexico	Branstetter et al., 1987a, 1987b)
382.2[g]	0.202	−1.110	4.470	90	0.28	East coast of South Africa	Wintner and Dudley (2000)
335.0	0.155	−0.619	4.240	28	0.20	Hawaii	De Crosta et al. (1984)

a–gTotal length back-calculated from fork length and/or pre-caudal length using length-length equations; [a, c, e, f, g] see Santana da Silva et al., (2024) for more details; [b]based on equations from Hung et al. (2024); [d] based on equations from Kohler et al. (1995) and Bass et al. (1975); [h]extrapolated from the y intercept of 85 cm considered by authors; [i]extrapolated from the y intercept of 78 cm considered by authors.

* L_∞, asymptotic total length; K, growth constant; t_0, hypothetical age at which the TL is zero; ϕ', growth performance index; n, sample size; M, natural mortality estimated using the estimator t_{max} (Table 1).

knowledge, there are only two studies that have assessed the age and growth of *G. cuvier* from the Indian Ocean (Jatmiko and Nugroho, 2020; Wintner and Dudley, 2000). The study from WIO (Wintner and Dudley, 2000) estimated an L_∞ of 382.2 cm pre-caudal length based on back-calculated lengths from vertebral growth ring counts for 90 individuals caught in the fishery off KwaZulu Natal (South Africa), while the study from the eastern part of the Indian Ocean (Jatmiko and Nugroho, 2020) used length-frequency data to compute the L_∞ at 380 cm TL (Table 2). However, it is known that tiger sharks measuring 600 cm have been caught in the Maldives, and that individuals measuring 200 to 400 cm are frequently caught in the atolls of the island (Anderson and Ahmed, 1993; Vossgaetter et al., 2024).

Galeocerdo cuvier is generally known to be a fast-growing shark with some individuals attaining a growth rate of 118 cm year^{-1} (Afonso et al., 2012), and reaching around 400 cm by the time they are five years old (Meyer et al., 2014). However, growth rates are also known to depend on geographical areas, and populations within the same ocean (e.g., Atlantic; Afonso et al., 2012; Branstetter et al., 1987a, 1987b; Natanson et al., 1999), and between different oceans, show varying growth rates (Table 2). For example, it has been demonstrated that Hawaiian populations of *G. cuvier* (particularly juveniles) grow at very fast rates (K = 0.31 y^{-1}) (Meyer et al., 2014). Based on our analysis, the Arabian Sea population exhibited a faster growth (based on growth coefficient, K = 0.25 y^{-1}) compared to populations along the western (South Africa) and eastern (Indonesia and Australia) peripheries of the Indian Ocean (0.067–0.202 y^{-1}) (Emmons et al., 2021; Jatmiko and Nugroho, 2020; Wintner and Dudley, 2000), as well as from the North Atlantic (0.131–0178 y^{-1}) (Kneebone et al., 2008; Natanson et al., 1999). However, the growth coefficient values we estimated were similar to a recent study from the Northwest Pacific (0.245 y^{-1}) (Hung et al., 2024).

Our estimates of natural, fishing and total mortalities were mostly higher than those obtained previously (see Table 2) – though similar or even higher values have also been obtained using both the length-based (Hung et al., 2024) as well as mark-recapture methods (Meyer et al., 2014). Very few estimates of mortality are available for *G. cuvier* from the Indian Ocean, making any regional comparisons difficult. The total mortality estimates we computed (1.08 y^{-1}) are significantly higher than those recorded from both the eastern part of the Indian Ocean (Jatmiko and Nugroho, 2020) as well as the Pacific (Hung et al., 2024) (around 0.3 y^{-1}), but comparable to those obtained previously for young of the year (YOY) and 1+ size classes from the Atlantic (0.93–1.02 y^{-1}) (Driggers III et al., 2008). This difference in mortality rates can be attributed to various factors, including (but not limited to) i) uneven sample sizes – 283 sub adults (Hung et al., 2024), and 335 YOY and 219 juveniles (Driggers III et al., 2008), compared to our sample size of 629 individuals and ii) duration of study – 10 months (Jatmiko and Nugroho, 2020), compared to our study period of 16 months. While fish species with faster growth rates have higher rates of mortality (Zhang and Megrey, 2006), the specific reasons for high natural mortality rates in *G. cuvier*, similar to those previously observed for groupers (*Epinephelus bleekeri*) in the Arabian Sea (Richu et al., 2018) needs further investigation. It may be likely that this high natural mortality is the consequence of specific habitat use (e.g., early life stages and juveniles of tiger sharks preferring shallow water habitats; Afonso and Hazin, 2015), and these habitats likely overlapping with those of larger predators (e.g., the Orca, *Orcinus orca*). Additionally, tiger sharks exhibit cannibalism (Lowe et al., 1996; Meyer et al., 2009), and the predation of juvenile sharks occupying the same habitat cannot be ruled out.

Galeocerdo cuvier became popular since the 1950s due to the increasing demand for the fin trade, and are regularly targeted throughout its range (Ferreira and Simpfendorfer, 2019; Ward-Paige et al., 2010). This species which contributed to minor quantities in the fishery at the Cochin harbour during the 1980s became an important commodity in 2008 contributing to 5.4 % of the total landings (Akhilesh et al., 2011). This increase in landings were largely driven by increased mechanization of vessels and expansion of fishing operations to deeper/oceanic waters through multiday fishing trips (Akhilesh et al., 2011). Our estimate of annual exploitation rate ($E = 0.71$) is greater than the exploitation rates that retains 50 % of the biomass ($E_{50} = 0.323$), and the maximum yield-per-recruit ($E_{max} = 0.551$), suggesting that *G. cuvier* are subjected to extremely high levels of fishing pressure in the Arabian Sea. The annual exploitation rate that we estimate from the Arabian Sea is also higher than those obtained recently from the Pacific (0.514; Hung et al., 2024) suggesting the presence of a much more intensive and unsustainable fishery in the WIO.

An additional challenge for management is the length at first capture (L_C) which was calculated at 172 cm TL. *Galeocerdo cuvier* are known to mature around 270 cm TL, with males maturing at smaller sizes than females (Holmes et al., 2015; Simpfendorfer, 1992; Stevens, 1984; Varghese et al., 2017). Close to 95 % of the individuals landed at the Cochin fisheries harbour during our study period were below the average size at first maturity indicating significant pressure on immature individuals, and a potential threat of recruitment overfishing.

Very few studies have been carried out on the reproductive biology of tiger sharks in the Indian Ocean (Sarangdhar, 1946; Jaquemet et al., 2012; Varghese et al., 2017). The size at first maturity for tiger sharks in the Arabian Sea has been observed to be 286.56 cm TL (♂) and 300.31 cm TL (♀), with the smallest mature female having a total length of 274 cm (Varghese et al., 2017). The size at birth of *G. cuvier* is known to range from 51 to 104 cm TL (Froese and Pauly, 2024), with a previous study from the Cochin fisheries harbour observing the size at birth to be 79.6 to 85.2 cm TL (Varghese et al., 2017). Assuming that individuals up to at least 100 cm TL are newly born, it is alarming that almost 7 % of the catches in the Cochin fisheries harbour represent neonate mortality. Our observations on the landings and informal discussions with the fishers reveal that tiger sharks <150 cm are normally landed as 'bycatch', and given that these individuals are certainly 'young of the year/YOY', almost 23 % of the total landings during the 16 months of our study are contributed by *G. cuvier* in this size-class. Many life history traits result in juvenile sharks being particularly vulnerable to exploitation, but the impacts of juvenile harvests have not been well quantified (Gallucci et al., 2006), including in *G. cuvier*.

Theoretical Y′/R and B′/R curves based on the growth parameters from the current study (Fig. 4) suggests that improving the fishery productivity can only be achieved by reducing the current exploitation, and increasing the length at first capture. The Y′/R analysis suggests that if the length at first capture is increased between 60 % to 80 % of the asymptotic length of the fish (i.e., 294–394 cm TL), then the fisheries will have an optimum Y′/R, as opposed to the current suboptimum Y′/R as a result of overfishing (Fig. 4a). This can only be achieved through a combination of approaches including enforcing strict regulations on catch-size, and voluntary release of smaller individuals from fishing boats.

An average of 15,000 t of sharks are caught every year in India (CMFRI, 2024), with landings having declined from 21,154 t in the year 2018 to 12,296 t in the year 2022, before increasing to 16,734 t in 2023 (CMFRI, 2024). Based on the landing data observed in the current study, we converted the length measurements of *G. cuvier* to weight, using two length-weight relationships – (i) the limited number of weight measurements available in our study suggesting a relationship $W = 0.000037\ TL^{2.6281}$ ($R^2 = 0.9660$, $n = 16$), and (ii) mean weight estimates available in FishBase (Froese and Pauly, 2024) suggesting $W = 0.0026\ TL^{3.24}$. Based on these weight estimates, anywhere between 37 and 76 t of *G. cuvier* is likely to have been landed at the Cochin fisheries harbour during the 16 months of our study.

In the context of a wide-ranging, conservation-concern species that shows a declining trend, regular assessments of population status are vital to inform management and conservation efforts across the global range (Holmes et al., 2017). The Arabian Seas region has for long been recognized as a potential area of risk for *G. cuvier* with declines in landings observed in Eritrea, Iran, the UAE, India and Pakistan, which have been extrapolated at 30–50 % across the larger region (Ferreira and

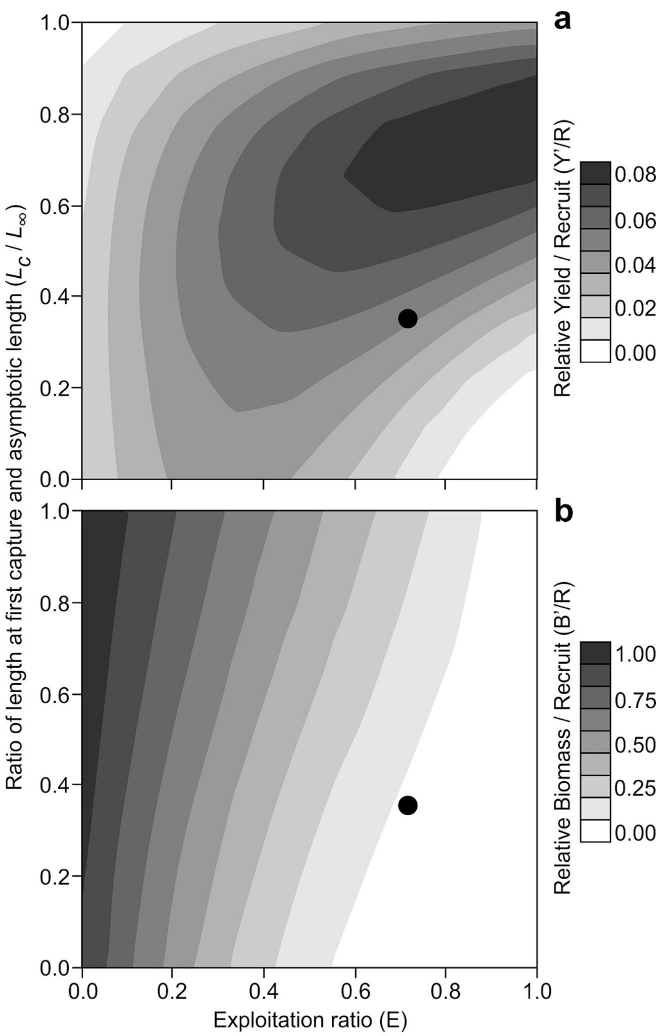

Fig. 4. Relative yield per recruit (Y′/R) and relative biomass per recruit (B′/R) analysis for different values of ratio of length at first capture and asymptotic length (L_c/L_∞) and exploitation ratio (E) using the natural mortality by growth constant (M/K) or 1.28. Black circle indicates current E for current L_c/L_∞. Data based on exploited catches landed at Thoppumpady, Cochin, India and caught from the Western Indian Ocean/Arabian Sea.

Simpfendorfer, 2019; Jabado et al., 2017). No species-specific conservation and management plans are however in place for *G. cuvier*, but some countries in the Arabian Seas region have imposed restrictions including banning of targeted shark fishing (e.g., Kuwait, Saudi Arabia, Sudan, and Maldives), while others have implemented temporal/seasonal closures (e.g., Iran, and the UAE) (Ferreira and Simpfendorfer, 2019; Jabado and Spaet, 2017).

The differences in the nature and effectiveness of management and conservation plans in various countries and the lack of fishing regulations in international waters represent a significant threat to migratory shark species (Dulvy et al., 2008) such as *G. cuvier*. The species is known to have a large, single Indo-Pacific population (Holmes et al., 2017) capable of making transoceanic migrations. In such a situation, unless regional (e.g., Arabian Seas region) and international (e.g., Indian Ocean rim countries) efforts to manage the sustainable exploitation of *G. cuvier* are developed and implemented, effective management will not be possible. Of >160 shark species recorded from India, only 26 sharks and rays have been listed in the various schedules of the Wild Life (Protection) Act 1972 (TRAFFIC India, 2024), with *G. cuvier* not receiving any level of protection. Similarly, in the state of Kerala where we carried out our study, there are minimum legal size (MLS) restrictions for 58 species of fish (including elasmobranchs) and shell-fishes, but this list does not include *G. cuvier*.

5. Challenges and opportunities for conservation

Our study has for the first time, provide insights into the population dynamics of *Galeocerdo cuvier* from the Western Indian Ocean/Arabian Sea. Together with high fishing pressure indicative of overfishing, the species is potentially subjected to recruitment overfishing, as well as unintentional harvests of YOY and neonates as bycatch. Given the market demand for tiger sharks, significant contributions of the fishery to local livelihoods, and a history of fisheries bans being either resented or being ineffective in India (see Akhilesh et al., 2023), inclusion of the species in the Indian Wildlife (Protection) Act, or subjecting them to blanket bans will only be detrimental to conservation. Implementation of closures, restrictions on gear and use of bycatch reduction devices in India has also been considered to be a challenge given their potentially high impact on fisher income (Gupta et al., 2020). Additionally, compliance by local fishers has been recognized as one of the major challenges for the success of shark fisheries management plans in India (Gupta et al., 2020). A holistic education and awareness program targeted at shark fishers is urgently required so as to develop a behavioural shift and change towards conservation and sustainability.

We propose three major conservation and management strategies (Fig. 5) which includes: (1) identifying and establishing additional 'Important Shark and Ray Areas'/ISRAs (see below) including tiger shark conservation zones (including aggregation sites, pupping and nursery grounds) in the WIO and Arabian Sea to help protect critical life history stages from exploitation pressure, (2) size-based restrictions including minimum legal size to reduce and eliminate growth overfishing, and (3) participatory research and monitoring for ensuring long-term sustainability and informing conservation plans.

Currently, there are only one two 'Important Shark and Ray Areas' (ISRAs) focused on tiger sharks in the WIO – the Fuvahmulah Atoll in southern Maldives, and the ~100 km Natal Southcoast Corridor in South Africa (Jabado et al., 2023). The Fuvahmulah Atoll, recognized as an important reproductive site for *G. cuvier* (Jabado et al., 2023; Vossgaetter et al., 2024) is within the larger area in the WIO where fishers from India (including boats that land sharks at Cochin) target this species (C. Abisha pers. comm.). Interactions with local fishers targeting tiger sharks also recognize similar sites (though not formally listed as an ISRA) along the south-west coast of India, e.g., the Wadge Bank, known for their abundance of tiger sharks. These sites could be identified and demarcated as 'no-take' areas, or subjected to temporal closures, at least during the pupping seasons.

Gestation in tiger sharks of eastern Arabian Sea is known to begin in January and the parturition takes place in May of the subsequent year (Varghese et al., 2017), but we encountered considerable numbers of YOY in the landings from the month of February onwards. This is likely because the parturition periods may vary geographically and according to populations. For example, pupping in the Western Indian Ocean (one of the fishing areas for boats operating from Cochin harbour) is estimated to occur between December and February (Jaquemet et al., 2012), a few months prior to the pupping season in the eastern Arabian Sea. Mandatory adjustments to fishing gear such as the use of larger mesh sizes in gillnets and trawl nets, specific limitations on length (or volume) of the mainline and the number of hooks in longlines should therefore be enforced during the months between February and July, so that both Arabian Sea and the larger Indian Ocean populations can be protected. Longlines should also be avoided around the vicinity of critical sites for reproduction and foraging (e.g., Wadge Bank), as well as at shallow depths. These measures are important because it is known that the type of gear influences the size of tiger sharks caught. For example, a multi-decadal (36 years) catch data of tiger sharks originating from KwaZulu-Natal bather protection program revealed that baited drumlines caught significantly smaller-sized sharks than gill nets,

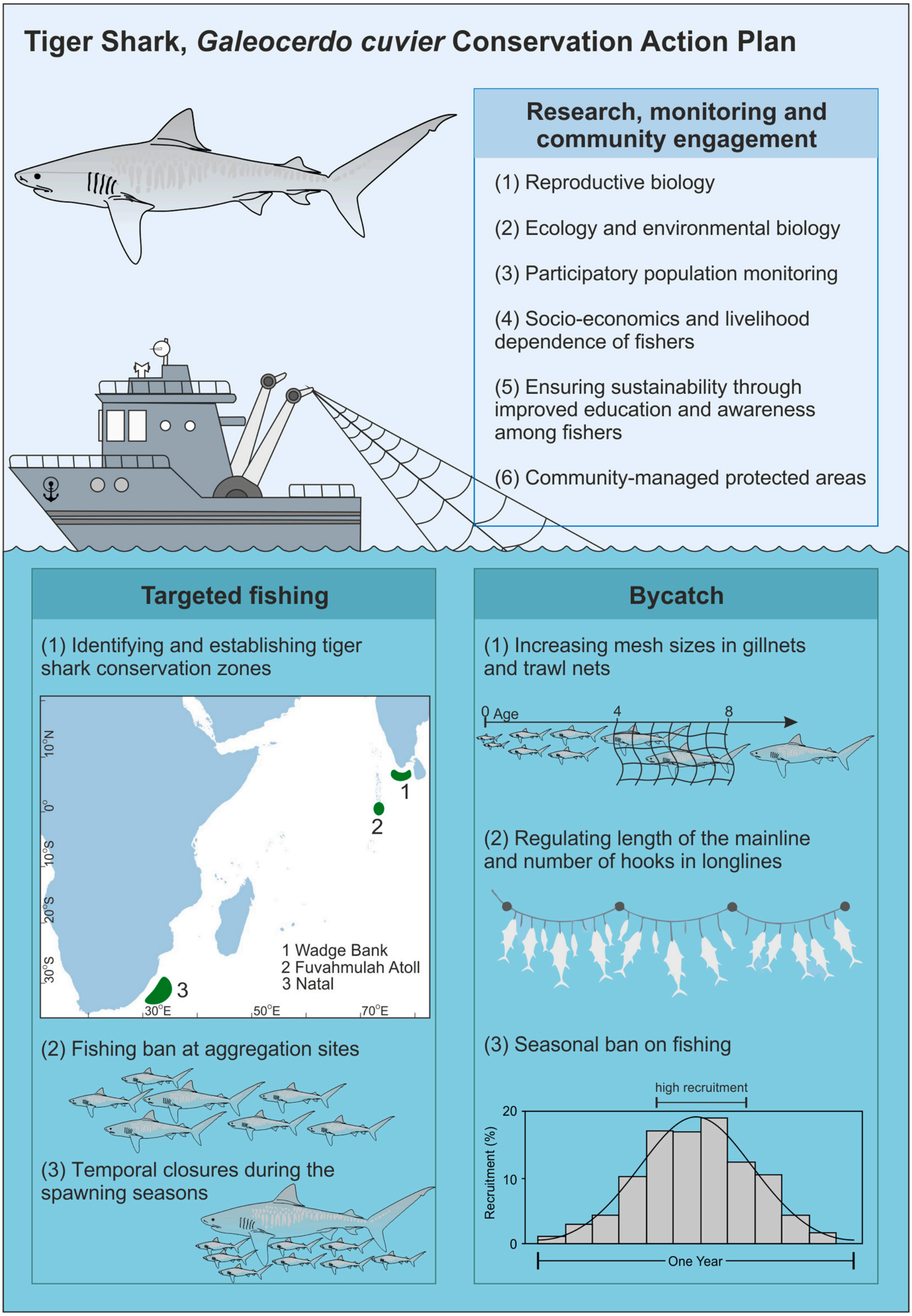

Fig. 5. A proposed conservation action plan framework for *Galeocerdo cuvier* in the Arabian Sea region.

due to the larger mesh-sizes used in the nets (Dicken et al., 2016). Given the available information on minimum size at maturity and the significant catches of immature individuals, we recommend a minimum legal size of 290 cm for *G. cuvier* along the Arabian Sea coast of India.

Elasmobranch fisheries in India cannot be made sustainable using generalized approaches and regulations, but requires species-specific management strategies (see Gupta et al., 2020). The challenge for shark conservation plans in India aligns with the general framework of the Tragedy of the Commons (Hardin, 1968), where unmanaged exploitation will result in large-scale population declines and even likely extinction of species, pushing the stakeholders into hardships. Most top-down approaches will be (and to an extent have been) resented. Securing the future of *Galeocerdo cuvier* in the Arabian Sea and the WIO will therefore have to depend on the development and implementation of effective community-based conservation and management plans that integrates biological, ecological and social frameworks, as well as participatory monitoring approach involving fishers and other relevant stakeholders.

CRediT authorship contribution statement

Muralikrishna Gurugubelli: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **C. Abisha:** Writing – original draft, Methodology, Investigation, Data curation. **T.A. Arundhathy:** Resources, Investigation, Data curation. **K. Ranjeet:** Writing – review & editing, Resources, Conceptualization. **Neelesh Dahanukar:** Writing – review & editing, Visualization, Validation, Software, Formal analysis. **Rajeev Raghavan:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are grateful to the authorities and local fishers at Thoppumpady (Cochin) and Thoothoor (Tamil Nadu) for their permission, cooperation and support during the study. MG and CA received funding from the Faculty of Fisheries, Kerala University of Fisheries and Ocean Studies, Kochi, India. Aneesh Kumar KV (Sacred Heart College, Thevara) provided useful insights on the impacts of various fishing gears. Three anonymous reviewers and the editor provided critical comments and suggestions that greatly helped improve an earlier version of this manuscript.

Data availability

Data will be made available on request.

References

Afonso, A.S., Hazin, F.H.V., 2015. Vertical Movement Patterns and Ontogenetic Niche Expansion in the Tiger Shark, *Galeocerdo cuvier*. PLoS ONE 10 (1), e0116720. https://doi.org/10.1371/journal.pone.0116720.

Afonso, A.S., Hazin, F.H.V., Barreto, R.R., Santana, F.M., Lessa, R.P., 2012. Extraordinary growth in tiger sharks *Galeocerdo cuvier* from the South Atlantic Ocean. J. Fish Biol. 81 (6), 2080–2085. https://doi.org/10.1111/j.1095-8649.2012.03455.x.

Akhilesh, K.V., Ganga, U., Pillai, N.G.K., Vivekanandan, E., Bineesh, K.K., Shanis, C.P.R., Manjebrayakath, H., 2011. Deep sea fishing for chondrichthyan resources and sustainability concerns-a case study from southwest coast of India. Indian J. Mar. Sci. 40 (3), 347–355.

Akhilesh, K.V., Kizhakudan, S.J., Muktha, M., Najmudeen, T.M., Thomas, S., Karnad, D., Sutaria, D., Fernandes, M., Gupta, T., Namboothri, N., Patankar, V., 2023. Elasmobranch conservation, challenges and management strategy in India: recommendations from a national consultative meeting. Curr. Sci. 124 (3), 292–303.

Anderson, R.C., Ahmed, H., 1993. The shark fisheries of the Maldives. Ministry of Fisheries and Agriculture, Republic of Maldives and food and agriculture organization (FAO) of the United Nations. 76p.

Balanin, S., Hauser-Davis, R.A., Giareta, E., Charvet, P., Wosnick, N., 2023. Almost nothing is known about the tiger shark in South Atlantic waters. PeerJ 11, 14750. https://doi.org/10.7717/peerj.14750.

Bass, A.J., D'Aubrey, J.D., Kistnasamy, N., 1975. Sharks of the east coast of southern Africa 3: the families Carcharhinidae (excluding *Mustelus* and *Carcharhinus*) and Sphyrnidae. Oceanographic Research Institute Investigational Report No. 38.

Baum, J.K., Myers, R.A., Kehler, D.G., Worm, B., Harley, S.J., Doherty, P.A., 2003. Collapse and conservation of shark populations in the Northwest Atlantic. Science 299 (5605), 389–392. https://doi.org/10.1126/science.1079777.

Bègue, M., Clua, E., Siu, G., Meyer, C., 2020. Prevalence, persistence and impacts of residual fishing hooks on tiger sharks. Fish. Res. 224, 105462. https://doi.org/10.1016/j.fishres.2019.105462.

Beverton, R.J.H., Holt, S.J., 1957. On the dynamics of exploited fish populations. Fish. Investig. 19, 1–533.

Bineesh, K.K., Akhilesh, K.V., Abdussamad, E.M., Prakasan, D., 2014. Seamount associated fishery of south-west coast of India - a preliminary assessment. Indian J. Fish. 61 (3), 29–34.

Branstetter, S., Musick, J.A., Colvocoresses, J.A., 1987a. A comparison of the age and growth of the tiger shark, *Galeocerdo-cuvieri*, from off Virginia and from the northwestern gulf-of-Mexico. Fish. Bull. 85 (2), 269.

Branstetter, S., Musick, J.A., Colvocoresses, J.A., 1987b. A comparison of the age and growth of the tiger shark, *Galeocerdo cuvier*, from off Virginia and from the northern Gulf of Mexico. Fish. Bull. 85, 269–279.

Brown, C.J., Roff, G., 2019. Life-history traits inform population trends when assessing the conservation status of a declining tiger shark population. Biol. Conserv. 239, 108230. https://doi.org/10.1016/j.biocon.2019.108230.

Bullock, R., Ralph, G., Stump, E., Al Abdali, F., Al Asfoor, J., Al Buwaiqi, B., Al Kindi, A., Ambuali, A., Birge, T., Borsa, P., Di Dario, F., Everett, B., Fennessy, S., Fonseca, C. Gorman, C., Govender, A., Ho, H., Holleman, W., Jiddawi, N., Khan, M., Larson, H., Linardich, C., Matiku, P., Matsuura, K., Maunde, C., Motomura, H., Munroe, T., Nair, R., Obota, C., Polidoro, B., Russell, B., Shaheen, S., Sithole, Y., Smith-Vaniz, W., Uiblein, F., Weerts, S., Williams, A., Yahya, S., Carpenter, K., 2021. The conservation status of marine biodiversity of the Western Indian Ocean. Gland, Switzerland: IUCN. Vii + 32 pp.

Cardeñosa, D., Shea, S.K., Zhang, H., Fischer, G.A., Simpfendorfer, C.A., Chapman, D.D., 2022. Two thirds of species in a global shark fin trade hub are threatened with extinction: conservation potential of international trade regulations for coastal sharks. Conserv. Lett. 15 (5), 12910. https://doi.org/10.1111/conl.12910.

CMFRI., 2024. Fish Catch Estimates. Central Marine Fisheries Research Institute, Kochi, India. Available from https://www.cmfri.org.in/fish-catch-estimates.

Compagno, L.J.V., 1984. FAO species catalogue. Vol. 4, sharks of the world. Part 2, Carcharhiniformes. FAO Fish. Synop. 125 (4), 251–655.

De Crosta, M.A., Taylor, L.R.J., Parrish, J.D., 1984. Age determination, growth, and energetics of three species of carcharhinid sharks in Hawaii. In: pp. (Ed.), Proceedings of the Second Symposium on Resource Investigations of the NW Hawaiian Islands (Grigg, R. W., Tanoue, K.Y., eds). University of Hawaii, Honolulu, HI, pp. 75–95.

Dicken, M.L., Cliff, G., Winker, H., 2016. Sharks caught in the KwaZulu-Natal bather protection programme, South Africa. 13. The tiger shark *Galeocerdo cuvier*. Afr. J. Mar. Sci. 38, 285–301.

Dicken, M.L, Hussey., N.E., Christiansen, H.M., Smale, M.J., Nkabi, N., Cliff, G., Wintner, S.P., 2017. Diet and trophic ecology of the tiger shark (*Galeocerdo cuvier*) from South African waters. PLoS One 12 (6), e0177897. https://doi.org/10.1371/journal.pone.0177897.

Driggers III, W.B., Ingram Jr., G.W., Grace, M.A., Gledhill, C.T., Henwood, T.A., Horton, C.N., Jones, C.M., 2008. Pupping areas and mortality rates of young tiger sharks *Galeocerdo cuvier* in the western North Atlantic Ocean. Aquat. Biol. 2 (2), 161–170. https://doi.org/10.3354/ab00045.

Dulvy, N.K., Baum, J.K., Clarke, S., Compagno, L.J., Cortés, E., Domingo, A., Fordham, S., Fowler, S., Francis, M.P., Gibson, C., Martínez, J., 2008. You can swim but you can't hide: the global status and conservation of oceanic pelagic sharks and rays. Aquat. Conserv. Mar. Freshwat. Ecosyst. 18 (5), 459–482. https://doi.org/10.1002/aqc.975.

Dulvy, N.K., Fowler, S.L., Musick, J.A., Cavanagh, R.D., Kyne, P.M., Harrison, L.R., Carlson, J.K., Davidson, L.N., Fordham, S.V., Francis, M.P., Pollock, C.M., 2014. Extinction risk and conservation of the world's sharks and rays. ELife 3, 00590. https://doi.org/10.7554/eLife.00590.

Dulvy, N.K., Pacoureau, N., Rigby, C.L., Pollom, R.A., Jabado, R.W., Ebert, D.A., Finucci, B., Pollock, C.M., Cheok, J., Derrick, D.H., Herman, K.B., 2021. Overfishing drives over one-third of all sharks and rays toward a global extinction crisis. Curr. Biol. 31 (21), 4773–4787. https://doi.org/10.1016/j.cub.2021.08.062.

Dureuil, M., Aeberhard, W.H., Burnett, K.A., Hueter, R.E., Tyminski, J.P., Worm, B., 2021. Unified natural mortality estimation for teleosts and elasmobranchs. Mar. Ecol. Prog. Ser. 667, 113–129. https://doi.org/10.3354/meps13704.

Ebert, D.A., Fowler, S., Compagno, L., 2013. Sharks of the World: A Fully Illustrated Guide. Wild Nature Press, Plymouth, United Kingdom.

Emmons, S.M., D'Alberto, B.M., Smart, J.J., Simpfendorfer, C.A., 2021. Age and growth of tiger shark (*Galeocerdo cuvier*) from Western Australia. Mar. Freshw. Res. 72 (7), 950–963. https://doi.org/10.1071/MF20291.

Ferreira, L.C., Simpfendorfer, C. 2019. *Galeocerdo cuvier*. The IUCN red list of threatened species 2019: e.T39378A2913541. doi:https://doi.org/10.2305/IUCN.UK.2019-1.RLTS.T39378A2913541.en. (Accessed on 07 November 2024).

Ferreira, L.C., Thums, M., Heithaus, M.R., Barnett, A., Abrantes, K.G., Holmes, B.J., Zamora, L.M., Frisch, A.J., Pepperell, J.G., Burkholder, D., Vaudo, J., 2017. The trophic role of a large marine predator, the tiger shark *Galeocerdo cuvier*. Sci. Rep. 7 (1), 7641. https://doi.org/10.1038/s41598-017-07751-2.

Frisk, M.G., Miller, T.J., Fogarty, M.J., 2001. Estimation and analysis of biological parameters in elasmobranch fishes: a comparative life history study. Can. J. Fish. Aquat. Sci. 58 (5), 969–981. https://doi.org/10.1139/f01-05.

Froese, R. and D. Pauly. (Eds.)., 2024. FishBase. World Wide Web electronic publication. Version (06/2024). https:// www.fishbase.org.

Gallucci, V.F., Taylor, I.G., Erzini, K., 2006. Conservation and management of exploited shark populations based on reproductive value. Can. J. Fish. Aquat. Sci. 63 (4), 931–942. https://doi.org/10.1139/f05-267.

Gayanilo, F.C., Sparre, P., Pauly, D., 2005 The FAO–ICLARM Stock Assessment Tools II (FiSAT II). User's Guide. Revised Version FAO Computerized Information Series (Fisheries): Vol. vol. 8. (Food and Agricultural Organization of the United Nations: Rome, Italy). Available at http://www.fao.org/3/y5997e/y5997e00.htm.

Gulland, J.A., 1970. The fish resources of the ocean. FAO Fisheries Technical Paper Number *97,* Food and Agriculture Organization of the United Nations, Rome, Italy.

Gupta, T., Booth, H., Arlidge, W., Rao, C., Manoharakrishnan, M., Namboothri, N., Shanker, K., Milner-Gulland, E.J., 2020. Mitigation of elasmobranch bycatch in

trawlers: a case study in Indian fisheries. Front. Mar. Sci. 7, 571. https://doi.org/10.3389/fmars.2020.00571.
Gupta, T., Karnad, D., Kottillil, S., Kottillil, S., Gulland, E.M., 2022. Shark and ray research in India has low relevance to their conservation. Ocean Coast. Manag. 217, 106004. https://doi.org/10.1016/j.ocecoaman.2021.106004.
Hammerschlag, N., Gallagher, A.J., Wester, J., Luo, J., Ault, J.S., 2012. Don't bite the hand that feeds: assessing ecological impacts of provisioning ecotourism on an apex marine predator. Funct. Ecol. 26 (3), 567–576. https://doi.org/10.1111/j.1365-2435.2012.01973.x.
Hardin, G., 1968. The tragedy of the commons. Science 162, 1243–1248.
Heithaus, M.R., Frid, A., Wirsing, A.J., Worm, B., 2008. Predicting ecological consequences of marine top predator declines. Trend. Ecol. Evol. 23 (4), 202–210. https://doi.org/10.1016/j.tree.2008.01.003.
Heithaus, M.R., Wirsing, A.J., Dill, L.M., Heithaus, L.I., 2007. Long-term movements of tiger sharks satellite-tagged in Shark Bay, Western Australia. Mar. Biol. 151, 1455–1461. https://doi.org/10.1007/s002270060583-y.
Holland, K.N., Anderson, J.M., Coffey, D.M., Holmes, B.J., Meyer, C.G., Royer, M.A., 2019. A perspective on future tiger shark research. Front. Mar. Sci. 6, 37. https://doi.org/10.3389/fmars.2019.00037.
Holmes, B.J., Peddemors, V.M., Gutteridge, A.N., Geraghty, P.T, Chan, R.W.K., Tibbetts, I.R., Bennett, M.B., 2015. Age and growth of the tiger shark *Galeocerdo cuvier* off the east coast of Australia. J. Fish Biol. 87(2), 422–448. doi:https://doi.org/10.1111/jfb.12732.
Holmes, B.J., Sumpton, W.D., Mayer, D.G., Tibbetts, I.R., Neil, D.T., Bennett, M.B., 2012. Declining trends in annual catch rates of the tiger shark (*Galeocerdo cuvier*) in Queensland. Australia. Fish. Res. 129, 3845. https://doi.org/10.1016/j.fishres.2012.06.005.
Holmes, B.J., Williams, S.M., Otway, N.M., Nielsen, E.E., Maher, S.L., Bennett, M.B., Ovenden, J.R., 2017. Population structure and connectivity of tiger sharks (*Galeocerdo cuvier*) across the indo-Pacific Ocean basin. R. Soc. Open Sci. 4 (7), 170309. https://doi.org/10.1098/rsos.170309.
Hung, S.Y., Huynh, H.H., Tsai, W.P., 2024. Population dynamics of the data-poor tiger shark (*Galeocerdo cuvier*) in the Northwest Pacific Ocean: measurement of growth parameters and mortality rates. Reg. Stud. Mar. Sci. 75, 103526. https://doi.org/10.1016/j.rsma.2024.103526.
Jabado, R.W., Kyne, P.M., García-Rodríguez, E., Charles, R., Armstrong, A.O., Mouton, T. L., Gonzalez-Pestana, A., Battle-Morera, A., Rohner, C.A., 2023. Western Indian Ocean: A Regional Compendium of Important Shark and Ray Areas. IUCN SSC Shark Specialist Group, Dubai. https://doi.org/10.59216/ssg.isra.2023.r7.
Jabado, R.W., Kyne, P.M., Pollom, R.A., Ebert, D.A., Simpfendorfer, C.A., Ralph, G.M., Al Dhaheri, S.S., Akhilesh, K.V., Ali, K., Ali, M.H., Al Mamari, T.M., 2018. Troubled waters: threats and extinction risk of the sharks, rays and chimaeras of the Arabian Sea and adjacent waters. Fish Fish. 19 (6), 1043–1062. https://doi.org/10.1111/faf.12311.
Jabado, R.W., Kyne, P.M., Pollom, R.A., Ebert, D.A., Simpfendorfer, C.A., Ralph, G.M., Dulvy, N.K. (Eds.), 2017. The Conservation Status of Sharks, Rays, and Chimaeras in the Arabian Sea and Adjacent Waters. Environment Agency - Abu Dhabi & IUCN Species Survival Commission Shark Specialist Group, Vancouver, Canada.
Jabado, R.W., Spaet, J.L., 2017. Elasmobranch fisheries in the Arabian seas region: characteristics, trade and management. Fish Fish. 18 (6), 1096–1118. https://doi.org/10.1111/faf.12227.
Jaquemet, S., Smale, M.J., Blaison, A., Guyomard, D., Soria, M., 2012. First observation of a pregnant Tiger shark (*Galeocerdo cuvier*) at Reunion Island, Western Indian Ocean. Western Indian Ocean J. Mar. Sci. 11, 205–207.
Jatmiko, I., Nugroho, S.C., 2020. Biological and population parameters of tiger shark *Galeocerdo cuvier*, landed in Tanjung Luar, West Nusa Tenggara. In: E3S Web Conference 147, 02010. Sciences, EDP.
Karnad, D., Narayani, S., Kottillil, S., Kottillil, S., Gupta, T., Barnes, A., Dias, A., Krishna, Y.C., 2024. Regional hotspots and drivers of shark meat consumption in India. Conserv. Sci. Pract. 6 (1), e13069. https://doi.org/10.1111/csp2.13069.
Kindong, R., Sarr, O., Wu, F., Tian, S., 2022. Length-based assessment methods for the conservation of a pelagic shark, *Carcharhinus falciformis* from the tropical Pacific Ocean. Fishes 7, 184. https://doi.org/10.3390/fishes7040184.
Kneebone, J., Natanson, L.J., Andrews, A.H., Howell, W.H., 2008. Using bomb radiocarbon analyses to validate age and growth estimates for the tiger shark, *Galeocerdo cuvier*, in the western North Atlantic. Mar. Biol. 154, 423–434. https://doi.org/10.1007/s00227-008-0934-y.
Kohler, N.E., Casey, J.G., Turner, P.A., 1995. Length-weight relationships for 13 species of sharks from the Western North Atlantic. Fish. Bull. 93, 411–417.
Lowe, C.G., Wetherbee, B.M., Crow, G.L., Tester, A.L., 1996. Ontogenetic dietary shifts and feeding behaviour of the tiger shark, *Galeocerdo cuvier*, in Hawaiian waters. Environ. Biol. Fish 47, 203–211.
Manuzzi, A., Jiménez-Mena, B., Henriques, R., Holmes, B.J., Pepperell, J., Edson, J., Bennett, M.B., Huveneers, C., Ovenden, J.R., Nielsen, E.E., 2022. Retrospective genomics highlights changes in genetic composition of tiger sharks (*Galeocerdo cuvier*) and potential loss of a South-Eastern Australia population. Sci. Rep. 12, 6582. https://doi.org/10.1038/s41598-022-10529-w.
Meyer, C.G., Dale, J.J., Papastamatiou, Y.P., Whitney, N.M., Holland, K.N., 2009. Seasonal cycles and long-term trends in abundance and species composition of sharks associated with cage diving ecotourism activities in Hawaii. Environ. Conserv. 36, 104–111. https://doi.org/10.1017/S0376892909990038.
Meyer, C.G., O'Malley, J.M., Papastamatiou, Y.P., Dale, J.J., Hutchinson, M.R., Anderson, J.M., Royer, M.A., Holland, K.N., 2014. Growth and maximum size of tiger sharks (*Galeocerdo cuvier*) in Hawaii. PLoS One 9, e84799. https://doi.org/10.1371/journal.pone.0084799.
Moreau, J., Cuende, F.X., 1991. On improving the resolution of the recruitment patterns of fishes. Fishbyte 9, 45–46.
Myers, R.A., Baum, J.K., Shepherd, T.D., Powers, S.P., Peterson, C.H., 2007. Cascading effects of the loss of apex predatory sharks from a coastal ocean. Science 315 (5820), 1846–1850. https://doi.org/10.1126/science.1138657.
Natanson, L.J., Casey, J.G., Kohler, N.E., Colket, T., 1999. Growth of the tiger shark, *Galeocerdo cuvier*, in the western North Atlantic based on tag returns and length frequencies; and a note on the effects of tagging. Fish. Bull. 97 (4), 944–953.
Nurdin, E., Kembaren, D.D., 2023. Stock assessment and management strategies for shark fisheries in the Arafura Sea: a length-based analysis of *Carcharhinus sealei*. Egypt. J. Aquat. Res. 49, 261–267. https://doi.org/10.1016/j.ejar.2023.02.001.
Pacoureau, N., Rigby, C.L., Kyne, P.M., Sherley, R.B., Winker, H., Carlson, J.K., Fordham, S.V., Barreto, R., Fernando, D., Francis, M.P., Jabado, R.W., 2021. Half a century of global decline in oceanic sharks and rays. Nature 589 (7843), 567–571. https://doi.org/10.1038/s41586-020-03173-9.
Parappurathu, S., Ramachandran, C., Menon, M., Baiju, K.K., Rohit, P., Kumar, R.N., Padua, S., Kumar, S., 2020. Harnessing artisanal prowess in offshore fisheries: the case of Thoothoor fishers from India. Mar. Policy 121, 104174. https://doi.org/10.1016/j.marpol.2020.104174.
Pauly, D., 1979. Gill Size and Temperature as Governing Factors in Fish Growth: A Generalization of von Bertalanffy's Growth Formula. Ph.D. Thesis,. Christian-Albrechts-Universität Kiel, Kiel, Germany.
Pauly, D., 1980. On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. ICES J. Mar. Sci. 39, 175–192. https://doi.org/10.1093/icesjms/39.2.175.
Pauly, D., 1984. Fish population dynamics in tropical waters: a manual for use with programmable calculators. ICLARM Stud. Rev. 8, 325.
Pirog, A., Jaquemet, S., Ravigné, V., Cliff, G., Clua, E., Holmes, B.J., Hussey, N.E., Nevill, J.E., Temple, A.J., Berggren, P., Vigliola, L., 2019. Genetic population structure and demography of an apex predator, the tiger shark *Galeocerdo cuvier*. Ecol. Evol. 9 (10), 5551–5571. https://doi.org/10.1002/ece3.5111.
Rajkumar, M., Remya, L., Kizhakudan, S.J., 2021. Tiger shark landed at Mookaiyur fisheries harbour, Tamil Nadu. Mar. Fish. Inf. Serv. Tech. Ext. Ser. 247, 35.
Randall, J.E., 1992. Review of the biology of the tiger shark (*Galeocerdo cuvier*). Mar. Freshw. Res. 43 (1), 21–31. https://doi.org/10.1071/MF9920021.
Reid, D.D., Robbins, W.D., Peddemors, V.M., 2011. Decadal trends in shark catches and effort from the New South Wales, Australia, shark meshing program 1950–2010. Mar. Freshw. Res. 62 (6), 676–693. https://doi.org/10.1071/MF10162.
Richu, A., Dahanukar, N., Ali, A., Ranjeet, K., Raghavan, R., 2018. Population dynamics of a poorly known serranid, the duskytail grouper *Epinephelus bleekeri* in the Arabian Sea. J. Fish Biol. 93 (4), 741–744. https://doi.org/10.1111/jfb.13762.
Roff, G., Brown, C.J., Priest, M.A., Mumby, P., 2018. Decline of coastal apex shark populations over the past half century. Commun. Biol. 1, 223. https://doi.org/10.1038/s42003-018-0233-1.
Rostek, F., Bard, E., Beaufort, L., Sonzogni, C., Ganssen, G., 1997. Sea surface temperature and productivity records for the past 240 kyr in the Arabian Sea. Deep Sea res. Part II: Topical Stud. Oceanogr. 44, 1461–1480.
Santana da Silva, F.M., Lessa, R., Afonso, A.S., Hazin, F.H., Barreto, R.R., 2024. Age and growth of the tiger shark, *Galeocerdo cuvier* (Péron & Lesueur, 1822) from the equatorial South Atlantic Ocean. Research Square. https://doi.org/10.21203/rs.3.rs-4000814/v1.
Sarangdhar, P.N., 1946. On the breeding of the tiger shark (*Galeocerdo tigrinus* Muller & Henle). J. Bom. Nat. Hist. Soci. 461, 192–193.
Sherman, C.S., Simpfendorfer, C.A., Haque, A.B., Digel, E.D., Zubick, P., Eged, J., Matsushiba, J.H., Sant, G., Dulvy, N.K., 2023a. Guitarfishes are plucked: undermanaged in global fisheries despite declining populations and high volume of unreported international trade. Mar. Policy 155, 105753. https://doi.org/10.1016/j.marpol.2023.105753.
Sherman, C.S., Simpfendorfer, C.A., Pacoureau, N., Matsushiba, J.H., Yan, H.F., Walls, R. H., Rigby, C.L., VanderWright, W.J., Jabado, R.W., Pollom, R.A., Carlson, J.K., 2023b. Half a century of rising extinction risk of coral reef sharks and rays. Nat. Commun. 14 (1), 15. https://doi.org/10.1038/s41467-022-35091-x.
Shriram, M., Katkar, B.N., 2004. Landing of tiger shark *Galeocerdo cuvieri* at new ferry wharf, Mumbai. Mar. Fish. Inf. Serv. Tech. Ext. Ser. 179, 22.
Simpfendorfer, C., 1992. Biology of tiger sharks (*Galeocerdo cuvier*) caught by the Queensland shark meshing program off Townsville. Australia. Mar. Fresh. Res. 43 (1), 33–43. https://doi.org/10.1071/MF9920033.
Stevens, J.D., 1984. Biological observations on sharks caught by sport fisherman of New South Wales. Mar. Freshw. Res. 35 (5), 573–590. https://doi.org/10.1071/MF9840573.
Taylor, C.C., 1958. Cod growth and temperature. ICES J. Marine Sci. 23, 366–370. https://doi.org/10.1093/ICESJMS/23.3.366.
Then, A.Y., Hoenig, J.M., Hall, N.G., Hewitt, D.A., 2015. Evaluating the predictive performance of empirical estimators of natural mortality rate using information on over 200 fish species. ICES J. Mar. Sci. 72 (1), 82–92. https://doi.org/10.1093/icesjms/fsu136.
TRAFFIC India., 2024. "Netted in Illegal Wildlife Trade: Sharks of India". Factsheet. TARFFIC India. Available online from https://www.traffic.org/publications/reports/factsheet-netted-in-illegal-wildlife-trade-sharks-rays-and-skates-of-india/ (accessed 08 November 2024).
Varghese, S.P., Unnikrishnan, N., Gulati, D.K., Ayoob, A.E., 2017. Size, sex and reproductive biology of seven pelagic sharks in the eastern Arabian Sea. J. Mar. Biol. Assoc. U. K. 97 (1), 181–196. https://doi.org/10.1017/S0025315416000217.
Vidthayanon, C., 2005. Thailand Red Data: Fishes Office of Natural Resources and Environmental Policy and Planning. Bangkok, Thailand.

Vossgaetter, L., Dudeck, T., Crouch, J., Cope, M., Ivanova, T., Siyan, I., Niyaz, A., Riyaz, M., Araujo, G., 2024. Non-invasive methods characterise the world's largest tiger shark aggregation in Fuvahmulah, Maldives. Sci. Rep. 14, 21998. https://doi.org/10.1038/s41598-024-73079-3.

Ward-Paige, C.A., Mora, C., Lotze, H.K., Pattengill-Semmens, C., McClenachan, L., Arias-Castro, E., Myers, R.A., 2010. Large-scale absence of sharks on reefs in the greater-Caribbean: a footprint of human pressures. PLoS One 5 (8), 11968. https://doi.org/10.1371/journal.pone.0011968.

Wetherall, J.A., Polovina, J.J., Ralston, 1987. Estimating growth and mortality in steady-state fish stocks from length-frequency data. ICLARM Conf. Proc. 13, 53–74.

Wintner, S.P., Dudley, S.F.J., 2000. Age and growth estimates for the tiger shark, *Galeocerdo cuvier*, from the east coast of South Africa. Mar. Freshw. Res. 51 (1), 43–53. https://doi.org/10.1071/MF99077.

Worm, B., Davis, B., Kettemer, L., Ward-Paige, C.A., Chapman, D., Heithaus, M.R., Kessel, S.T., Gruber, S.H., 2013. Global catches, exploitation rates, and rebuilding options for sharks. Mar. Policy 40, 194–204. https://doi.org/10.1016/j.marpol.2012.12.034.

Varghese, S.P., Vijayakumaran, K., Gulati, D.K., 2013. Pelagic megafauna bycatch in the tuna longline fisheries off India. Indian Ocean Tuna Commission (IOTC). 1–15.

Worm, B., Orofino, S., Burns, E.S., D'Costa, N.G., Manir Feitosa, L., Palomares, M.L., Schiller, L., Bradley, D., 2024. Global shark fishing mortality still rising despite widespread regulatory change. Science 383(6679), 225–230. https://www.science.org/doi/https://doi.org/10.1126/science.adf8984.

Xu, Y., Dai, X., Huang, Z., Sun, M., Chen, Z., Zhang, K., 2022. Stock assessment of four dominant shark bycatch species in bottom trawl fisheries in the northern South China Sea. Sustainability 14, 3722. https://doi.org/10.3390/su14073722.

Zhang, C.I., Megrey, B.A., 2006. A revised Alverson and carney model for estimating the instantaneous rate of natural mortality. Trans. Am. Fish. Soc. 135 (3), 620–633. https://doi.org/10.1577/T04-173.1.