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BEYOND SIZE: ASSESSING THE STATUS OF THREE ELASMOBRANCHS IN SRI LANKAN WATERS USING LENGTH-BASED SPAWNING POTENTIAL RATIO

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ABSTRACT

The status of three elasmobranch species, *Carcharhinus falciformis*, *Neotrygon indica*, and *Glaucostegus granulatus*, in Sri Lankan waters was assessed through a comprehensive study incorporating biometric analyses and assessment using the length-based Spawning Potential Ratio (LBSPR). Biometric analyses included examining length-frequency distributions, length-weight relationships, and maturation data (L_{50} and L_{95}) for all species. Notably, this study provided the first investigation into the biological aspects of *N. indica* and *G. granulatus* in Sri Lankan waters. Trained researchers collected biometric data (length, weight, and sexual maturity) of all three study species from November 2017 to December 2023. The length-weight relationships revealed a positive allometric growth pattern ($b > 3$) for all three species. The study estimated L_{50} to be 196.5 cm for male (n=370) *C. falciformis*. For *N. indica*, the estimated L_{50} was 34.1 cm for females (n=76) and 30.2 cm for males (n=2,356). For *G. granulatus*, the estimated L_{50} was 82.2 cm for females (n=45) and 68.6 cm for males (n=288). The study revealed that high fishing pressure has resulted in an overfished condition for both *C. falciformis* and *N. indica*, with the mean spawning potential ratios (SPR) being below the limit reference point of 20% SPR. For *C. falciformis*, the SPR was 7%, indicating overfishing, while for *N. indica*, the SPR ranged from 14% to 27% from 2018 to 2023, with the 2023 value exceeding the limit reference point. A stock rebuilding strategy would be required to increase the spawning stock biomass of both species. Potential management strategies for the conservation of elasmobranch populations in Sri Lankan waters include implementing a minimum legal size for harvest, establishing marine protected areas, and implementing effort controls.

Keywords: Elasmobranch, *Carcharhinus falciformis, Neotrygon indica, Glaucostegus granulatus,* Spawning Potential Ratio (SPR), Length-based stock assessment, Sri Lanka.

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ABBREVIATIONS

BRT	Blue Resources Trust
CITES	Convention on the International Trade in Endangered Species of Fauna and Flora
CMS	Convention on Migratory Species
CMSY	Catch-based surplus production model
DFRA	Department of Fisheries and Aquatic Resources
EEZ	Exclusive Economic Zone
FARA	Fisheries and Aquatic Resources Act
GDP	Gross Domestic Product
IOTC	Indian Ocean Tuna Commission
IUCN	International Union for Conservation of Nature
LBSPR	Length-based Spawning Potential Ratio
LRP	Limit Reference Point
MFARD	Ministry of Fisheries and Aquatic Resources Development
MSY	Maximum Sustainable Yield
NARA	National Aquatic Resources Research and Development Agency
NPOA	National Plan of Action
SPR	Spawning Potential Ratio
TRP	Target Reference Point
UNCLOS	United Nations Convention on the Law of the Sea
UNESCO	United Nations Educational, Scientific and Cultural Organization

1 INTRODUCTION

1.1 Background

Sri Lanka is an island nation situated in the Indian Ocean southwest of the Bay of Bengal. Sri Lanka is located between the northern latitudes of 5° 55' and 9° 51' and the eastern longitudes of 79° 41’ to 81° 53’, giving it a strategic location along major maritime routes (Joseph, 2001; Kodikara et al., 2017). As an island nation, Sri Lanka has an extensive coastline that spans almost 1600 km. The country possesses an extensive maritime territory in proportion to its total land area (Figure 1)**Error! Reference source not found.**. The exclusive economic zone (EEZ) of Sri Lanka is approximately 7.8 times (517,000 km2) the size of its total land area (65,610 km2) (Bandara & Radampola., 2017; Joseph., 2001).

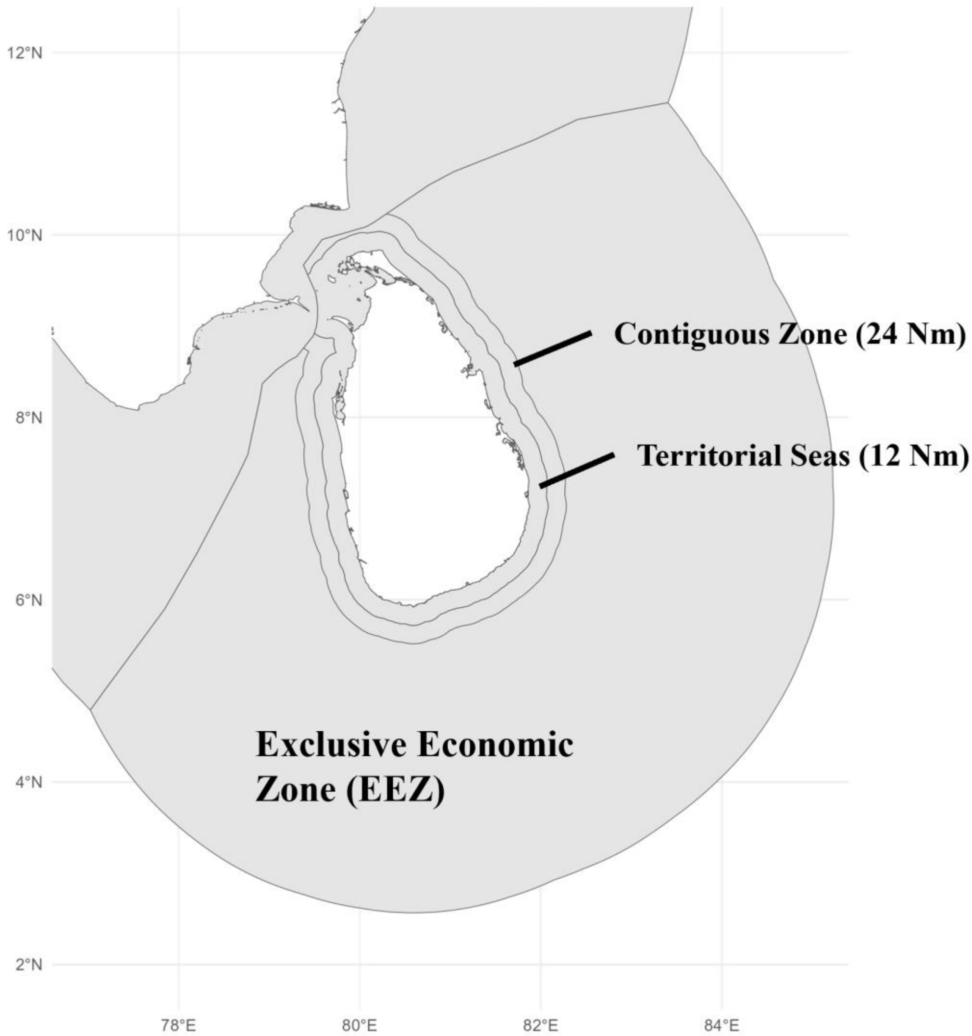

Figure 1: Map of Sri Lanka with major marine zonations.

Sri Lanka has various coastal and offshore habitats, including estuaries, lagoons, mangroves, seagrass beds, salt marshes, coral reefs, beaches, and deep-sea canyons. As a tropical island, its surrounding waters contain a great diversity of marine organisms, including elasmobranchs (Joseph, 2001).

The fisheries sector plays a significant role in the economy of Sri Lanka, with marine capture fisheries contributing approximately 1.1% of the GDP. Sri Lankan marine capture fisheries are divided into two categories: coastal or artisanal fisheries and offshore or commercial fisheries. Coastal fisheries contribute over 58% of marine fishery products (MFARD, 2022). Fishing is the primary source of income for the majority of coastal villages and provides a significant amount of protein in the diet of the country´s inhabitants. There are 224,190 active fishermen involved in this sector, and the annual marine fish production was 331,675 metric tons in 2021 (Bandara & Radampola, 2017; MFARD, 2022).

Shark and ray fisheries in Sri Lanka are of considerable importance to the fisheries sector. The majority of elasmobranch landings are incidental catches; however, some fisheries target elasmobranchs. Some examples include the deep-sea shark fishery that targets Gulper Sharks for liver oil production, the bottom-set gillnet fishery that targets stingrays, and the remaining fleet of shark longline fishery (Herath & Maldeniya, 2013, BRT unpublished data). Fresh and dry meat of sharks and rays has popular demand in the Sri Lankan domestic market, and as such, fishers never discard their carcasses at sea (Herath & Maldeniya, 2013).

1.2 Justification

The International Union for Conservation of Nature (IUCN) carried out an assessment of the extinction risk of chondrichthyans. The assessment included 1,199 species, and the results showed that more than one-third of chondrichthyans, including sharks, rays, and chimaeras, are threatened with extinction globally (Dulvy et al., 2021). Overfishing is the primary threat to the majority of sharks and rays and is a key threat to all 391 threatened species. Over 50% of the threatened sharks and rays were widely used for human consumption. The international demand for shark fins and mobulid gill plates, and the expanding local market for elasmobranch meat consumption have spurred unregulated fisheries and the overexploitation of these species on a global scale (Jabado et al., 2018). In addition to human consumption, they have been used for various purposes, including animal food, leather/material production, medicine, and aquarium livestock (Dulvy et al., 2021; Jabado et al., 2018).

Until the 1990s, the shark fishery in Sri Lanka targeted several species, such as the Silky Shark, Bull Shark, Oceanic Whitetip Shark, and Thresher Sharks (Hasarangi et al., 2012). However, there has been a shift in recent decades because of the continuous exploitation of the shark population, and they are now predominantly caught as bycatch (Herath & Maldeniya, 2013). Since August 2017, the Blue Resources Trust (BRT) has systematically gathered elasmobranch data across the country. According to the BRT national database, there are 102 species of elasmobranchs in Sri Lankan waters, comprising 52 shark species (belonging to five orders and 19 families) and 50 ray species (belonging to four orders and 13 families). They are predominantly landed as non-discarded bycatch in both artisanal and commercial gillnet, longline, purse seine, and trawler fisheries. In addition to documenting small-scale shark target fisheries, the organisation has recorded the presence of seasonal fisheries that target stingrays throughout the country (Herath & Maldeniya, 2013; BRT unpublished data).

Most elasmobranchs are considered highly vulnerable to overexploitation because of their conservative life histories, which include slow growth rates, long lifespans, late sexual maturity, and the birth of a few pups in each reproductive cycle (Dulvy et al., 2014; Hoenig & Gruber, 1990). Because of these traits, elasmobranch populations can be depleted at a much faster rate than many teleost populations. Once these populations decline, they cannot recover quickly, even with a reduction in fishing pressure (Hutchings & Reynolds, 2004).

Recent declines in the populations and catches of many species of elasmobranchs have highlighted the importance of implementing management measures for these species (Dulvy et al., 2021). Fish stock assessment is a crucial step in determining the status of a population, which is necessary for effective fishery management. Understanding the population dynamics of a stock and how these dynamics are affected by exploitation is vital for the effective management of elasmobranchs. Information on catch, effort, relative abundance, and various life history parameters (length distributions, age structure, and mortality rates) is usually required for a comprehensive stock assessment (Gervasi et al., 2023). For data-rich stocks with reliable landing records and robust fishery-independent data, full stock assessments can be conducted using age-based or integrated models (Legault et al., 2023).

However, in Sri Lanka, as in most developing countries, there is a substantial lack of fisheries-independent data for most fish species, including commercially important fish. Another challenge for elasmobranch stock assessments is the difficulty in reliably estimating the age of individuals. Elasmobranch age estimation is not straightforward because they lack otoliths, which are normally used for age estimation in bony fish. Age estimation in elasmobranchs is based on translucent and opaque bands found in calcified parts, such as vertebrae and dorsal spines (Goldman, 2005). Recent studies using bomb radiocarbon (14C) dating to validate the age of elasmobranch species have revealed uncertainties in age estimation when relying on hard structures of elasmobranchs, such as vertebrae and dorsal spines (Andrews & Kerr, 2015). These elasmobranch ageing methods require advanced technologies which are often not available in many developing countries such as Sri Lanka due to a lack of advanced infrastructure and financial resources.

In small-scale and data-limited fisheries, where acquiring age data is frequently hindered by a lack of technical expertise and financial constraints, researchers and managers often rely solely on length composition data as the primary source of information for stock assessments. Therefore, the available data must be assessed and appropriate data-limited methods selected to achieve reliable estimates of stock status with the available data (Legault et al., 2023; Prince et al., 2015).

1.3 Objectives of the study

The primary goal of this study is to assess the status of three elasmobranch species (*Carcharhinus falciformis*, *Neotrygon indica* and *Glaucostegus granulatus*) found in Sri Lankan waters. The assessments will be conducted using the Length-Based Spawning Potential Ratio (LBSPR) method, which can potentially contribute to national elasmobranch management. The specific goals of the objectives include:

- Characterisation of length-frequency distributions
- Estimation of length-weight relationships
- Estimation of maturation parameters
- Calculation of exploitation rates using the Length-Based Spawning Potential Ratio (LBSPR)

The first three points involve data exploration and establishing empirical relationships that can be used as inputs for stock assessment models. The final point involves applying the LBSPR to each stock using raw data and parameter estimates obtained from previous analyses.

2 LITERATURE REVIEW

2.1 Elasmobranchs

Elasmobranchii is a subclass of Chondrichthyes fish that comprises sharks (superorder Selachii), rays, and skates (superorder Batoidea). Elasmobranchs form a distinct group known for their anatomical features, particularly the absence of bony skeletons replaced entirely by cartilage, providing flexibility and reduced weight compared to bony fish. They have 5-7 pairs of gill slits for respiration. Unlike bony fish, they do not have a swim bladder and rely on their fatty liver for buoyancy. With over 1,200 species, elasmobranch fishes are distributed worldwide, predominantly occupying various ecological niches within marine ecosystems, from coastal areas to deep-sea environments, but are also found in brackish water and even in freshwater systems (Ebert et al., 2021; Last et al., 2016).

Many elasmobranchs are apex predators that exhibit specialised adaptations for hunting and capturing prey. Sharp teeth, powerful jaws, and keen senses contribute to their success as predators. All elasmobranchs require internal fertilisation, but they exhibit various reproductive strategies. Some species lay eggs (oviparous), whereas others give birth to live young (viviparous). There are also species that use a combination of these strategies; without a placental connection, embryos develop within the uterus or egg capsule and hatch internally before the offspring are born (ovoviviparous) (Conrath, 2005; Ebert et al., 2021; Last et al., 2016).

2.2 Study species

2.2.1 Silky Shark

The Silky shark (*Carcharhinus falciformis*) belongs to the family Carcharhinidae within the order Carcharhiniformes. They are a highly migratory elasmobranch species with a broad distribution in pelagic and offshore environments. Found in tropical and subtropical waters, including the Atlantic, Pacific, and Indian Oceans, it has a wide-ranging habitat that underscores its adaptability to diverse oceanic conditions. *C. falciformis* is currently listed as vulnerable (VU) on the International Union for Conservation of Nature (IUCN) Red List (Bernard et al., 2016; Rigby et al., 2017).

C. falciformis has a streamlined and slender body with a characteristic silky texture to their skin. They are known for their distinct sickle-shaped pectoral fins and relatively large second dorsal fins (Figure 2)Figure 2: Lateral view of a silky shark (Carcharhinus falciformis). *C. falciformis* attains a maximum total length of 350 cm, and males are generally smaller than females (Varghese et al., 2016). *C. falciformis* is a predator, and its diet primarily consists of teleost fish, cephalopods, and a small percentage of crustaceans, turtles, and small sharks (Estupiñán-Montaño et al., 2018; Filmalter et al., 2017; Flores-Martínez et al., 2017). *C. falciformis* is viviparous and gives birth to live young, with litters typically ranging from two to 18 pups per litter (Clarke et al., 2015).

C. falciformis is estimated to be the second most dominant shark species caught in the Indian Ocean region (Cramp et al., 2021). It is also the second most common shark contributing to the global shark fin trade in the world's largest shark fin markets in Hong Kong (Cardeñosa et al., 2018; Fields et al., 2017). *C. falciformis* is the major bycatch species among pelagic sharks in both industrial and artisanal fisheries in Sri Lanka, predominantly using drift gillnets, tuna longlines, and purse seine (Balawardhana et al., 2023; Cramp et al., 2021). The south and west coasts of Sri Lanka contribute to a major part of the *C. falciformis* landings from the industrial tuna fishery. Cramp et al. (2021), was done prior research to estimate the biomass of the *C. falciformis* stock in the Indian Ocean by using a catch-based surplus production model (CMSY). According to the findings of this study, the current stock status of *C. falciformis* in the Indian Ocean is uncertain; it is either overfished or overfishing is taking place.

Figure 2: Lateral view of a silky shark (Carcharhinus falciformis).

2.2.2 Indian Ocean Bluespotted Maskray

The Indian Ocean Bluespotted Maskray (*Neotrygon indica*) is a member of the family Dasyatidae, situated within the order Myliobatiformes and the genus Neotrygon. The genus Neotrygon, commonly known as Maskrays and distributed in the Indo-West Pacific Ocean, comprises 11 described species, including *N. indica*, which was recently described by Pavan Kumar and team in 2018 (Borsa et al., 2018; P. R. Last & White, 2008; Pavan-Kumar et al., 2022). Earlier, all blue-spotted mask rays were classified as a single species, *Neotrygon kuhlii*. However, recent genetic sequencing studies have restructured the genus *Neotrygon* and confirmed that they are closely related but different species (Fernando et al., 2019; Pavan-Kumar et al., 2022).

N. indica is a small stingray, which typically has a flattened body with a circular disc and the dorsal surface is adorned with distinctive blue spots (Figure 3: Dorsal view of the Indian Ocean bluespotted maskray (Neotrygon indica)). This species was recently described, and there are not many detailed studies about them, nor has it been evaluated by the IUCN. Fernando et al. (2019) confirmed the presence of *N. indica* in Sri Lankan waters. *N. indica* is the most frequently encountered elasmobranch species in Sri Lanka as a target or bycatch of small-scale artisanal fisheries. *N. indica* are most abundant shallow continental shelf regions and they were identified as viviparous with litter sizes of 1–2 pups (BRT unpublished data).

Figure 3: Dorsal view of the Indian Ocean bluespotted maskray (Neotrygon indica).

2.2.3 Sharpnose Guitarfish

The sharpnose guitarfish (*Glaucostegus granulatus*) is a medium-range giant guitarfish classified within the order Rhinopristiformes. Rhinopristiformes can be referred to as 'shark-like' rays because their phylogenetic position is closer to rays, but their morphology is more similar to that of sharks. *G. granulatus* has a geographical distribution restricted to the Northern Indian Ocean region, where it is estimated that >80% of the population has declined (Kyne et al., 2020, 2022). They inhabit a variety of coastal environments and more often found in shallow coastal waters, can be found in relatively shallow waters. They may occur at depths ranging from the intertidal zone to 120 m on the continental shelf. The *G. granulatus* is one of seventeen critically endangered rhino rays. They have been exploited as incidental catches, leading to severe population declines and several localised disappearances (Jabado et al., 2018; Kyne et al., 2022; Moore, 2017).

The sharpnose guitarfish has a distinctive appearance with a flattened body and pointed snout, which gives it the name 'sharpnose' (Figure 4)Figure 4: Dorsal view of a sharpnose guitarfish (Glaucostegus granulatus). *G. granulatus* attains a maximum total length of 229 cm and males are generally smaller than females. They are viviparous, with litter sizes of 6–18 pups (Kyne et al., 2022). The *G. granulatus* is a benthic species with a diet that primarily consists of various benthic invertebrates, small fishes, and crustaceans. It is a bottom-dwelling species. Apart from one feeding ecology study conducted in the Eastern Arabian Sea, there have been no other biological studies on *G. granulatus* globally.

Figure 4: Dorsal view of a sharpnose guitarfish (Glaucostegus granulatus).

2.3 Management plans for sharks and rays in Sri Lanka

The Fisheries and Aquatic Resources Act, No. 2 of 1996 (FARA), is the primary tool for the regulation, development, conservation, and management of Sri Lankan fisheries. Sri Lanka is a party to several regional and international committees, such as the Indian Ocean Tuna Commission (IOTC), Convention on Migratory Species (CMS), Convention on the International Trade in Endangered Species of Fauna and Flora (CITES), and the United Nations Convention on the Law of the Sea (UNCLOS). Sri Lanka has established various national instruments, encompassing policy guidelines, laws, regulations, and action plans, to fulfil the commitments outlined in the aforementioned treaties (SLNPOA-Sharks, 2013).

Through a series of amendments, five species of sharks are nationally protected, including the oceanic whitetip shark (*Carcharhinus longimanus*), whale shark (*Rhincodon typus*), and three species of thresher sharks from the family Alopiidae (*Alopius vulpinus*, *A. superciliosus*, and *A. pelagicus*) (SLNPOA-Sharks, 2013). In 2019, the IOTC adopted resolution 19/03 on the conservation of mobulid rays caught in association with fisheries in the IOTC area of competence. It prohibits the intentional setting of any gear type for mobulid rays in the IOTC Area of Competence and the retention of these species. However, it has not yet been implemented in national law (IOTC, 2019).

2.4 Data-limited stock assessment methods

Traditional stock assessments rely on comprehensive and detailed biological, ecological, and catch data. These assessments often involve collecting information on age structure, growth rates, reproductive parameters, and historical catch data of the species. Data-limited stock assessment methods are crucial for managing fisheries where comprehensive data on the population dynamics and biology of the target species are limited (Gervasi et al., 2023; Legault et al., 2023; Prince et al., 2015). These methods aim to provide reliable estimates of stock status and inform sustainable management practices, despite the scarcity of traditional data. Data-limited assessment methods, including the length-based Thompson and Bell (TB) model (Thompson & Bell, 1934), length-based spawning potential ratio (LBSPR) (Hordyk et al., 2015), length-based integrated mixed effects (Rudd & Thorson, 2018), and length-based risk analysis (Ault et al., 2019), are gaining prominence in management practices for reporting the regional status of fish stocks (Chong et al., 2020).

In small-scale and data-poor fisheries, age data are frequently hindered by a lack of technical expertise and financial constraints. The lack of clarity on defined annual growth rings in otoliths or other hard parts makes it more challenging to estimate the age of tropical fish species. Owing to the above constraints, researchers and managers often turn to length composition data as their primary source of information (Hordyk et al., 2015; Prince et al., 2015).

2.5 Length-Based Spawning Potential Ratio (LBSPR)

Over the past decade, the Length-Based Spawning Potential Ratio (LBSPR) has become a popular method for approaching fisheries stock assessments in data-limited situations. Hordyk et al. (2015) first introduced, described, and validated the LBSPR model through simulations and subsequently Prince et al. (2015) applied the model to real data and showed the pros and cons of the model.

The spawning potential ratio (SPR) serves as a reliable and well-established biological reference point, offering crucial estimates that can inform management decisions, particularly in the context of data-limited fisheries. The SPR index functions as a key index, reflecting the relative rate of reproduction within an exploited stock, and is widely used as an instant management tool to set target and limit reference points for fisheries (Hordyk et al., 2015).

The implementation of the LBSPR model requires several key inputs, such as the annual length composition of the catch, life history parameters such as natural mortality (M/k) and asymptotic length (L_{inf}), and estimates of lengths at maturity (L_{50} and L_{95}). The LBSPR uses life history ratios to describe length composition, spawning-per-recruit, and spawning potential ratio to estimate the SPR of a stock directly from the size composition of the catch.

Previous studies that used the LBSPR model for elasmobranch stocks are listed in Table 1.

Table 1: Recent stock assessment studies on sharks using the LBSPR model.

Year of publication	Study region	Study species	MK	Citation
2023	Lampung Bay waters, Indonesia	*Sphyrna lewini*	0.18/K	(Nugraha et al., 2023)
2022	Tropical Pacific Ocean	*Carcharhinus falciformis*	2.983	(Kindong et al., 2022)
2022	West Java	*Carcharhinus sealei*	0.805	(Nurdin et al., 2023)
2022	Biscay and Iberian Coast	*Scyliorhinus canicula*	1.5	(Cousido-Rocha et al., 2022)

All four studies were recent attempts to use length-based data-limited methods for each shark species. Nugraha et al. (2023) applied the LBSPR model to scalloped hammerhead sharks in

Lampung Bay waters, and the results indicated that the stock was fully exploited in a recruitment overfishing condition. Kindong et al. (2022) applied two models, LBSPR and LBB (Length-Based Bayesian biomass), and the results indicated that silky shark stock was in an overfished state with a low reproductive potential.

Nurdin et al. (2023) employed the SPR model, and the results indicated that the spawning potential ratio of the blackspot shark was below the optimal level. This suggests that the spawning biomass of blackspot sharks is insufficient to sustain ideal stock replacement. Cousido-Rocha et al. (2022) applied two models, LBSPR and Length-Based Index (LBI), and the LBI findings highlighted that the small-spotted catshark stock is exploited close to the MSY level. The LBSPR results showed that their stock was not exploited at the MSY level but was close to collapse. It should be noted that the indicators for each method were not the same. However, length measurement data do not represent juveniles, which may explain some biased observations in LBI.

3 METHODOLOGY

3.1 Study site

Since November 2017, the Blue Resources Trust (BRT) has been conducting landing site surveys across the country. Surveys were conducted at fishing harbours, beach fish landing sites, beach fish markets, and central fish markets. Owing to the high number of survey sites and some being close to each other, the nearest sites were grouped based on the closest towns and similar fishing practices. As a result, 19 different survey sites were listed in Sri Lanka (Figure 5)Figure 5: Map of Study locations: All points show main survey sites around Sri Lanka

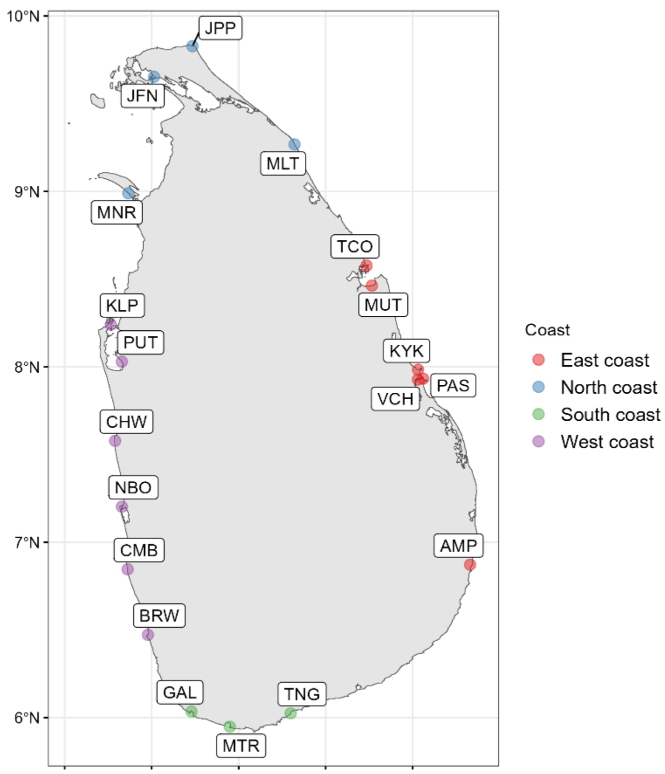

Figure 5: Map of Study locations: All points show main survey sites around Sri Lanka and different coloured points based on the part of the coast. Three letter codes are unique code developed by BRT for the documentation.

and different coloured points based on the part of the coast. Three letter codes are unique code developed by BRT for the documentation.. Markets were indicated by a unique three-letter code developed by the Blue Resources Trust.

3.2 Sources of data

This study used two types of data: length frequency distributions (landings) and empirical (life history and maturity) data from either Blue Resources Trust (BRT) or reliable sources such as peer-reviewed journals.

Between November 2017 and December 2023, the BRT surveyed for a total of 2,969 days throughout Sri Lanka. Landing site surveys were conducted by trained field researchers from the BRT, who followed a systematic survey protocol developed by the BRT expert team. For data collection, each responsible researcher visited different landing sites based on a pre-planned survey schedule. The visit time was dependent on the active fish landing or fish market time. During the survey, data were collected on each elasmobranch specimen landed at the market, including identification photographs, size measurements, sex, maturity of males, fishing gear caught in, and catch location, if possible (Figure 6)Figure 6: Elasmobranchs length and weight data collection by BRT researchers at the fish markets.. Male maturity was recorded based on clasper calcification. Details of female maturity were not recorded because females do not have any clear external features to indicate their maturity unless they are pregnant.

The maturity of male elasmobranchs was assessed externally based on clasper size and the

Figure 6: Elasmobranchs length and weight data collection by BRT researchers at the fish markets.

extent of calcification, and for females, by the size and expansion of the uterus, as adapted from various studies (Alahyene et al., 2022; Osaer et al., 2015; Pierce et al., 2009; Powter & Gladstone, 2008) (Table 2)Table 2. Male maturity stages were classified into three stages of sexual development, and females were classified into four stages of sexual development. Therefore, male maturity data for all three species were collected in the field. Female maturity data are only available for *G. granulatus* and *N. indica*; these data were collected from short-term projects conducted during the data collection period.

Table 2: Determining female and male maturity; males based on claspers, and females based on the visual state of the ovary and uterus during dissection.

Sex		stage	Classification
Males	**1**	Clasper not calcified; it is very short and does not extend the tip of the pelvic fin	Immature I
	2	Clasper is partially calcified and flexible; it is longer and extends the tip of the pelvic fin	Immature II
	3	Clasper is fully calcified; it is long and hard along almost the entire length	Mature
Females	**1**	Ovaries small and without yoked eggs, uterus very thin	Immature I
	2	Ovaries becoming larger and small yoked eggs developing. Uterus slightly becoming enlarged at one end	Immature II
	3	Ovaries containing some large, yoked eggs. Uterus large along entire length	Mature
	4	Pregnant: Uterus containing embryos or large eggs	Mature

Through the overall data collection, 102 species of elasmobranchs were documented, comprising 52 shark species (belonging to five orders and 19 families) and 50 ray species (belonging to four orders and 13 families). In this study, three elasmobranch species were selected from the 102 species due to their special concerns. Species with the maximum number of individual length data points were prioritised, with one species chosen from each group. Specifically, *Carcharhinus falciformis* was selected from the shark group, *Neotrygon indica* from the ray group, and *Glaucostegus granulatus* from the rhino rays. Data for the selected study species were filtered from the BRT national database and organised for empirical analyses. All statistical analyses were performed using the R programming language (version: RStudio/2023.12.1+402).

3.3 Empirical analyses of study species

3.3.1 Morphometric data analysis (Length frequency distributions)

Total length data was used for the analysis of length frequency distributions for *C. falciformis* and *G. granulatus*, while disc width was used for *N. indica*. A Welch two-sample t-test was performed to assess whether there were significant differences in the mean length among different sexes, and a one-way analysis of variance (ANOVA) was performed to assess whether there were significant differences in the mean length among different years (2018-2023).

3.3.2 Length-weight relationships

The length-weight relationship for all three species (*C. falciformis*, *N. indica, and G. granulatus*) was estimated separately for both sexes by applying the following regression equation (Ricker, 1975) to the sex-specific weight-length pairs for each species:

$$W = aL^b$$

where W is total weight (kg), L is total length (cm) for *C. falciformis* and *G. granulatus* and disc width (cm) for *N. indica*. The coefficients "a" and "b" correspond to the linear coefficient and slope, respectively.

A Welch two-sample t-test was performed to assess whether there were significant differences in the mean weight among different sexes, and an ANOVA was performed to investigate the influence of length (TL) and sex on the weight (W) of *C. falciformis*.

3.3.3 Maturity analysis (L_{50}, L_{95})

The maturity observations were converted to binary values, with a value of "0" if they are immature and "1" if mature. Logistic regression models were chosen because they are suitable for binary response variables and are commonly used in maturation studies. For each species, a logistic regression model was fitted to the maturation data. The "glm" function from the "stats" package in R was used for model fitting. The key parameters L_{50} and L_{95} were estimated from the fitted logistic regression models, which corresponded to the lengths at which 50% and 95% of the stock were expected to be mature, respectively.

3.3.4 Growth parameters (L_{inf} and k)

3.3.4.1 Asymptotic length (L_{inf})

Estimating the asymptotic length directly is a difficult task without reliable length and age data. Therefore, L_{inf} was calculated using the rule of thumb derived by Pauly (1984), which defined the asymptotic length to be approximately 5% longer than the maximum observed length.

$$Linf = \frac{Lmax}{0.95}$$

where L_{inf} is the asymptotic length (cm) and L_{max} is the maximum observed length (cm) of the species. In this equation, here, L_{max} for *C. falciformis* and *G. granulatus* is the maximum total length (cm) and for *N. indica* L_{max} is the maximum disc width (cm).

3.3.4.2 Growth coefficient (k)

Because of the absence of reliable length and age data, the growth coefficient (k) was taken from previous studies and utilised to calculate the MK value, which serves as one of the input parameters in the LB-SPR model (**Error! Reference source not found.**). For *C. falciformis*, estimates of k were taken from the study by Hall et al. (2012) which conducted a comprehensive evaluation of various empirical data such as L_{max}, L_{inf}, L50, and L95. This study was chosen because its empirical data closely resembled the results of our current study (Hall et al., 2012). There have been no biological studies of *N. indica* which have estimated k. Therefore, the value of k was taken from a study of *N. kuhlii* (Jacobsen & Bennett, 2010) which belongs to the same family and genus and has similar biological characteristics.

Table 3: Empirical parameters drawn from (Hall et al. (2012) and Jacobsen and Bennett (2010)) to evaluate the reliability of the data to use the growth coefficient (k) for the current study.

Parameters	*C. falciformis* (*Hall et al., 2012*)	*N. kuhlii* (Jacobsen & Bennett, 2010)
Maximum length (L_{max})	♂ 240.9 cm (TL)	♂ 35.00 cm (DiscW)
	♀ 262.3 cm (TL)	♀ 40.20 cm (DiscW)
Length–weight relationship parameter (a)	♂ $1{\cdot}580 * 10^{-6}$	$0.505 *10^{-6}$
	♀ $2{\cdot}045 * 10^{-6}$	
Length–weight relationship parameter (b)	♂ 3.157	2.913
	♀ 3.129	
Lengths at maturity-50% (L_{50})	♂ 207.6 cm (TL)	♂ 28.54 cm (DiscW)
	♀ 215.6 cm (TL)	♀ 26.68 cm (DiscW)
Lengths at maturity-95% (L_{95})	♂ 221.9 cm (TL)	♂ NA
	♀ 223.9 cm (TL)	♀ NA
Asymptotic length (L_{inf})	♂ 277.3 cm (TL)	♂ 43.86 cm (DiscW)
	♀ 320.4 cm (TL)	♀ 44.06 cm (DiscW)
Growth coefficient (k)	0.066	0.08

3.3.5 Estimation of natural mortality (M)

The natural mortality of *C. falciformis* and *N. indica* was estimated using the online natural mortality tool developed by Cope & Hamel (2022). This tool contains multiple empirical estimators of natural mortality using various combinations of biological parameters. In this study, L_{inf} and k were given as input parameters which resulted in four estimates of M for each species.

3.4 Length-Based Spawning Potential Ratio (LBSPR)

The LBSPR model requires a series of length composition data from each species, as well as species-specific life history parameters (Hordyk et al., 2015). The assessment was performed using the Length-Based Spawning Potential Ratio concept developed by Hordyk et al. (2014). This was implemented using the R package LBSPR (Hordyk, 2021), representing the proportion of unfished reproductive potential at a given level of fishing pressure. As suggested by Hordyk et al. (2015), a target of 40% was set to maintain a healthy stock, with a reference point of 20% established as the limit for exploitation.

Empirical analysis of *G. granulatus* showed that there was a lack of length frequency data from 2018-2020 and 2023 to run the LBSPR model. In the current study, LBSPR analysis was performed only for *C. falciformis* and *N. indica*, and female empirical data were used as input parameters. These included asymptotic length (L_{inf}), parameters for size-at-maturity (L_{50} and L_{95}), linear coefficient (a), slope (b), growth coefficient (k), and natural mortality (M).

The LBSPR model was first fitted to the length distribution data of *C. falciformis* and *N. indica*. The model estimated selection-at-length (SL_{50}), relative fishing mortality (F/M), and Spawning Potential Ratio (SPR). Subsequently, the model fits to the annual length distributions were plotted to visually assess how well the model fit the data. Additionally, the maturity ogive and estimated selection patterns for each year were compared to determine the immature stock removal. To assess the stock status, the estimated SPR values were compared against the SPR target values such as 20% and 40%. Furthermore, several sensitivity analyses were conducted to determine how sensitive the estimated SPR is to assumptions made about growth and natural mortality. These analyses provide insights into the robustness of the model and the implications of different assumptions on the assessment results.

4 RESULTS AND DISCUSSION

4.1 Empirical analyses of study species

4.1.1 Length frequency distribution

4.1.1.1 C. falciformis

In total, 1,984 individuals were recorded during the survey period, and 719 length measurements were collected and used in this study (male= 370, female=349). The length frequency distribution of *C. falciformis* caught in Sri Lankan waters is shown in Figure 7: A- Overall length frequency distribution of C. falciformis, B- Year-wise length frequency

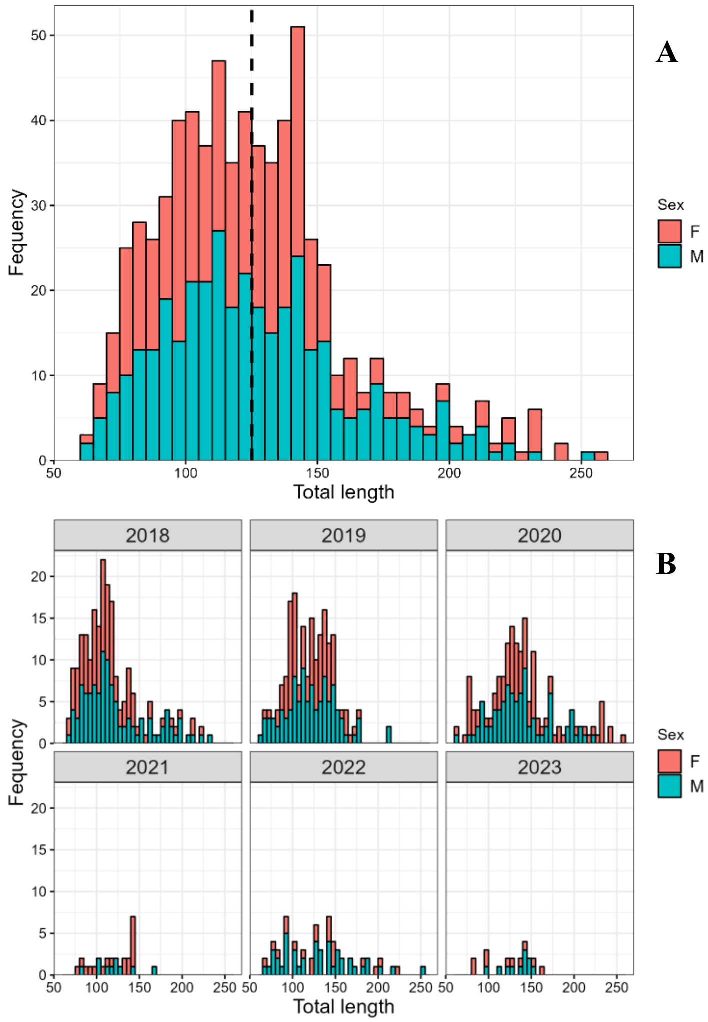

Figure 8: A- Overall length frequency distribution of C. falciformis, B- Year-wise length frequency distribution of C. falciformis. The dashed black line in A shows the overall mean length (124.99 cm).

distribution of C. falciformis. The dashed black line in A shows the overall mean length (124.99 cm)..

The total length (TL) of male *C. falciformis* ranged from 64 to 253 cm, with a mean length of 126 ± 35.4 cm. For females, the TL ranged from 63.5 to 256 cm, with a mean length of 124 ± 35.9 cm. The results of the Welch two-sample t-test revealed no significant difference in mean length between male and female *C. falciformis* ($t = 0.78494$, $df = 713.27$, $p = 0.4328$). The 95% confidence interval for the difference in means ranged from -3.134 to 7.310. The ANOVA test results revealed a significant effect of year on the total length of *C. falciformis* (F (6, 727) = 8.375, p < 0.001).

4.1.1.2 N. indica

In total 12,569 individuals were recorded during the survey period and from that 2,902 length measurements were collected and used in this study (male= 1,426, female=1,476). The length frequency distribution of *N. indica* caught in Sri Lankan waters is summarised in Figure 8: A-Overall length frequency distribution of N. indica, B- Year wise length frequency distribution

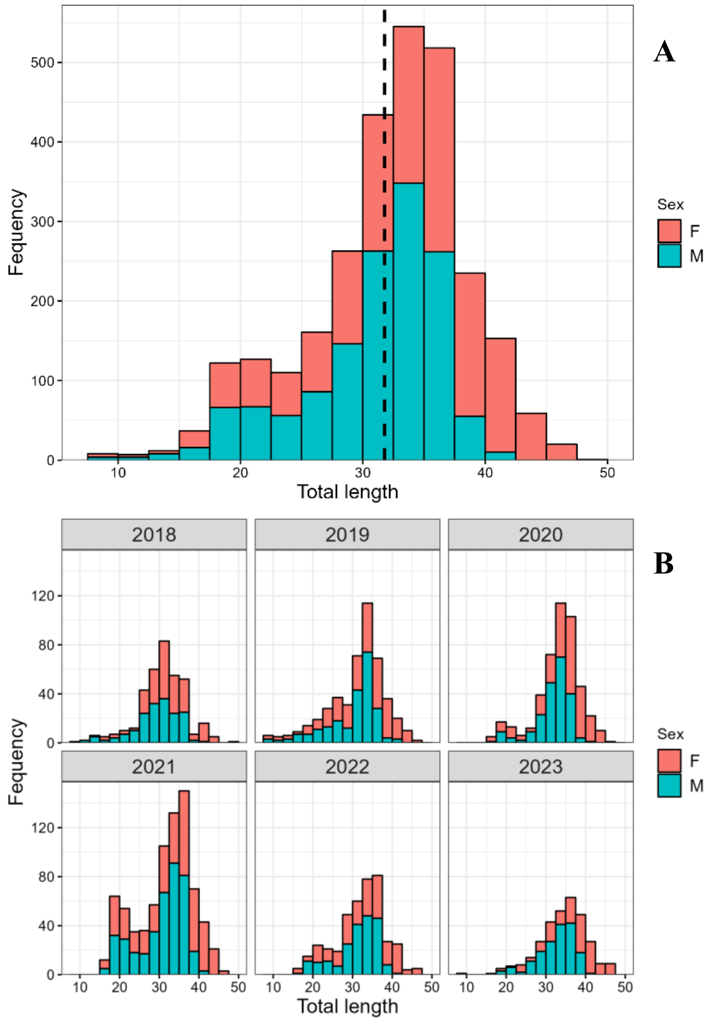

Figure 9: A-Overall length frequency distribution of N. indica, B- Year wise length frequency distribution of N. indica. The dashed black line in A shows the overall mean length (31.74 cm).

of N. indica. The dashed black line in A shows the overall mean length (31.74 cm)..

The disc width (DiscW) of male *N. indica* ranged from 9 to 41 cm, with a mean length of 30.6 ± 5.63 cm. For females, the DiscW ranged from 8.2 to 49 cm, with a mean length of 32.9 ± 7.01 cm. The results of the Welch two-sample t-test revealed a significant difference in mean length between male and female *N. indica* (t = -9.7027, df = 2806.9, p < 0.001). The 95% confidence interval for the difference in means ranged from -2.749840 to -1.825261. The ANOVA test results revealed a significant effect of year on the total length of *N. indica* (F(3, 34) = 5.568, p < 0.01).

4.1.1.3 G. granulatus

In total 787 individuals were recorded during the survey period and from that 339 length measurements were collected and used in this study (male= 198, female=141). The length frequency distribution of *G. granulatus* caught in Sri Lankan waters is summarised in Figure 9: A- Overall length frequency distribution of G. granulatus, B- Year wise length frequency distribution of G. granulatus. The dashed black line in A shows the overall mean length (81.39 cm)..

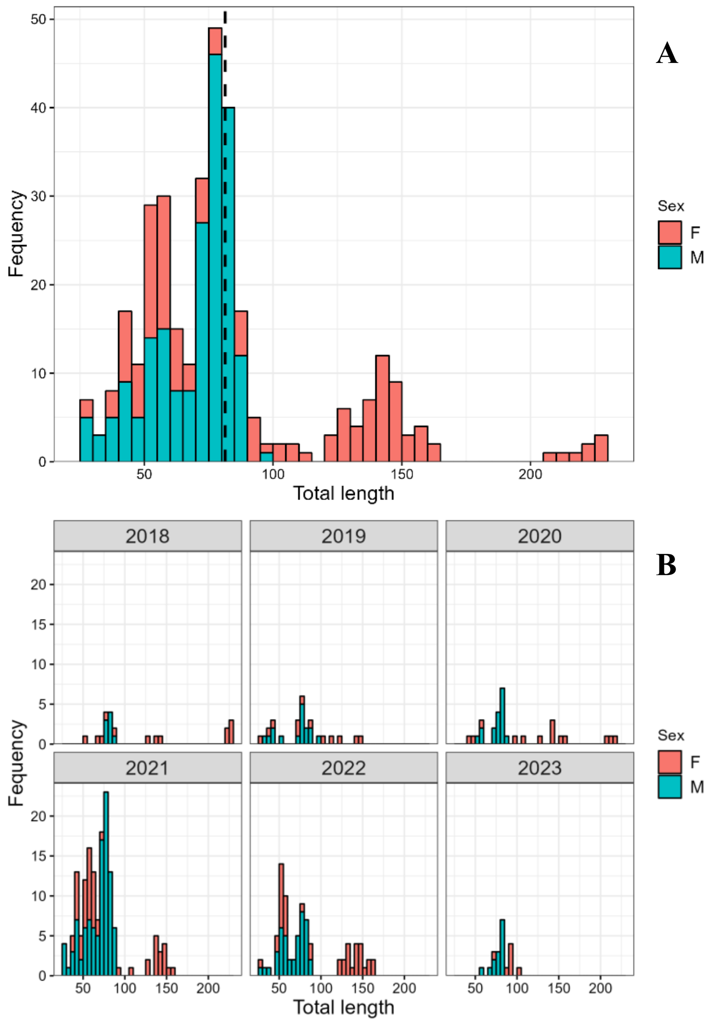

Figure 11: A- Overall length frequency distribution of G. granulatus, B- Year wise length frequency distribution of G. granulatus. The dashed black line in A shows the overall mean length (81.39 cm).

The total length of male *G. granulatus* ranged from 25 to 98 cm, with a mean length of 68.7 ± 15.5 cm. For females, the TL ranged from 25.5 to 230 cm, with a mean length of 99.2 ± 50.1 cm. The results of the Welch two-sample t-test revealed a significant difference in mean length between male and female *G. granulatus* ($t = -6.9885$, $df = 159.27$, $p < 0.001$). The 95% confidence interval for the difference in means ranged from -39.12717 to -21.88497. The ANOVA test results revealed a significant effect of year on the total length of *G. granulatus* ($F(5, 333) = 9.437$, $p < 0.001$).

4.1.2 Length-weight relationships

4.1.2.1 C. falciformis

The weight of *C. falciformis* ranged from 1.2 to 57 kg for males and from 1.55 to 56.4 kg for females. The graphical length-weight relationship is shown in **Error! Reference source not found.**, and the numerical relationship is as follows:

$$W = 1.9 * 10^{-6} L^{3.218} \text{- Males}$$

$$W = 2.6 * 10^{-6} L^{3.158} \text{- Females}$$

The length-weight relationship showed that *C. falciformis* exhibited positive allometric growth for both males and females (b > 3), whereas males showed a significantly higher 'b' value (b= 3.218) than females (b = 3.158).

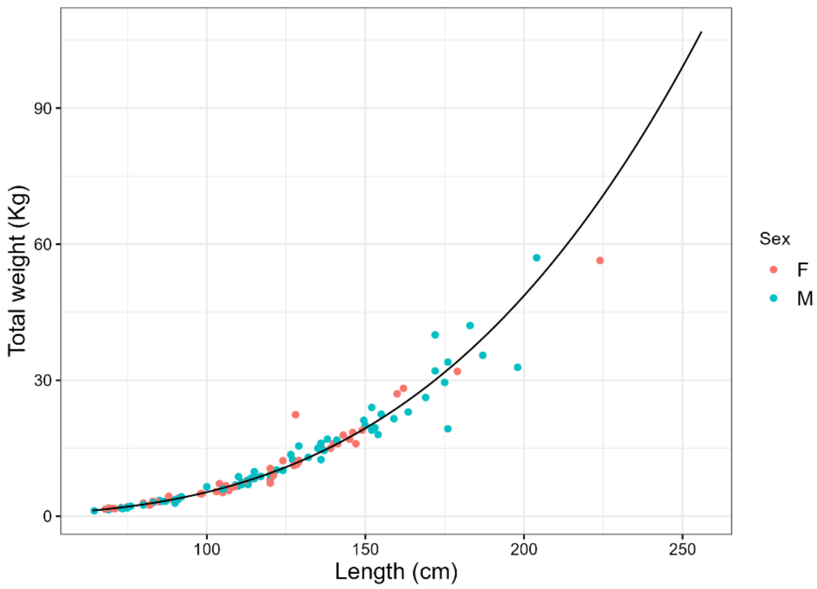

Figure 13: Overall length-weight relationship of C. falciformis.

The results of the Welch two-sample t-test revealed no significant difference in the mean weight between male and female *C. falciformis* (t = 1.331, df = 113.2, p = 0.1859). The 95% confidence interval for the difference in means ranged from -1.259 to 6.413. Analysis of variance (ANOVA) showed that length had a highly significant effect on total weight ($p < 0.001$). However, the effect of sex on total weight was not significant (p = 0.8635).

4.1.2.2 N. indica

The weight of *N. indica* ranged from 0.03 to 2.32 kg in males and from 0.035 to 3.5 kg in females. The equation describing the length-weight relationship for *N. indica* (Figure 11: Overall length-weight relationship of N. indica.) is as follows:

$$W = 1.5 * 10^{-6} L^{3.216} \text{- Males}$$

$$W = 1.9 * 10^{-6} L^{3.158} \text{- Females}$$

The length-weight relationship showed that *N. indica* exhibited positive allometric growth in both males and females (b > 3). Males showed a significantly higher 'b' value (b= 3.215) than females (b = 3.158).

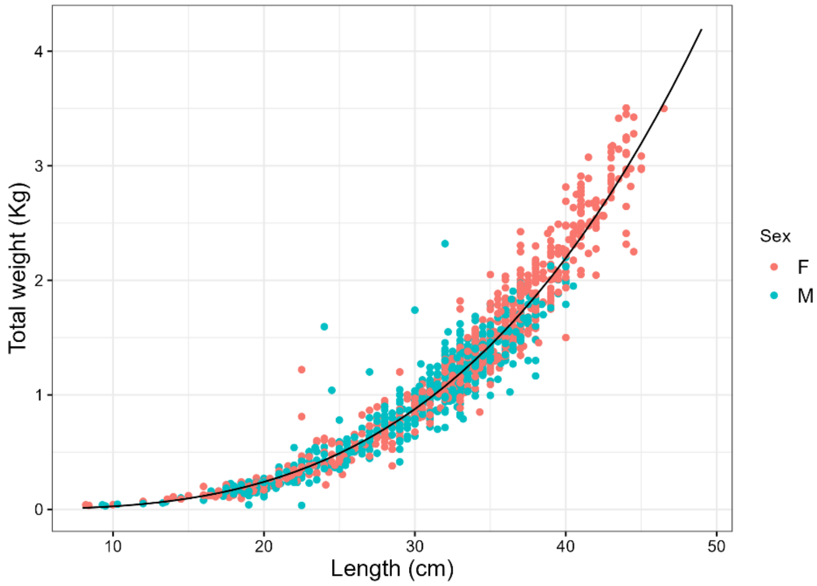

Figure 14: Overall length-weight relationship of N. indica.

The results of the Welch two-sample t-test revealed a significant difference in the mean weight between male and female *N. indica* (t = -10.195, df = 1113.6, p < 0.001). The 95% confidence interval for the difference in means ranged from -0.442 to -0.299. Analysis of variance (ANOVA) results showed that both length (F = 8443.9, p < 0.001) and sex (F = 108.2, p < 0.001) had a significant effect on the total weight (TW) of *N. indica*.

4.1.2.3 G. granulatus

The weight of *G. granulatus* ranged from 0.04 to 2.78 kg in males and from 0.055 to 17.5 kg in females. The equation describing the length-weight relationship for *G. granulatus* (Figure 12: Overall length-weight relationship of G. granulatus.) is as follows:

$$W = 1.5 * 10^{-6} L^{3.175} \text{ - Males}$$

$$W = 1.6 * 10^{-6} L^{3.165} \text{- Females}$$

The length-weight relationship showed that *G. granulatus* exhibits positive allometric growth in both males and females (b > 3). Males showed a significantly higher ‘b’ value (b= 3.175) than females (b = 3.165).

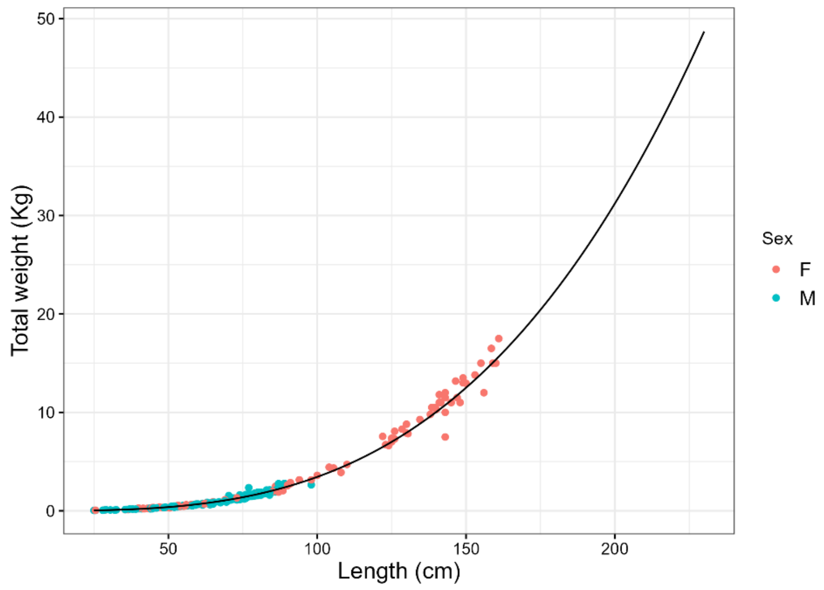

Figure 15: Overall length-weight relationship of G. granulatus.

The Welch two-sample t-test revealed a significant difference in the mean weight between male and female *G. granulatus* ($t = -6.7292$, $df = 118.43$, $p < 0.001$). The 95% confidence interval for the difference in means ranged from -4.025281 to -2.194875. The analysis of variance (ANOVA) results showed a significant effect of both length ($F = 2058.77$, $p < 0.001$) and sex ($F = 50.99$, $p < 0.001$) on the total weight (TW) of *G. granulatus*.

4.1.3 Maturity analysis (L_{50}, L_{95})

4.1.3.1 C. falciformis

There are no maturation data for female *C. falciformis*; therefore, maturity ogives were calculated for males only. The lengths at which 50% and 95% of the *C. falciformis* population were mature (L_{50} and L_{95}) were estimated to be 196.49 cm and 229.92 cm, respectively (Figure 13)**Error! Reference source not found.**.

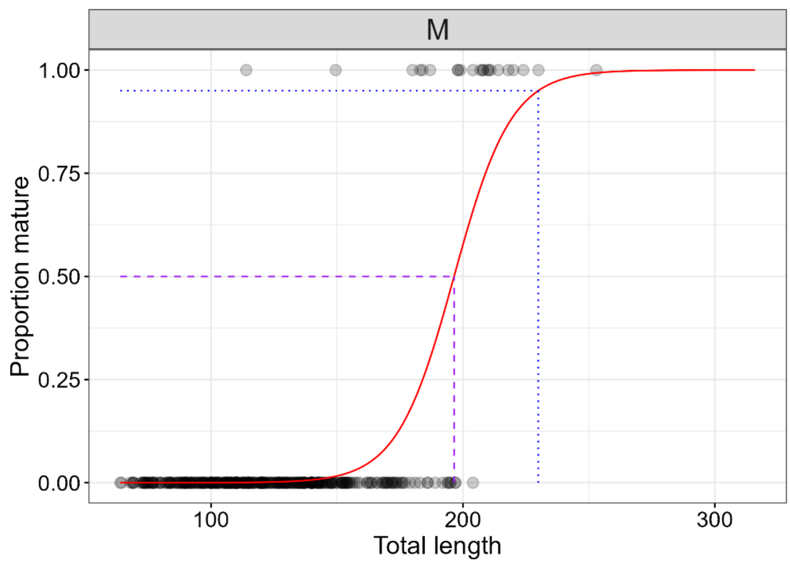

Figure 16: Maturity ogive for male C. falciformis; Purple colour dashed line indicates L_{50} and blue colour dotted line indicates L_{95}.

4.1.3.2 N. indica

Maturity ogives were calculated for both males and females of *N. indica*. The length at which 50% and 95% of the *N. indica* population are mature (L_{50} and L_{95}) were estimated to be 30.21 cm and 39.3 cm, respectively, for males (Figure 14-A)Figure 14: Maturity ogives for (A) male and (B) female N. indica; Purple colour dashed line indicates L_{50} and blue colour dotted line

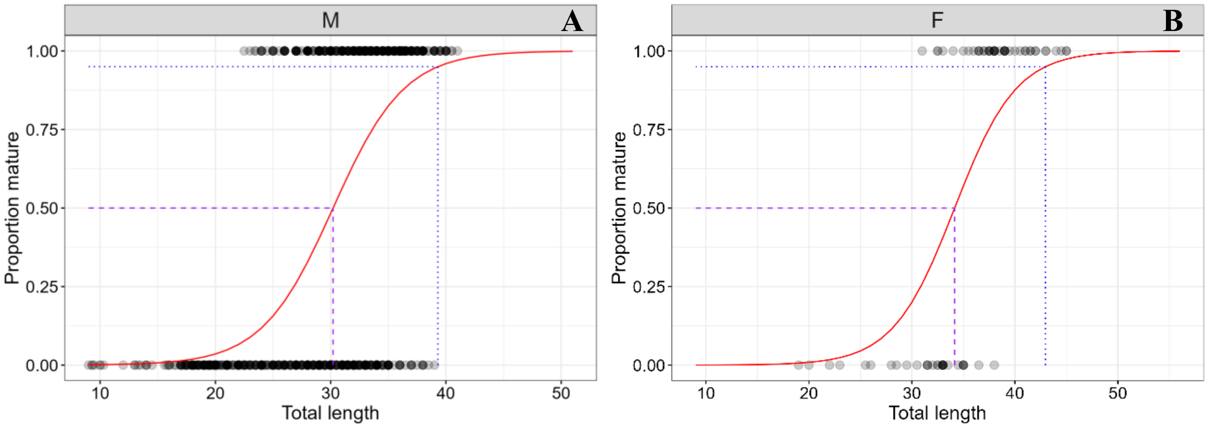

Figure 19: Maturity ogives for (A) male and (B) female N. indica; Purple colour dashed line indicates L_{50} and blue colour dotted line indicates L_{95}.

indicates L_{95}., and 34.15 cm and 42.97 cm, respectively, for females (Figure 14-B)Figure 14: Maturity ogives for (A) male and (B) female N. indica; Purple colour dashed line indicates L_{50} and blue colour dotted line indicates L_{95}..

4.1.3.3 G. granulatus

Maturity ogives were calculated for both male and female *G. granulatus*. The lengths at which 50% and 95% of the *G. granulatus* population were mature (L_{50} and L_{95}) were estimated to be 68.61 cm and 75.61 cm, respectively, for males (Figure 15: Maturity ogives for (A) male and (B) female G. granulatus; Purple colour dashed line indicates L_{50} and blue colour dotted line indicates L_{95}.-A), and 82.17 cm and 88.99 cm, respectively, for females (Figure 15: Maturity

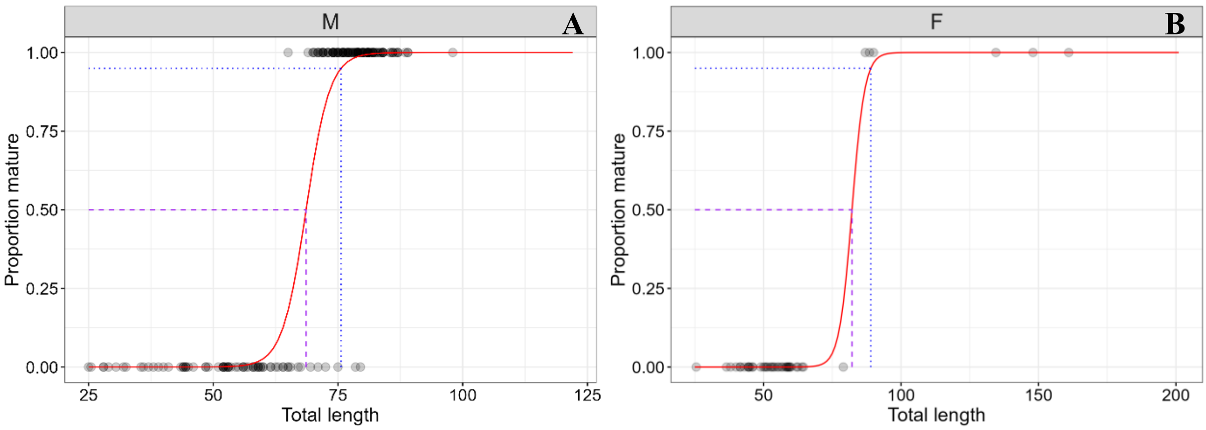

Figure 21: Maturity ogives for (A) male and (B) female G. granulatus; Purple colour dashed line indicates L_{50} and blue colour dotted line indicates L_{95}.

ogives for (A) male and (B) female G. granulatus; Purple colour dashed line indicates L_{50} and blue colour dotted line indicates L_{95}.-B).

4.1.4 Asymptotic length (L_{inf})

Asymptotic length (L_{inf}) was calculated using the equation of Pauly (1984). L_{inf} was calculated for each sex of each species. The results are presented in Table 4.

Table 4: Estimates of L_{inf}.

Species	♂ Male		♀ Female	
	L_{max} (cm)	L_{inf} (cm)	L_{max} (cm)	L_{inf} (cm)
C. falciformis	253	266	256	269.5
N. indica	41	43.15	49	51.56
G. granulatus	98	103.16	230	242.1

4.1.5 Estimation of natural mortality (M)

The estimates of natural mortality (M) for *C. falciformis* and *N. indica* are presented in Table 5. For *C. falciformis*, the estimates ranged from 0.089 to 0.106 and had a mean of 0.099 which was used as the baseline M value for the LB-SPR assessment. For *N. indica*, the estimates ranged from 0.12 to 0.177 and had a mean of 0.137 which was used as the baseline M value for the LB-SPR assessment.

Table 5: Natural mortality (M) results of C. falciformis and N. indica from Cope & Hamel, (2022).

Natural mortality estimator	*C. falciformis* (k = 0.066, L_{inf} = 269.5)	*N. indica* (k = 0.08, L_{inf} = 51.6)
Then_VBGF	0.089	0.177
Hamel_k	0.102	0.124
Jensen_k 1	0.099	0.12
Jensen_k 2	0.106	0.128
Mean	**0.099**	**0.137**

4.2 Length-based spawning potential (LBSPR)

4.2.1 Input parameters of the C. falciformis and N. indica for LBSPR model

The summaries of the empirical analyses for *C. falciformis* and *N. indica* are listed in Table 6.

Table 6: The estimated biological parameters for C. falciformis and N. indica that were used as inputs for the LBSPR model.

Parameters	*C. falciformis*	*N. indica*
Asymptotic length (L_{inf})	♂ 266.31 cm	♂ 43.16 cm
	♀ 269.47 cm	♀ 51.56 cm
Length–weight relationship parameter (a)	♂ $1 \cdot 9 * 10^{-6}$	♂ $1 \cdot 5 * 10^{-6}$
	♀ $2.6 * 10^{-6}$	♀ $1.9 * 10^{-6}$

Length–weight relationship parameter (b)	♂ 3.218 ♀ 3.158	♂ 3.215 ♀ 3.158
Lengths at maturity-50% (L_{50})	♂ 196.49 cm	♂ 30.21 cm
Lengths at maturity-95% (L_{95})	♂ 229.92 cm	♂ 39.3 cm
Natural mortality (M)	0.099	0.137
Growth coefficient (k)	0.066	0.08
M/k (MK)	1.5	1.71

4.2.2 LBSPR results of C. falciformis

The LB-SPR model was run from 2018-2020 for C. falciformis (Figure 16)**Error! Reference source not found.**. The years 2021-2023 were excluded from the analysis because they did not contain sufficient measurements. The model predicted size structures that matched the length compositions of the catch in each year (Figure 16). The histograms of length frequencies by year exhibited single modes where the highest peak occurs between 85 cm - 130 cm. The length ranges of *C. falciformis* in the catches were mostly smaller than the size at which 50% of the population matures (L_{50} = 196.49 cm). For *C. falciformis*, the estimated length at 50%

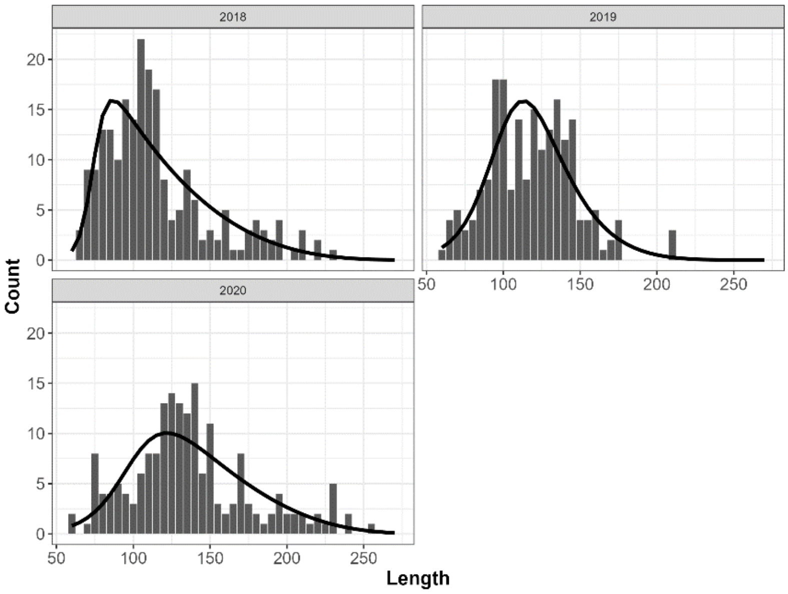

Figure 22: C. falciformis model results. The empirical length frequency distribution together with the fit from the LB-SPR model overlaid as a black solid line.

selectivity (SL_{50}) was much smaller than L_{50} (Figure 17)**Error! Reference source not found.**.

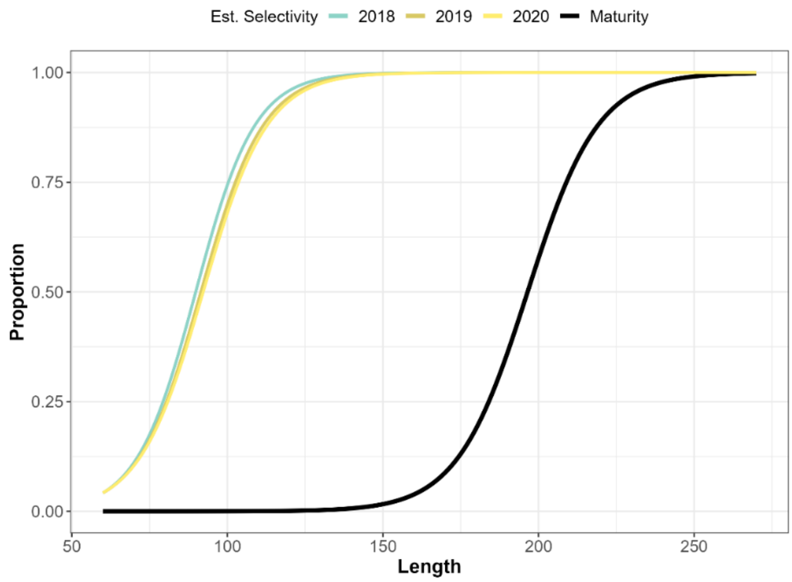

Figure 23: C. falciformis model results. The annual selectivity curves- SL50 (coloured lines) estimated by the model, together with the length at which 50% of the population matures L50 (solid black line) estimated from the data.

Error! Reference source not found. illustrates the trends in selectivity, relative fishing mortality (F/M), and spawning potential ratio (SPR) for *C. falciformis*. The estimated size selectivity for the years 2018-2020 was 89.83, 91.50, and 92.22, respectively, with the highest value observed in 2020. The estimated average F/M (1.82) exceeded the threshold of F/M (F/M=1). The total SPR was estimated to be 7% in 2018 and 2019, and up to 8% in 2020. The cumulative average SPR from 2013 to 2019 was 7.3%, which is relatively low and below the Limit Reference Point (LRP= 0.2).

Error! Reference source not found. shows the spawning potential ratio (SPR), relative yield curve of *C. falciformis*, and SSB/SSB0 ratio (relative spawning stock biomass to virgin spawning stock biomass). The model estimated that the relative yield can be maximised when the relative fishing mortality is approximately 0.5 (Figure 19)**Error! Reference source not found.**. The back calculation of the fishing mortality rate resulted in an F equal to 0.05.

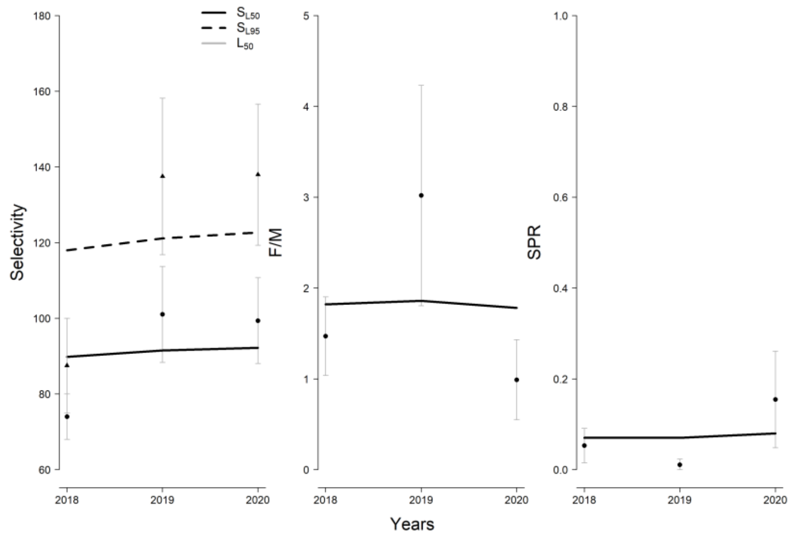

Figure 24: C. falciformis model results. Annual selectivity at 50 and 95%, F/M (relative fishing mortality) and deterministic SPR (spawning potential ratio).

Figure 25: C. falciformis model results. Expected unfished size structure and dependence of SPR, SSB/SSB0 and relative yield on relative fishing mortality (F/M).

4.2.3 LBSPR results of N. indica

The LBSPR model for *N. indica* was fit to six years (2018-2023) of length data. The model predicted the annual size structures that matched the length compositions of the catch (Figure 20)**Error! Reference source not found.**. The histograms of length frequencies by year exhibited single modes, where the highest peak occurs between 30 cm and 35 cm. It revealed that a large proportion of the catches of *N. indica* was similar to the length at which 50% of the population matures (L_{50} = 30.21 cm). The estimated length at 50% selectivity (SL_{50}) of *N. indica* was slightly higher than L_{50} **Error! Reference source not found.**).

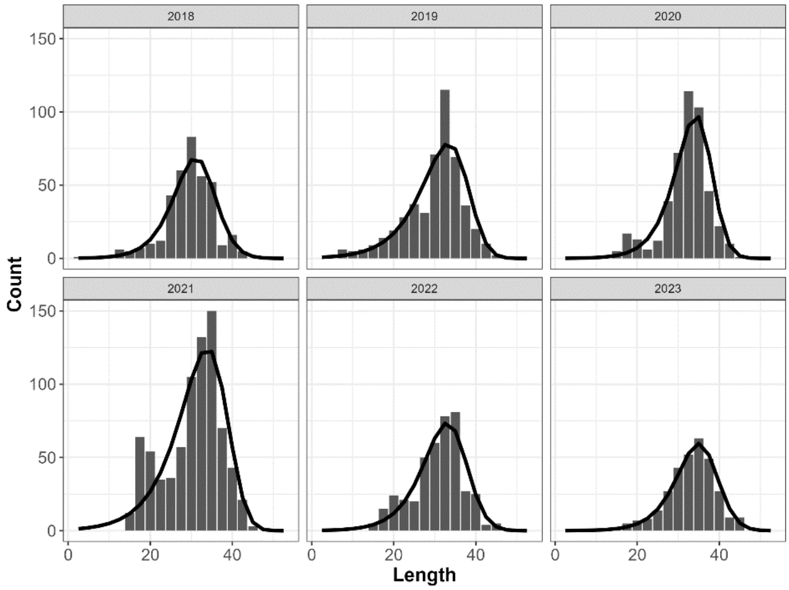

Figure 26: N. Indica model results. The empirical length frequency distribution together with the fit from the LB-SPR model overlaid as a black solid line.

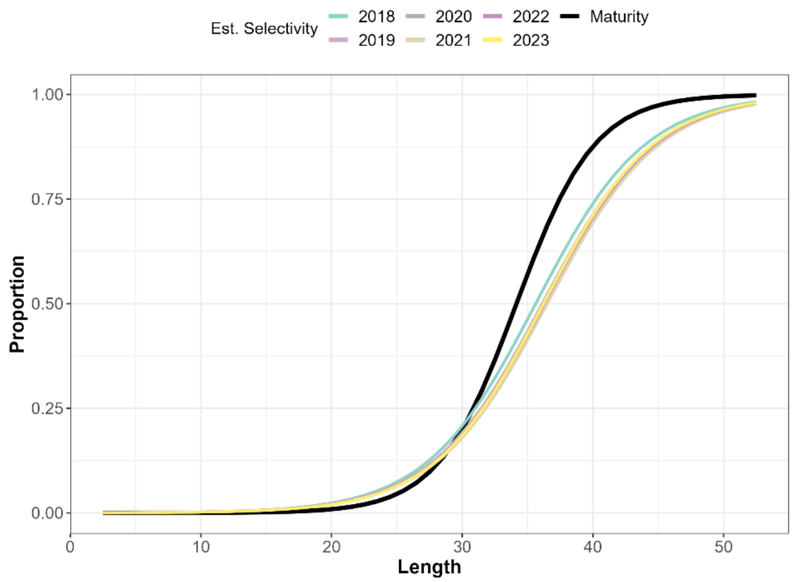

Figure 27: N indica model results. The annual selectivity curves- SL50 (coloured lines) estimated by the model, together with the length at which 50% of the population matures L50 (solid black line) estimated from the data.

Error! Reference source not found. shows the trends of selectivity, F/M, and SPR produced by the N. indica model. The estimated SL50 values for the years 2018-2023 were 30.88, 39.31, 36.51, 40.50, 34.52, and 35.70, respectively, with the highest value observed in 2022. The estimated average relative fishing mortality (F/M= 5.21) was higher than the threshold of F/M (F/M=1). The total SPR is estimated to be 14% in 2018, 17% in 2019, 19% in 2020, 19% in 2021, 19% in 2022 and up to 27% in 2023. The cumulative average SPR from 2018 to 2023 was 19.5%, which is relatively low and less than the Limit Reference Point of 20% SPR. For 2023, the SPR value is 0.27, which is above the Limit Reference Point of 20% SPR (Figure 22).

Error! Reference source not found. shows the spawning potential ratio (SPR), relative yield curves of *N. indica*, and SSB/SSB0 ratio (relative spawning stock biomass to virgin spawning stock biomass). The model estimated that the relative yield could be maximised at a relative fishing mortality (F/M) of approximately 1.5 (Figure 23)**Error! Reference source not found.**. The back calculation of the fishing mortality rate resulted in an F of 0.2.

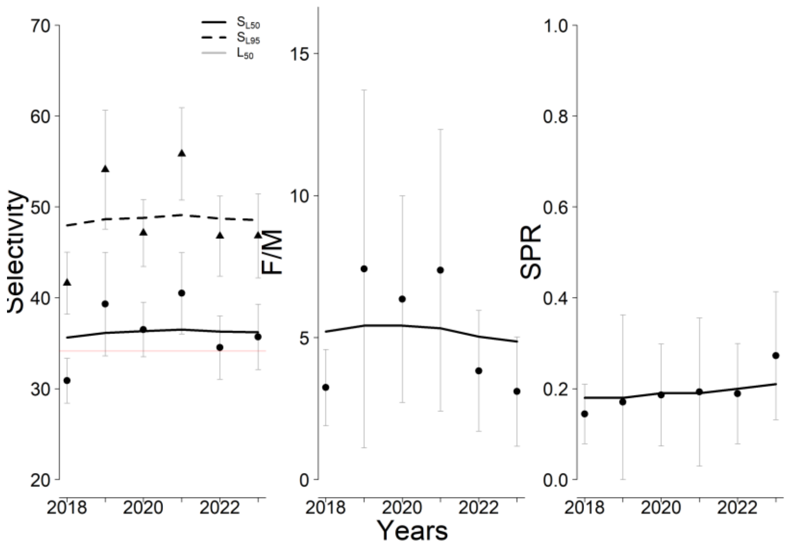

Figure 28: N. indica model results. Annual selectivity at 50 and 95%, F/M (relative fishing mortality) and deterministic SPR (spawning potential ratio).

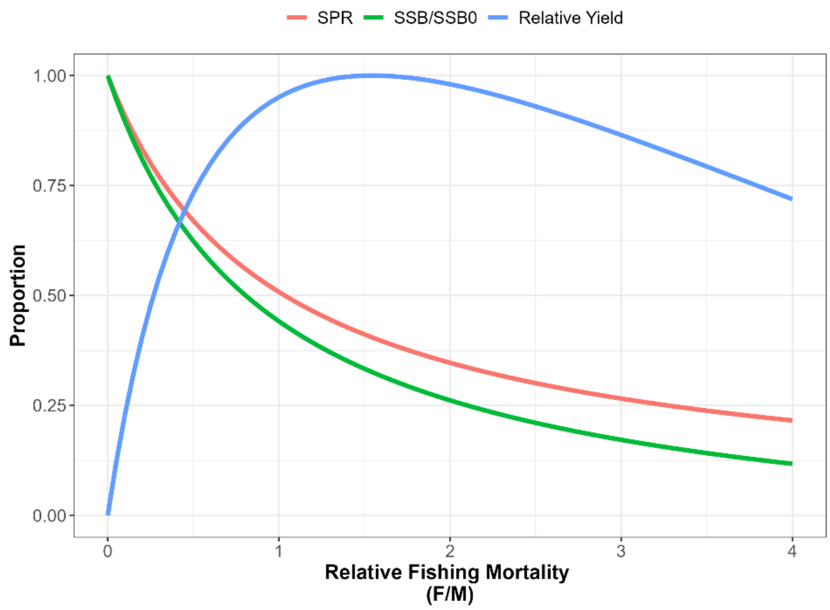

Figure 31: N. indica model results. Expected unfished size structure and dependence of SPR, SSB/SSB0 and relative yield on relative fishing mortality (F/M).

4.2.4 SPR trend in different scenarios

A sensitivity test was conducted to evaluate the sensitivity of the model to various input parameters. Four scenarios were created by changing the asymptotic length (L_{inf}) and natural mortality (M). Based on the biological history of each species, high and low values of L_{inf} and M were set for both species separately. The results of the sensitivity analysis are presented alongside the corresponding baseline scenarios in **Error! Reference source not found.**.

Table 7: Changes of SPR in five different scenarios: Baseline, high asymptotic length (High L_{inf}), low asymptotic length (Low L_{inf}), high natural mortality (High M) and low natural mortality (Low M)

Scenario	***C. falciformis***				***N. indica***			
	L_{inf}	M	M/K	SPR	L_{inf}	M	M/K	SPR
Baseline	269.5	0.099	1.5	0.07	51.6	0.137	1.71	0.19
High L_{inf}	269.5+10%	0.099	1.5	0.07	51.6+10%	0.137	1.71	0.13
Low L_{inf}	269.5-10%	0.099	1.5	0.14	51.6-10%	0.137	1.71	0.77
High M	269.5	0.099+10%	1.65	0.09	51.6	0.137+30%	2.23	0.38
Low M	269.5	0.099-10%	1.35	0.06	51.6	0.137-30%	1.2	0.17

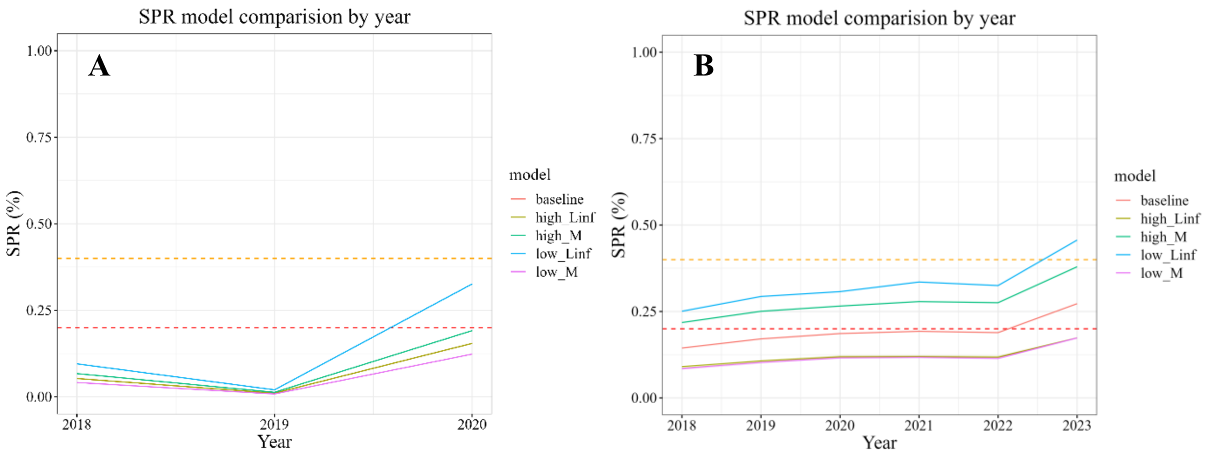

Figure 32: SPR value changes in different scenario; A - for C. falciformis, B - for N. indica.

5 DISCUSSION

5.1 C. falciformis

In this study, *C. falciformis* exhibited a smaller size (L_{max}=256 cm) than the global average of 371 cm (Serafy et al., 2012). However, its size was more closely aligned with records from the Indian Ocean, with a maximum length of 263 cm, as reported by Hall et al. (2012). The results of the Welch two-sample t-test indicated no significant difference in mean length between male and female *C. falciformis*, suggesting that sex does not influence catch selectivity. ANOVA results revealed temporal variations in the total length of *C. falciformis*, with particularly notable differences observed in 2020 compared to earlier years.

The length-weight relationship of *C. falciformis* shows positive allometric growth for both sexes ($b > 3$). Males exhibited a significantly higher 'b' value than females, indicating that males gained more weight relative to the per unit change in length than females. ANOVA results demonstrated that the length of the fish had a significant effect on total weight, whereas the sex of the fish did not. Overall, the results suggest that length is a strong predictor of total weight, which is consistent with previous studies (Najmudeen et al., 2019).

The size at maturity for *C. falciformis* was assessed only for males, with results indicating that the sexual maturity of males (L_{50}) falls within the global range of 180-230 cm (Bonfil, 2008; Hall et al., 2012; Oshitani et al., 2003; Sánchez-de Ita et al., 2011; Serafy et al., 2012). The analysis of the length frequency of *C. falciformis* revealed a high level of immature landings in Sri Lankan fisheries, which is concerning for the health of the population.

5.2 N. indica

There have been no detailed biological studies on *N. indica* due to its recent classification, although some previous studies have identified it as *N. kuhlii*. In this study, the maximum size of *N. indica* (female, L_{max}=49 cm) was recorded, surpassing the previously recorded maximum of 31.4 cm found in the literature (Pavan-Kumar et al., 2018). Figure 8: A-Overall length frequency distribution of N. indica, B- Year wise length frequency distribution of N. indica. The dashed black line in A shows the overall mean length (31.74 cm).A illustrates that female *N. indica* grow larger than males. The results of the Welch two-sample t-test indicated a significant difference in mean length between male and female *N. indica*, suggesting that sex influences the catch selectivity. ANOVA results also suggested temporal variations in the total length of *N. indica*, with a notable increase in the mean total length from 2019 to 2020. However, the mean total length in 2022 did not differ significantly from that in other years.

The length-weight relationship of *N. indica* exhibited positive allometric growth for both males and females ($b > 3$), with males showing a significantly higher 'b' value than females. This indicates that males gained a higher weight relative to a unit change in length than females. The Welch two-sample t-test results suggest that the mean weight of the catch is influenced by sex, with the mean weight of females being slightly higher than that of males. The ANOVA summary showed that the variation in total weight could be significantly explained by both length and sex. These findings indicate that both length and sex have a significant impact on the total weight of *N. indica* catch.

The size at maturity assessment for *N. indica* was conducted separately for males and females. The observed size at 50% maturity (L_{50}) for females (34.15 cm) was higher than that for males (30.21 cm). The results of the current study showed reproductive development similar to *that of N. kuhlii* from the same genus. In addition, female *N. kuhlii* exhibit a significantly larger size at maturity than males (Pierce et al., 2009). The male L_{50} value suggests that the length selectivity of *the N. indica* fishery exerts high pressure on adult populations (63%). Conversely, for females, the length selectivity of the fishery exerted high pressure on juvenile populations (52%).

5.3 G. granulatus

G. granulatus is another species with limited biological studies, except for a feeding ecology study (Sreekanth et al., 2022). This study documented a maximum length (L_{max}) of 230 cm for females, breaking the previous record of 229 cm (P. Last et al., 2016). Figure 9: A- Overall length frequency distribution of G. granulatus, B- Year wise length frequency distribution of G. granulatus. The dashed black line in A shows the overall mean length (81.39 cm).A shows that female *G. granulatus* grow larger than males, indicating clear sexual dimorphism in this species. The results of the Welch two-sample t-test suggested a significant difference in mean length between male and female *G. granulatus*, indicating that sex influences the selectivity of the catch. Additionally, the ANOVA results indicated a significant effect of year on the total length of *G. granulatus*, suggesting that there are differences in total length across the years under consideration.

The length-weight relationship of *G. granulatus* showed positive allometric growth for both males and females ($b > 3$), with males exhibiting a slightly higher ‘b’ value than females. The Welch two-sample t-test indicated that the mean weight of the catch is influenced by sex, with the mean weight of males being lower than that of females. The ANOVA summary suggested a significant difference in total weight between different lengths and sexes.

Size at maturity assessment for *G. granulatus* was performed separately for males and females, revealing that the size at 50% maturity (L_{50}) for females (82.17 cm) is higher than that for males (68.61 cm). The male L_{50} was close to the mean length of male catches (68.7 cm), and the harvest proportion put high pressure on adult populations. Conversely, for females, over 90% of the harvest consisted of mature fish, indicating high pressure on the spawning stock.

The empirical results for *G. granulatus* provide a basic understanding of the status of fishing pressure on this species. They also revealed the limitations of the current data for applying the LBSPR assessment. Therefore, future data collection methods should be reconsidered to further understand the population status. In addition, alternative and reliable stock assessment methods suitable for current data should be explored.

5.4 Length-based spawning potential (LBSPR)

The assessment of the Spawning Potential Ratio (SPR) is crucial for evaluating the reproductive potential of fish stocks and guiding effective management strategies (Hordyk et al., 2015). Fish populations tend to be robust and able to withstand fishing pressure when their spawning populations remain abundant, which is achieved by maintaining capture lengths above the maturity length (Prince & Hordyk, 2019). The effectiveness of the LBSPR model lies in its ability to provide efficient stock status and offer a cost-effective approach to fishery management (Chong et al., 2020).

In this study, the LBSPR model was used to assess the stock status of the most dominant commercial shark species, *C. falciformis*, and the most dominant elasmobranch in the country, *N. indica*. Based on the model results, both *C. falciformis* and *N. indica* appear to be overexploited in Sri Lankan waters. The estimated selectivities for *C. falciformis* showed that the juvenile portion of the stock is heavily exploited, leading to growth overfishing. This pattern is clearly observed in the catch composition data, with a large portion of the length measurements below L_{50}. Conversely, the estimated selectivities for *N. indica* showed that selection is towards the mature population with an $SL_{50} > L_{50}$.

For *C. falciformis*, the assessment showed that the SPR is below the Limit Reference Point (LRP) and, therefore, overexploited. Cramp et al. (2021) assessed the Indian Ocean *C. falciformis* and suggested that they are either overfished or in an overfished state. Our study, conducted in Sri Lankan waters, which are part of the Indian Ocean, supports these findings and emphasises the need for effective management. The results of our study indicate that *C. falciformis* in this region is overexploited, reinforcing the conclusions of a previous study. Urgent action is required to address their management issues.

The average SPR value for *N. indica* is also below the LRP. In 2023, the SPR value rose above the LRP level but below the Target Reference Point (TRP), indicating that the stock is still below the target level for optimal sustainability. Simulation modelling of the relationship between SPR and FM under various fishing mortalities revealed that the current SPR of both species cannot sustain the maximum sustainable yield. This highlights the need for an urgent action plan to reduce the juvenile harvest of *C. falciformis* and apply balanced harvest to *N. indica*.

For both stocks, the models were fit assuming a logistic S-shaped selection pattern. This assumption means that the absence of larger fish from the empirical length distributions is ascribed to exploitation rather than reflecting gear-induced absence. Further work using the LB-SPR model on these stocks should investigate potential alternative selection curves (Hommik et al., 2020).

In the sensitivity analyses (Figure 24), different L_{inf} and natural mortality (M) scenarios were implemented. The estimated SPRs showed significant changes from the baseline values. The SPR and thus the classified status of *N. indica* was more sensitive to the alternative scenarios than *C. falciformis*. Although the SPR improved in some scenarios, the mean SPR was always below 20% for *C. flaciformis* and 40% for *N. indica*, which reinforces the conclusions reached in the baseline model. These results emphasise the importance of continuous monitoring and data collection to reduce the uncertainty in the estimates of the input parameters for the model. With more reliable parameter estimates, our confidence in the resulting SPR values will improve.

The current LB-SPR study provides valuable insights into the status of *C. falciformis* and *N. indica* populations in Sri Lankan waters, aligning with the objectives of SDG 14. By assessing the spawning potential ratios and identifying overfished conditions, this study contributes to the conservation of their stocks. Healthy elasmobranch populations are essential components of marine ecosystems, and our findings emphasize the importance of maintaining spawning stock biomass above critical thresholds. This supports the goal of SDG 14 to promote the conservation and sustainable use of marine resources. Moreover, this study underscores the need for effective fishery management strategies to ensure the long-term sustainability of fish stocks.

6 CONCLUSION

Empirical results show that there is no size difference between male and female *C. falciformis*. In contrast, *N. indica* and *G. granulatus* showed females typically displaying larger body sizes than males, indicating sexual dimorphism. All three species showed positive allometric growth in both sex and sexual maturity (L_{50}) of female greater than male in *N. indica* and *G. granulatus*. The catch selectivity of *C. falciformis* indicates high juvenile removal from the ecosystem, and *N. indica* shows more mature landings. The SPR findings for both species indicate that the fishery is in a depleted state, characterised by low reproductive potential of the stocks. Furthermore, considering the exploratory nature of this study and the uncertainty associated with the estimated parameters, caution should be exercised when deriving management advice from these findings.

7 RECOMMENDATIONS

- Based on the results of the current study, immediate management actions need to be implemented. For *C. falciformis*, a minimum size limit can be applied to reduce the juvenile catch. For *N. indica*, area or seasonal closures are recommended to reduce broodstock harvest and support reproduction.
- Further studies should assess more elasmobranch species, including the species in the current study, data collection should be improved with continuous monitoring of the fishery, and regular stock assessments should be conducted.
- Increasing the measurements of female maturation data and exploring alternative approaches for estimating growth parameters can improve the accuracy of the model.
- Explore alternative data-limited methods for assessing stock status to compare with this study to support management actions.
- Further investigation into the spatial and temporal variations in catch, gear selectivity, and spawning cycles, coupled with habitat-based monitoring, should be prioritised to implement more effective fishing methods.

- Implementing minimum size limits, establishing marine protected areas, and adopting sustainable fishing practices are crucial for achieving SDG 14 targets related to marine conservation and sustainable resource management.

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