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Stock Assessment of Four Dominant Shark Bycatch Species in Bottom Trawl Fisheries in the Northern South China Sea

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Abstract: Sharks occupy an important ecological niche in marine ecosystems. As top predators, they can restrict and control the behavior, numbers and composition of other species through downward effects, and play an essential role in ecosystem stability. Shark fishery data are limited, and for most Chondrichthyes species there is no formal fishery resource assessment at a global level. In this study, we applied the length-based Bayesian biomass (LBB) estimation method to assess the stock status of four common shark bycatch species of which more than 100 samples were collected in coastal waters of the northern South China Sea. Estimates of the length of 50% of individuals captured by gear/the length at first capture that maximized the catch and biomass (L_c/L_{c_opt}) of a species ranged from 0.49 to 1.4; the draughtsboard shark *Cephaloscyllium sarawakensis* had the highest value, and the shortnose dogfish *Squalus brevirostris* had the lowest. Estimates of the collected biomass/biomass of the maximum sustainable yield (B/B_{MSY}) ranged from 0.86 to 1.9. Both *C. sarawakensis* and the spadenose shark *Scoliodon laticaudus* were fully exploited, while the spatulasnout catshark *Apristurus platyrhynchus* and *S. brevirostris* were in good condition. To verify the stability of the LBB, length frequency data for the most common species *S. laticaudus* were divided into different size-class intervals; simulations revealed estimated parameters based on these to be insensitive to differences in intervals, except for the smallest (10 mm), which did not affect evaluation results. These results can be used to provide a scientific basis on which shark fisheries in this region can be managed and prior parameters for related resource assessment methods can be determined.

Keywords: chondrichthyes; maximum sustainable yield; stock status; occurrence; LBB

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1. Introduction

Sharks occupy an important ecological position, and play an essential role in marine ecosystems. As top predators, they can restrict and control the behavior, abundance, and composition of other species through top-down effects [1,2]. In most marine ecosystems, a decrease in the number of sharks leads to changes in the structure and function of food webs through trophic cascades [3–5].

As important marine biological resources, sharks are worth at least USD 1.5 billion annually in fisheries, trade, and tourism [6]. However, high fishing mortality caused by overfishing and the conservative life history characteristics of these animals render many species vulnerable [7–11]. The growing demand for shark-derived commodities (e.g., shark fins, meat, cartilage, liver oil) is the main reason why sharks are subjected to such intense fishing pressure [12,13]. For example, the demand for shark fins in Asian markets has led to the mass killing of sharks [12], increasing shark fin imports more than 214% from 2648 mt in 1985 to 8323 mt in 1998. Similarly, shark fin imports in Thailand increased 42% from 97 to 138 mt. Based on weight, the total estimated number of sharks killed in 2000 was about 100 million, and in 2010 about 97 million, with global estimates ranging from 63 to 273 million sharks annually [11].

Sharks killed for their fins (for which the body is discarded) distort catch data, exacerbating management problems. Distorted production data can cause erroneous assessments of fishing mortality and stock status [13,14], leading to the ill-informed expansion of current global shark fisheries; this is mainly due to serious bycatch and the lack of publicity for shark protection policies. Because of limited and chaotic management policies [11,15,16], a lack of economic incentives, and limited data, current shark fishery management is inadequate [11,17–19]. No formal fishery resource assessment exists for most cartilaginous fish in the world [20], and the IUCN Red List cites a square of cartilaginous species as threatened by overfishing, with only one-third of species regarded as safe [1], and 44% of species unable to be accurately assessed because of a lack of data.

In China's waters, catches of sharks, rays, and skates are estimated to have reduced by 67% between 1950 and 2014 [21]. Highly productive coastal waters are affected by multiple stressors, such as human activity, environmental pollution, and climate change, and fishery resources in this region are declining [22,23]. As an apex predator in coastal waters, coastal sharks experience increasingly severe conditions, and because they are long-living and slow-growing animals with low productivity [24–27] they are especially vulnerable. Shark recovery from overfishing can take a long time due to habitat degradation and the bioaccumulation and biomagnification of environmental pollutants through the bionet process [28].

Coastal tropical and subtropical waters of the northern South China Sea (NSCS) contain many fishery resources, and are traditional bottom trawl fishing grounds for the Hainan, Guangxi, and Guangdong provinces. Recent increases in the number and power of fishing boats in this region have caused serious declines in offshore fishery resources [29]. Fishing rates declined by 72% from the early 1960s to the late 1990s [30], with the effects of fishing and environmental changes considered primarily responsible [23]. Historically, research on fish in this region has focused on fish morphology, biology, genetics, species composition, and discussions on protection and management strategies [31–34]. Of the 146 species of shark reported from China's waters, 13 have been reported in bottom trawl catches from the NSCS [35]. However, because of a lack of accurate catch and survey data, a punctual assessment of shark stocks in this region, and therefore a formulation of science-based fishery management, cannot be achieved. Alternative methods are needed to assess shark stocks in the coastal NSCS.

When possible, fishery management actions are based on estimates of current stock status and management targets produced from full age-structured stock assessment models; however, most unassessed stocks lack data and commercial importance for a full age-based stock assessment. Three types of assessment models are commonly used in poor-data fishery management: CMSY (catch–maximum sustainable yield), AMSY (abundance—maximum sustainable Yield), and LBB (length-based Bayesian biomass). Catch-based methods cannot be used to assess shark stock for the northern SCS because they are the bycatch of bottom trawl fisheries and the catch data have not been counted. Meanwhile, existing abundance index (e.g., CPUE) data series are not accurate enough to assess the biomass of these species, so the AMSY method is not a good choice for stock assessment. We estimated the parameters of the LBB method directly by a Bayesian Monte Carlo Markov chain process, requiring only length frequency data. This process estimates asymptotic length, length at first capture, relative natural mortality, and relative fishing mortality of a species. The resource statuses of poor-data fish species in China have been previously evaluated using this method [36–38]. Thus, we estimated the population parameters of four dominant (bycatch) shark species and assessed their stock status using the LBB method based on length frequency data collected by bottom trawl surveys from 2019 to 2021 in the NSCS. The results provide a scientific basis for regional shark protection and management.

2. Materials and Methods

2.1. Data Resource

We sourced data for four shark species from bottom trawl surveys (August 2019, March–April 2020, July–September 2020, and January 2021) conducted by the South China Sea Fisheries Research Institute in offshore waters of the NSCS. A steel fishing vessel "Guibeiyu 69068" (engine power 441 kW) was engaged in these surveys. The same gear—a net 80.4 m × 60.54 m (head line: 37.70 m)—was used in each survey. Each site (Figure 1) was trawled once for 1 h at an average speed of 3.5 kn. All shark samples were frozen and then returned to the laboratory for measurement, where their lengths were measured to the nearest 0.1 cm; sharks were identified to species with dichotomy key-based morphological characteristics, and their scientific and common names were verified using FishBase. A total of 952 shark individuals referable to 12 species were collected. Those species, for which more than 100 individuals were retained, were selected for LBB analysis.

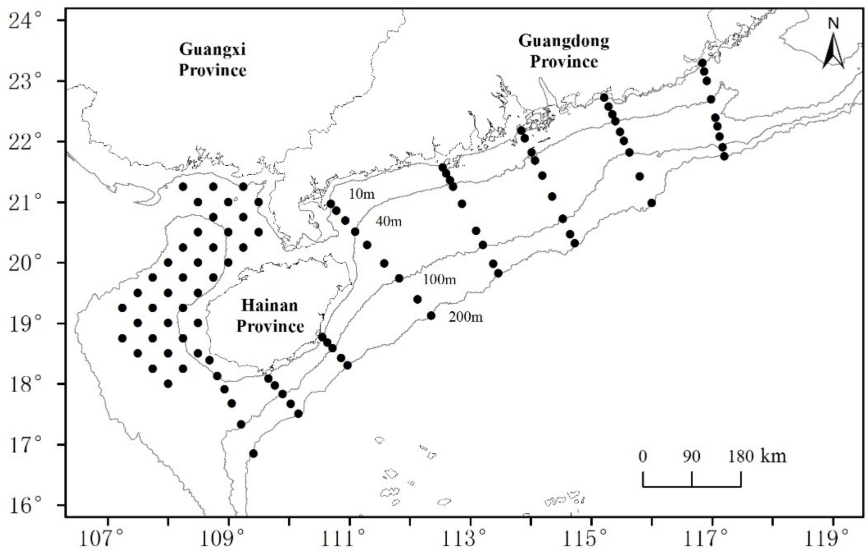

Figure 1. Trawl survey sampling sites, northern South China Sea.

Life history characteristics of these dominant shark species are as follows.

Cephaloscyllium sarawakensis

This benthopelagic species mainly inhabits the Pacific Ocean. In the South China Sea its distribution extends from southwestern Taiwan, Hong Kong, and Vietnam, to Malaysia, from 10 to 200 m. Males and females attain maximum lengths of 39.7 cm and 44.1 cm, respectively [39].

Apristurus platyrhynchus

This small shark is found in the western Pacific, the Philippines, South and East China seas, and northward to Suruga Bay, Japan. Maximum male and female lengths are 80.0 cm and 63.0 cm, respectively. It lives mainly on the continental slope, and is oviparous, probably producing a single egg per oviduct at a time [40].

Scoliodon laticaudus

This demersal, shallow-dwelling species matures at 34.3 cm (33–35 cm) and reaches a maximum length of 100.0 cm. It is found widely throughout the Indo-West Pacific (Persian Gulf, Somalia, Tanzania, Mozambique, Pakistan, and Java, Indonesia), and the waters of Japan and China. It feeds on small bony fish, shrimps, and cuttlefish. It is viviparous, with litter sizes ranging from 1 to 14, producing pups of about 13–15 cm total length [40].

Squalus brevirostris

This demersal species is found mainly in the western Pacific, from southern Japan to the South China Sea. Its maximum total length is 60 cm, and it is ovoviviparous [41].

2.2. LBB Method

The LBB method can analyze length frequency data from commercial catches of continuously growing species, such as most commercially exploited fish and invertebrates [36,42]. The key to the LBB method is the von Bertalanffy growth function (VBGF), described as [43]:

$$L_t = L_{\text{inf}}[1 - e^{-K(t-t_0)}] \tag{1}$$

where L_t is the length at age t, L_{inf} is the asymptotic length, K is the rate at which L_{inf} is approached, and t_0 is the theoretical age at length zero.

If fishing gear operates with full selectivity, the curvature of the catch in the numbers-at-length curve is the value of the total mortality Z relative to K (Z/K); Z comprises natural and fishing mortality ($Z = M + F$), with the curve expressed by the following equation [44]:

$$N_L = N_{L_{\text{start}}}\left(\frac{L_{\text{inf}} - L}{L_{\text{inf}} - L_{\text{start}}}\right)^{Z/K} \tag{2}$$

where N_L is the number of survivors to length L, $N_{L_{\text{start}}}$ is the number at length L_{start}, and L_{start} is the minimum length with full selection (all individuals entering the gear are retained by the gear).

Fishing gear selectivity (here assumed trawl-like) for species is given by the following equation:

$$S_L = \frac{1}{1 + e^{-\alpha(L - L_c)}} \tag{3}$$

where S_L is the fraction of individuals that are retained by the gear at length L, L_c is the length of 50% of the individuals captured by the gear, and α represents the steepness of the ogive [44].

Parameters L_{inf}, L_c, α, M/K, F/K, and the selection ogive, are estimated by fitting the following two equations [42]:

$$N_{L_i} = N_{L_{i-1}}\left(\frac{L_{\text{inf}} - L_i}{L_{\text{inf}} - L_{i-1}}\right)^{\frac{M}{K} + \frac{F}{K} S_{L_i}} \tag{4}$$

$$C_{L_i} = N_{L_i} S_{L_i} \tag{5}$$

where N_{Li} is the number of individuals in length class L_i, the subindex i in L_i represents the serial numbers of length classes, and N_{Li-1} is the number of individuals in the previous length class. C_{Li} refers to the number of individuals vulnerable to the gear, proportionally represented in the catch for length class L_i.

For a given fishing pressure (F/M), the length at first capture $L_{\text{c\_opt}}$ that maximizes the catch and biomass can be obtained from:

$$L_{\text{c\_opt}} = \frac{L_{\text{inf}}(2 + 3\frac{F}{M})}{(1 + \frac{F}{M})(3 + \frac{M}{K})} \tag{6}$$

An index catch per unit of effort ($CPUE'/R$) is obtained by dividing the relative yield-per-recruit (Y'/R) by F/M, as presented by Froese [42]:

$$\frac{Y'}{R} = \frac{F/M}{1+F/M}(1 - L_c/L_{\text{inf}})^{M/K} \left(1 - \frac{3(1-L_c/L_{\text{inf}})}{1+1/(M/K+F/K)} + \frac{3(1-L_c/L_{\text{inf}})^2}{1+2/(M/K+F/K)} - \frac{(1-L_c/L_{\text{inf}})^3}{1+3/(M/K+F/K)}\right) \tag{7}$$

$$\frac{CPUE'}{R} = \frac{\frac{Y'}{R}}{\frac{F}{M}} = \frac{1}{1+F/M}(1 - L_c/L_{\text{inf}})^{M/K} \left(1 - \frac{3(1-L_c/L_{\text{inf}})}{1+1/(M/K+F/K)} + \frac{3(1-L_c/L_{\text{inf}})^2}{1+2/(M/K+F/K)} - \frac{(1-L_c/L_{\text{inf}})^3}{1+3/(M/K+F/K)}\right) \tag{8}$$

The relative biomass in the exploited situation if no fishing occurs is given by:

$$\frac{B_0{}'>Lc}{R} = (1 - L_c/L_{\text{inf}})^{M/K} \left(1 - \frac{3(1-L_c/L_{\text{inf}})}{1+\frac{1}{M/K}} + \frac{3(1-L_c/L_{\text{inf}})^2}{1+\frac{2}{M/K}} - \frac{(1-L_c/L_{\text{inf}})^3}{1+\frac{3}{M/K}}\right) \tag{9}$$

where $B_0{}' > L_c$ denotes the exploitable fraction ($>L_c$) of the unfished biomass (B_0).

The ratio of fished to unfished biomass is described as:

$$\frac{B}{B_0} = \frac{\frac{CPUE'}{R}}{\frac{B_0{}'>L_c}{R}} \tag{10}$$

A proxy for the relative biomass that can produce B_{msy}/B_0 was obtained by re-running Equations (7)–(10) with F/M = 1 and $L_c = L_{c\_opt}$ (Froese [42]).

Herein, L_{inf} priors are generated as the maximum length obtained from the present study if the maximum length is unknown, or the recorded maximum length in Fishbase (www.fishbase.org, accessed on 15 June 2021) is smaller than that of the present study; otherwise, the recorded maximum length in Fishbase is used for all other situations [42]. All analyses were implemented using LBB_30a.R, an R-code algorithm presented by Froese [42]. Stocks were classified into categories based on B/B_{MSY} values; they were considered overexploited when $B/B_{\text{MSY}} < 0.8$, fully exploited when $0.8 \leq B/B_{\text{MSY}} \leq 1.2$, and non-fully exploited when $B/B_{\text{MSY}} > 1.2$ [45]. A simulation was presented to understand if the estimations were sensitive to different size-class intervals using the LBB method. We set five groups with different size-class intervals (10 cm, 20 cm, 30 cm, 40 cm, and 50 cm) of *S. laticaudus* to run LBB. We chose *S. laticaudus* as an example because its length range was wide, from 200 mm to 700 mm.

3. Results

The distributions of each shark species are depicted in Figure 2. *A. platyrhynchus* was found in the Beibu Gulf, while other species were found on the northern continental shelf of the NSCS and southern waters of Hainan Island, in deep water. Most *A. platyrhynchus* were found in the shallower eastern part of the Beibu Gulf. Species composition, numbers of sharks retained in trawls, basic information and the priors of four dominant shark species are shown in Tables 1 and 2.

Table 1. Species composition and numbers of sharks retained in trawls from the northern South China Sea.

Scientific Name	Common Name	Numbers
Triakis maculata (Kner and Steindachner, 1867)	Spotted houndshark	4
Squalus brevirostris (Tanaka, 1917)	Shortnose dogfish	149
Apristurus platyrhynchus (Tanaka, 1909)	Spatulasnout catshark	182
Scoliodon laticaudus (Müller and Henle, 1838)	Spadenose shark	280
Halaelurus buergeri (Müller and Henle, 1838)	Blackspotted catshark	12
Pristiophorus japonicus (Günther, 1870)	Japanese sawshark	3
Carcharhinus sorrah (Valenciennes, 1839)	Spot-tail shark	13
Galeus sauteri (Jordan and Richardson, 1909)	Blacktip sawtail catsharks	94
Chiloscyllium plagiosum (Anonymous (Bennett), 1830)	Whitespotted bambooshark	5
Cephaloscyllium fasciatum (Chan, 1966)	Reticulated swellshark	12
Cephaloscyllium sarawakensis (Yano, Ahmad and Gambang, 2005)	Sarawak pygmy swell shark	195
Eridacnis radcliffei (Smith, 1913)	Pygmy Ribbontail Cat Shark	3

Table 2. Basic information and priors of model parameters of four dominant shark species from the northern South China Sea.

Scientific Name	Min (mm)	Max (mm)	Class Interval	Numbers	L_{inf} Prior	Z/K Prior	M/K Prior	F/K Prior	L_c Prior	Alpha Prior
Cephaloscyllium sarawakensis	182	470	10	195	47.7	1.6	1.5	0.123	31.6	11.8
Apristurus platyrhynchus	258	442	20	182	44.5	1.4	1.5	0.300	36.2	33.4
Scoliodon laticaudus	200	700	40	280	74.0	2.6	1.5	1.120	28.6	18.5
Squalus brevirostris	237	772	40	149	94.4	1.9	1.5	0.437	32.6	41.6

Note: L_{inf} is the asymptotic length; Z/K is the total mortality Z relative to K; K is the rate at which L_{inf} is approached; M/K is the natural mortality M relative to K; F/K is the fishing mortality F relative to K; L_c is the length of 50% of the individuals captured by the gear; *Alpha* represents the steepness of the LBB curve ogive.

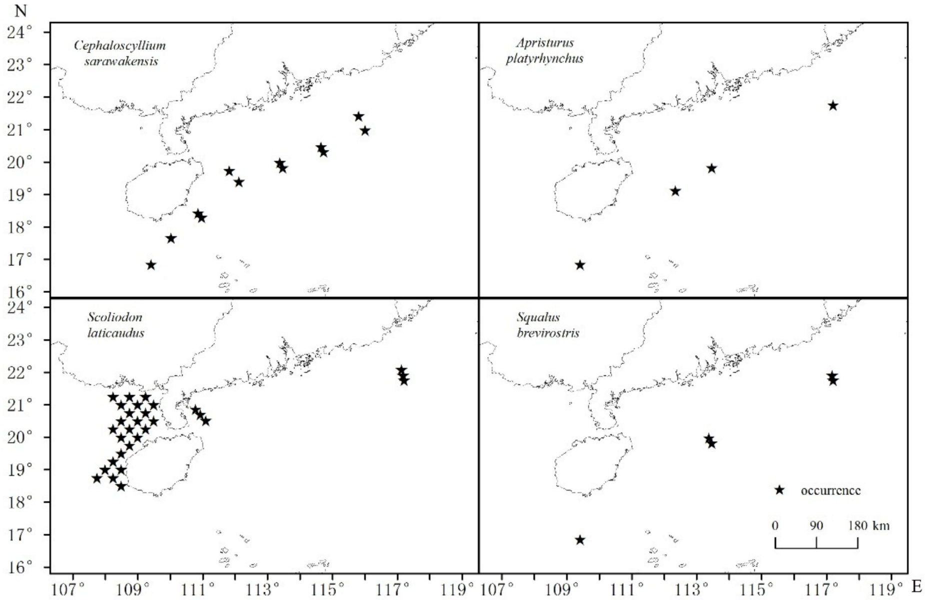

Figure 2. Distributions of the four shark species in the northern South China Sea.

The results of these four shark species in offshore NSCS waters produced by LBB methods are presented in Figure 3 and summarized in Table 3. All length–frequency distributions are unimodal. Estimated L_{inf} values for *C. sarawakensis* and *A. platyrhynchus* were smaller than the maximum length (L_{max}), while the L_{max} was lower than estimated values of L_{inf} for *S. laticaudus* and *S. brevirostris*.

Estimates of L_c/L_{c_opt} ranged from 0.49 to 1.4, with *C. sarawakensis* having the highest value, and *S. brevirostris* the lowest. The maximum and minimum trend in L_c/L_{c_opt} was the same as the estimate of Z/K, ranging from 1.4 to 4.97. The estimated L_c/L_{c_opt} value for *A. platyrhynchus* was higher than that for *S. laticaudus*, while the estimated Z/K of *A. platyrhynchus* was lower than that of *S. laticaudus*.

Estimates of B/B_{MSY} for each species from the northern continental shelf of the NSCS made a difference, ranging from 0.86 to 1.9. In the LBB method, an evaluation of fish resource status can be judged by the ratio of B/B_{MSY}. Combining the results of the model and judgment criteria of Amorim [45], *C. sarawakensis* and *S. laticaudus* were both fully exploited, and *A. platyrhynchus* and *S. brevirostris* were non-fully exploited.

To verify the stability of the LBB model, *S. laticaudus* length data were divided into different size-class intervals; simulations revealed estimated parameters (L_{inf}, L_c/L_{c_opt}, Z/K, B/B_0, and B/B_{MSY}) to be insensitive to different intervals, with the exception of the shortest (10 mm) interval (Table 4).

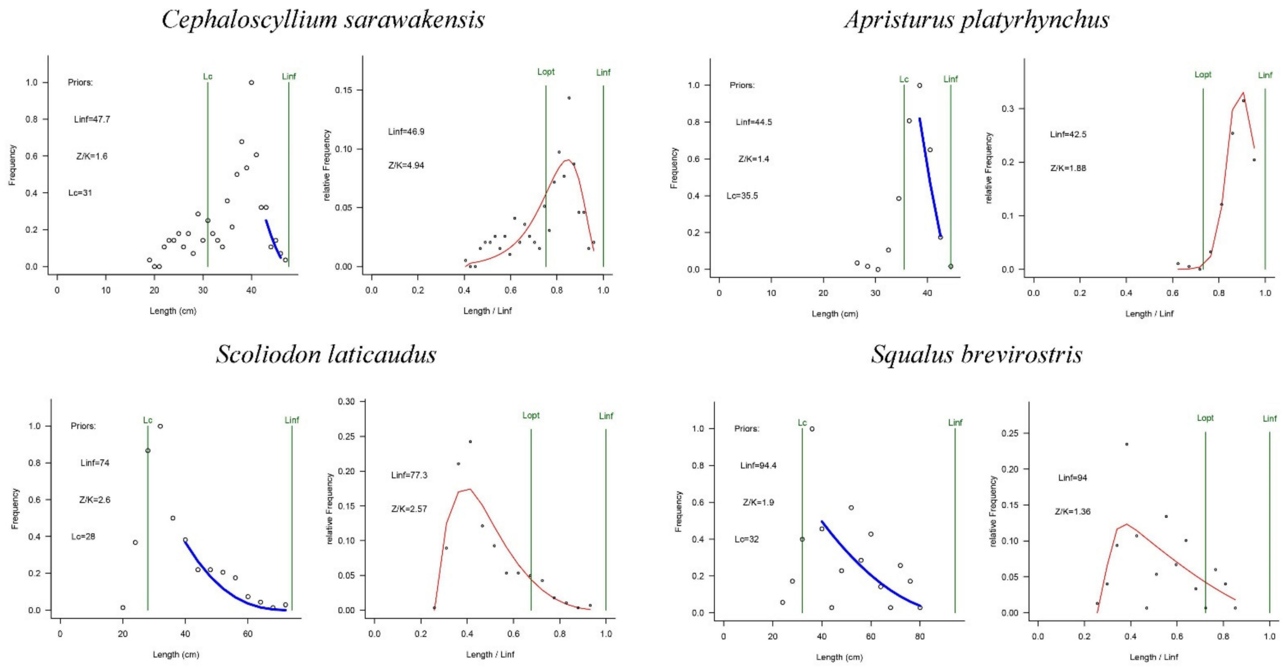

Figure 3. Trends in population parameters of the four shark species in the northern South China Sea. The left curve shows the LBB model fits to accumulated length frequency data; the right curve indicates the LBB method prediction.

Table 3. Summary of LBB outputs and status for four dominant shark species in the northern South China Sea.

Scientist Name	L_{inf} (cm)	L_c/L_{c_opt}	Z/K	B/B_0	B/B_{MSY}	Status
Cephaloscyllium sarawakensis	46.9 (46.6–47.5)	1.40	4.97 (3.58–6.74)	0.34 (0.13–0.6)	0.86 (0.33–1.50)	Fully exploited
Apristurus platyrhynchus	42.5 (41.8–43.3)	1.30	1.88 (1.68–2.21)	0.55 (0.28–1.10)	1.40 (0.72–2.80)	Non-fully exploited
Scoliodon laticaudus	77.3 (76.3–78.2)	0.67	2.57 (2.44–2.72)	0.34 (0.19–0.56)	0.92 (0.52–1.50)	Fully exploited
Squalus brevirostris	96.5 (95.2–98.1)	0.49	1.40 (1.30–1.50)	0.74 (0.08–1.70)	1.90 (0.22–4.40)	Non-fully exploited

Note: Numbers between parentheses represent 95% confidence intervals for a parameter.

Table 4. Estimated parameters of the LBB for size-class intervals for a simulated data series for *Scoliodon laticaudus*.

Class Interval (mm)	L_{inf} (cm)	L_c/L_{c_opt}	Z/K	B/B_0	B/B_{MSY}
10	74.5 (73.5–75.8)	0.57	3.38 (3.22–3.60)	0.22 (0.13–0.34)	0.61 (0.34–0.94)
20	74.0 (73.0–75.1)	0.59	2.50 (2.30–2.60)	0.40 (0.15–0.65)	1.10 (0.41–1.8)
30	73.6 (72.3–74.7)	0.61	2.40 (2.20–2.60)	0.44 (0.18–0.80)	1.20 (0.50–2.20)
40	77.3 (76.3–78.2)	0.67	2.57 (2.44–2.72)	0.34 (0.19–0.56)	0.92 (0.52–1.50)
50	77.4 (76.5–78.5)	0.57	2.40 (2.30–2.60)	0.42 (0.20–0.62)	1.10 (0.55–1.70)

Note: Numbers between parentheses represent 95% confidence intervals for a parameter.

4. Discussion

This study is the first to assess bottom trawl bycatch shark species resources in the NSCS. The results indicated that the level of relative biomass (B/B_{MSY}) of two species (*C. sarawakensis*, *S. laticaudus*) was <1, indicating that these sharks have been considerably impacted by fisheries; for two species (*A. platyrhynchus*, *S. brevirostris*) it was >1, indicating they have not been considerably impacted by fisheries. We suggest applying a variety of methods to effectively assess the shark stock status in the NSCS, and formulate optimal fishery management policies.

Length frequency data were sourced from sharks retained in four bottom trawl surveys in the NSCS from 2019 to 2021, from all four seasons. Bottom trawling has poor fishing gear selection [46], and the survey depth range (10–200 m) basically covered the different sizes and habitat of each dominant species. Therefore, our data satisfy the requirements of Froese [42], who emphasized that length–frequency data used in the LBB method should represent the entire target stock.

Globally, the stock status of most shark species cannot be assessed because of a lack of catch data [47], mainly because sharks are caught as bycatch in most fisheries and the bodies are discarded after the fins have been cut off. Traditional stock assessments are only routinely performed on large shark species, such as blue shark *Prionace glauca* and mako shark *Isurus oxyrinchus* [48–50]. Because of the low economic value of small coastal sharks and a lack of production data because of bycatch, there is currently no specific resource assessment for them in the NSCS. Research is instead focused on species composition, community structure, and life history characteristics which do not require catch or CPUE data [51,52].

Among the assessed species, *C. sarawakensis* is classified Not Applicable (NA), *S. laticaudus* as Near Threatened (NT), *A. platyrhynchus* as Least Concern (LC), and *S. brevirostris* as Endangered (EN) in the International Union for Conservation of Nature (IUCN) Red List of Threatened Species. The relative biomass levels of *C. sarawakensis* and *S. laticaudus* were 0.86 and 0.92, indicating that their stocks were fully exploited. The widely distributed *C. sarawakensis* occurs mainly in deeper coastal waters of the NSCS. Because this species has often been confused with *Cephaloscyllium umbratile* [53], identifications may have been incorrect in previous related research [51]. The habitat of *S. laticaudus* is close to the coast and therefore under heavy fishing pressure [54,55], but it is a fertile species, with the female carrying 8–19 embryos [56]. Our results on the status of *S. laticaudus* are consistent with those from the Bay of Bengal, Bangladesh, using the FiSAT-II evaluation method [57] and the waters around Taiwan [47]. The relative biomass of *A. platyrhynchus* was 1.4, with that for *S. brevirostris* even greater (to 1.9). Neither species was non-fully exploited, indicating that regional stocks are in good condition, possibly because those species may live deeper, outside of traditional bottom trawl operation areas, and are not target species due to their low economic value. *S. brevirostris* was also the dominant shark species in the southwestern sea of the Nansha Islands; combined with the results of this study (non-fully exploited), this indicates that *S. brevirostris* is widely distributed and abundant in the South China Sea [51]. The Chinese government has tried since the 1980s to restrict fishing in response to inshore fishery depletion caused by demersal trawling and stake nets; however, the status of fishery resources has recovered somewhat in recent years [58].

To verify the influence of body length frequency size-class intervals on model evaluation results, we divided length–frequency data for the most common species *S. laticaudus* into different length–frequency intervals. While different class intervals do affect results, they do not affect the final evaluation of a stock as being over, fully, or non-fully exploited. To improve this model, a standard class spacing could be considered.

While various concerns have been expressed about the reliability of the LBB method to evaluate resource status [59], for sharks, for which there are limited data, this method enables an evaluation of resource status that is otherwise not possible. Ours is the first study to attempt to analyze the resource status of small sharks in coastal NSCS waters. These results can be used to provide a scientific basis on which shark fisheries in this region can be managed and prior parameters for related resource assessment methods can be determined [60]. Besides, due to the limitations of sampling numbers, the results of this study can only be used as an attempt to study the status of shark resources in this sea area, and provide a preliminary accumulation for further in-depth research in the future.

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Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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