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**Research Article**

# Yield Per Recruit and Spawning per Recruit of Brownbanded Bamboo Shark, *Chiloscyllium Punctatum* in Southeast Asia

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## ABSTRACT

The brownbanded bamboo shark (*Chiloscyllium punctatum*) is a benthic shark species distributed in Southeast Asia. The species was listed as "Near Threatened" by IUCN only from indirect information. In this study, the yield per recruit (YPR) and the spawning per recruit (SPR) analysis were conducted to determine the current stock status. Data were obtained from three major landing sites of this species—Sihanoukville, Cambodia (Sv), Songkhla, Thailand (Sk), and Kota Kinabalu, Malaysia (KK). The von Bertalanffy's growth curve parameters $L_\infty$ and $K$ were estimated as 81.62 cm and 0.37 year$^{-1}$ for Sv, 88.09 cm and 0.51 year$^{-1}$ for Sk, and 86.48 cm and 0.40 year$^{-1}$ for KK. The YPR and SPR analysis results showed that the $F_{curr}$, $F_{0.1}$, and $F_{30\%}$ were 0.29, 0.26, and 0.21 year$^{-1}$ for Sv, 0.39, 0.23, and 0.23 year$^{-1}$ for Sk, and 0.06, 0.24, and 0.24 year$^{-1}$ for KK. The results indicated that the fisheries for brownbanded bamboo shark in KK was efficient and sustainable, but in Sv and Sk, it was almost inefficient and has no room to increase fishing mortality for sustainability. Some fisheries management measures were recommended for the sustainable fisheries of the stocks.

**Keywords:** brownbanded bamboo shark, BRPs, stock assessment, per recruit analysis, Southeast Asia.

## INTRODUCTION

The brownbanded bamboo shark (*Chiloscyllium punctatum*) is the largest member of the family Hemiscylliidae with the maximum recorded total length can be over 140 cm found in the Southeast Asian waters. This shark species plays an important role in marine ecosystems by control the population of small teleosts and invertebrates in coastal and coral reef areas (Ahmad and Lim, 2012; Krajangdara, 2017). Brownbanded bamboo shark is caught by various kinds of fishing gear, such as bottom trawl and gillnets, from the traditional

to commercial scale, for local consumption and sale in the aquarium trade (Krajangdara, 2014; Dharmadi *et al*., 2015; Dudgeon *et al*., 2016;).

All elasmobranch were known to having a low resilience from fishing activity regarding the slower growth rate and smaller in the number of offspring production compared to other teleost fish. For the conservation status, the International Union for Conservation of Nature's Red List of Threatened Species or IUCN Red List was categorizing brownbanded bamboo shark as "Near Threatened" without scientific stock assessments. The decision was based only on the rapid decline of the total shark landing within the last decade (Krajangdara, 2014; Dudgeon *et al*., 2016).

The inappropriate data collections made the status of this species unclear (Reuter *et al*., 2010). For example, poor species identification and inappropriate catch have been reported regarding the lack of taxonomic skills. Additionally, landings data have not been collected annually in some areas (Wanchana *et al*., 2016).

To respond to this situation, the Southeast Asian Fisheries Development Center (SEAFDEC), a regional inter-governmental organization, was conducted a data collection project on elasmobranch including shark, ray, and skate. This project aimed to improve the data collection procedures and species identification techniques for elasmobranch in the region during 2015 – 2016 as an attempt to conduct the scientific based fishery management (Wanchana *et al*., 2016).

For the data-poor fisheries, where the age determination is very difficult and the long-term catch and effort series cannot be provided, "per-recruit" analyses such as yield per recruit (YPR) and spawning per recruit (SPR) analyses were identified as models providing Biological Reference Points (BRPs) based on the limited data (Beverton and Holt, 1957; Goodyear, 1993; Sparre and Venema, 1998; Noranarttragoon et al., 2011). In the case of YPR analysis, the BRPs provide indicators of "growth overfishing" when the fish stock cannot produce the maximum yield under the fishing pressure at that time. For the SPR, BRPs provide indicators of "recruitment overfishing" which is the status of unsustainable fisheries because the amount of the spawners escaped from the fisheries are insufficient for producing the next generation (Goodyear, 1993; Chen *et al*., 2007).

This study aimed to investigate the stock status of brownbanded bamboo shark in Southeast Asia by using YPR and SPR analyses as the growth and recruitment overfishing thresholds, respectively.


**MATERIALS AND METHODS**

*Data collection*

This study uses secondary data from the "Regional Sharks, Rays and Skates Data Collection project" which was conducted during 2015 – 2016. All species were identified by SEAFDEC and well-trained local experts following the identification book following the Standard Operation Procedure (SEAFDEC, 2017). Data were collected from the commercial otter board trawl fishery landing sites in Sihanoukville, Cambodia (Sv), Songkhla, Thailand (Sk), and Kota Kinabalu, Malaysia (KK) where the total composition of *C. punctatum* was 40% of all elasmobranch (Wanchana *et al*., 2020) as shown in Figure 1.
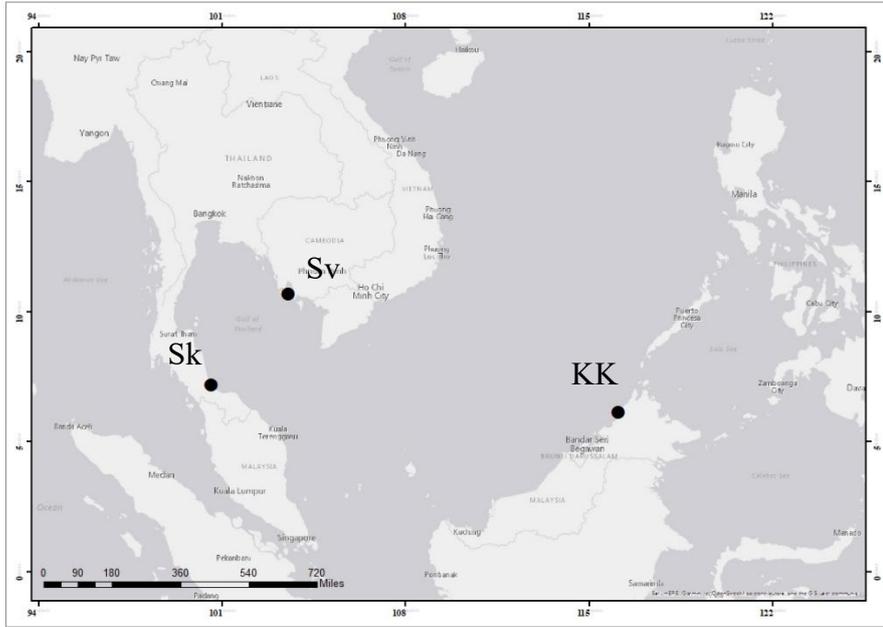
Figure 1.  Sampling sites of brownbanded bamboo shark specimen collection: Sihanoukville, Cambodia (Sv), Songkhla, Thailand (Sk), and Kota Kinabalu, Malaysia (KK).

*Length-weight relationship*

The length-weight relationship can provide essential information about the biological growth pattern of a species. The parameters of the length-weight relationship shown in Equation 1 (Ricker, 1975) were estimated using linear regression after logarithmic conversion. The equation is:

$$W = \alpha TL^{\beta} \qquad (1)$$

The parameters for all equations were explained in Table 1.

Table 1. The summary table for parameter symbols

| Symbols | Explanations |
|---|---|
| $\Phi'$ | Growth performance index |
| $\alpha$ | Condition factor for length-weight relationship |
| $a$ | The intercept of the linear regression for the observed probability of capture |
| $a'$ | The intercept of the linear regression for the estimated probability of capture |
| $\beta$ | Regression factor for length-weight relationship |
| $b'$ | Regression factor for the estimated probability of capture |
| $c$ | The intercept of the linear regression for total mortality estimation |
| $C_{L1,L2}$ | Number of fish caught at length interval between $L_1$ and $L_2$ |
| $E$ | Exploitation ratio |
| $F$ | Fishing mortality (year$^{-1}$) |
| $F_{curr}$ | Fishing mortality of current situation (year$^{-1}$) |
| $F_{0.1}$ | Fishing mortality produced from the 10% of the tangent of YPR curve (year$^{-1}$) |
| $F_{max}$ | Fishing mortality produced from the peak of YPR curve (year$^{-1}$) |
| $F_{X\%}$ | Fishing mortality that spares X% of spawning stock (year$^{-1}$) as $F_{30\%}$ and $F_{20\%}$ |

| $K$ | vBGC parameter ($year^{-1}$) |
|---|---|
| $M$ | Natural mortality ($year^{-1}$) |
| $mL$ | Mid-length between length interval (cm) |
| $L_1$ and $L_2$ | Lower and Upper length interval (cm), respectively |
| $L_{25}$, $L_{50}$, $L_{75}$ | The length at 25, 50, and 75% selectivity, respectively |
| $L_m$, $t_m$ | Length at first maturity (cm) and age at first maturity (year), respectively |
| $L_r$, $t_r$ | Length at recruitment (cm) and age at recruitment (year), respectively |
| $L_t$ | Length (cm) at age $t$ (year) |
| $L_\infty$ | vBGC parameter (average maximum length) (cm) |
| $S_t$, $S_t'$ | Observed and Estimated selectivity |
| $TL$ | Total length (cm) |
| $\Delta t_{L1,L2}$ | Difference in age between length $L_1$ and $L_2$ (year) |
| $t_\lambda$ | Age endpoint (year) |
| $t_{max}$ | Maximum age (year) |
| $t_{mL}$ | Age at mid-length from length interval (year) |
| $t_0$ | vBGC parameter (theoretical age at length 0) (year) |
| $t_c$ | Age at first capture (year) |
| $t_L$ | Age at length $L$ (year) |
| $W_\infty$ | Average maximum weight (kg) |
| $Z$ | Total mortality ($year^{-1}$) |

Differences between sex and area were tested for statistical significance from the log-linear transformation of Equation 1 using the R package 'FSA' provided by Ogle *et al.* (2020).

*Growth parameters estimation*

von Bertalanffy's growth curve is expressed as:

$$L_t = L_\infty\left(1 - e^{-K(t-t_0)}\right) \tag{2}$$

The parameters of the growth curve $L_\infty$, $K$, and $t_0$ were estimated by the electronic length-frequency analysis incorporating with the genetic algorithm, ELEFAN_GA provided in TropFishR (Taylor and Mildenberger *et al.*, 2017). It can search for the best combination of $L_\infty$ and $K$ in a broader randomized manner by using the genetic algorithm, which is an optimising method inspired by genetic mutation and selection for the evolution (Scrucca, 2013). It is expected to find better growth parameters faster than the previous algorithms even if the data is not enough and continuous (Mildenberger *et al.*, 2017). The number of iterations for ELEFAN_GA were set as 1000 as recommended, and the initial value for $L_\infty$ was set based on the estimator from Powell-Weatherall's method, the method which initial value for $L_\infty$ was estimated from the ratio between intercept and slope of the curve between $L'$ and $\bar{L} - L'$ (Powell, 1979).

The inverse von Bertalanffy's growth function (Mackay and Moreau, 1990) was used for the age estimation. The equation is as follows:

$$t = t_0 - \left(\frac{1}{K}\right)\ln\left(1 - \frac{L_t}{L_\infty}\right) \tag{3}$$

Using the growth parameters from von Bertalanffy's growth equation, the growth performance index, $\Phi'$, was calculated (Pauly and Munro, 1984) for the comparison of the growth curve between the same species or species with similar shape by the equation:

$$\Phi' = \log K + 2 \log L_\infty \tag{4}$$

*Estimation of mortality, gear selectivity, and maturation size at age*

The length-converted catch curve (Pauly, 1984, 1983) was applied to estimate mortality and gear selectivity by utilizing the size frequency of the sample in each length class to estimate the negative slope of the catch curve as the total mortality.

Total mortality ($Z$) was estimated from a linear regression using Equation 5:

$$\ln \frac{C_{L1,L2}}{\Delta t_{L1,L2}} = c - Z * t_{mL} \tag{5}$$

where $t_{mL}$ was estimated from $mL$ which is the middle length between $L_1$ and $L_2$ by using Equation 3.

The difference in age between upper and lower interval, $\Delta t_{L1,L2}$, was calculated using Equation 6:

$$\Delta t_{L1,L2} = \frac{1}{K} \ln \left( \frac{L_\infty - L_1}{L_\infty - L_2} \right) \tag{6}$$

Natural mortality was estimated using Tanaka's equation (Tanaka, 1960),

$$M = \frac{2.5}{t_{max}} \tag{7}$$

where $M$ is natural mortality, and $t_{max}$ is the maximum age (years). The $t_{max}$ was estimated based on the maximum body length in the sample and Equation 3.

Fishing mortality $F$ was estimated by subtracting $M$ from $Z$. The exploitation ratio $E$ was estimated from the ratio between $F/Z$

The observed selection ogive, $S_t$, was estimated using Equation 8:

$$S_t = \frac{C_{L1,L2}}{\Delta t_{L1,L2} e^{a - Z t_{mL}}} \tag{8}$$

and the estimated selection ogive, $S_t'$, was calculated using Equation 9:

$$S_t' = \frac{1}{1 + e^{a' + b'}} \tag{9}$$

Catch selectivity was parameterized by $L_{25}$, $L_{50,}$ and $L_{75}$. The results are provided by age and converted to length. Size selectivity for YPR and SPR analyses was assumed to be knife-edge at $L_{50}$. The $L_{50}$ and the length at first maturity, $L_m$, were converted to $t_c$ and $t_m$ using Equation 3.

The $L_m$ was assumed to be 65 cm referring to the previous studies (Ahmad and Lim 2012; Dudgeon et al. 2016; Krajangdara 2017).

*Sensitivity test*

A sensitivity test for growth parameters, $L_\infty$ and $K$, and $t_{max}$ to the estimation of the current fishing mortality, $F_{curr}$, was examined by varying parameters by $\pm$ 1%, 3%, and 5%, independently.

*Per-recruit analysis*

YPR was calculated via Equation 10, expressed as:

$$\frac{Y}{R} = FW_\infty e^{-M(t_c-t_r)} \times \sum_{n=0}^{3} \frac{A_n e^{-nK(t_c-t_0)}}{F+M+nK}\left\{1 - e^{-(F+M+nK)(t_\lambda-t_c)}\right\} \qquad (10)$$
$$\begin{cases} n &= 0, & 1, & 2, & 3 \\ A_n &= 1, & -3, & 3, & -1 \end{cases}$$

The $t_\lambda$ for YPR and SPR was assumed to be 20 years to involve the possible range of the maximum age of the species (Dudgeon *et al*., 2016). $W_\infty$ was calculated using $L_\infty$ substituted into Equation 1.

SPR analysis was conducted using the following equations.

For $t_c \leq t_m$,
$$SPR = W_\infty e^{-M(t_c-t_r)-(F+M)(t_m-t_c)} \sum_{n=0}^{3} A_n e^{-nK(t_m-t_0)}\left\{\frac{1-e^{-(F+M+nK)((t_\lambda-t_m))}}{F+M+nK}\right\},$$

For $t_c > t_m$,
$$\begin{aligned} SPR = \quad & W_\infty e^{-M(t_m-t_r)} \sum_{n=0}^{3} A_n e^{-nK(t_m-t_0)}\left\{\frac{1-e^{-(M+nK)((t_c-t_m))}}{M+nK}\right\} \\ + \quad & W_\infty e^{-M(t_c-t_r)} \sum_{n=0}^{3} A_n e^{-nK(t_c-t_0)}\left\{\frac{1-e^{-(F+M+nK)((t_\lambda-t_m))}}{F+M+nK}\right\} \end{aligned} \quad\cdots\cdots\cdots(11)$$
$$\begin{cases} n &= 0, & 1, & 2, & 3 \\ A_n &= 1, & -3, & 3, & -1 \end{cases}$$

The %SPR was estimated from Equation 12.

$$\%SPR = 100\% \times \frac{SPR}{SPR_{F=0}} \qquad (12)$$

*Biological reference points (BRPs)*

The reference points for YPR were $F_{0.1}$ and $F_{max}$ (Beverton and Holt, 1957; Chen *et al*., 2007). $F_{max}$ provides the fishing mortality, $F$, which maximizes the yield, at the given age at first capture and assumed constant recruitment. $F_{0.1}$ is a precautionary reference point for the $F$ where the slope of the YPR curve is 10% of the slope at the origin (Goodyear, 1993; Zhou *et al*., 2020). $F_{0.1}$ is referred to as a target BRP, which is recommended upper limit of the fishing mortality considering the uncertainties of the estimations. $F_{max}$ is referred to as a limit BRP, which is the upper limit without considering the uncertainties.

For SPR, the BRPs were provided as X%SPR, the fishing mortality producing $X$% of the expected spawning stock biomass per recruit in the absence of fishing (Goodyear, 1993). The critical level was usually set in the range of 20%–30%. Zhou *et al*. (2020) noted that the $F_{\%SPR}$ for elasmobranchs should be higher than that for teleosts. Thus, values for $F_{30\%}$ and $F_{20\%}$ were used as target and limit BRPs respectively.

**RESULTS**

The total landing of brownbanded bamboo shark was highest in Sv (7,282 kg) followed by Sk (3,875) and KK (2,201 kg). Regarding the catch composition, brownbanded bamboo shark occupied a higher percentage of the total elasmobranch as 52.36, 43.78, and 18.76% for Sv, Sk, and KK, respectively.

The mean total lengths for Sv, Sk, and KK were 58.60 ± 13.77, 55.78 ± 14.68, and 74.38 ± 11.06 cm, respectively. The sample size of elasmobranch by number were 709, 2,704, and 957 tails for Sv, Sk, and KK, respectively (Table 3). The ratio of landing by weight of brownbanded bamboo shark in three landing sites is shown in Figure 2.
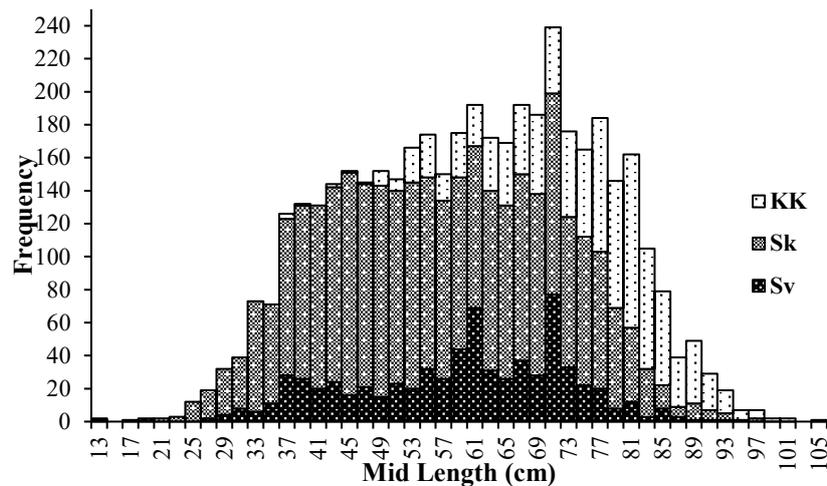


Figure 2. Size frequency of brownbanded bamboo shark by area

*The length-weight relationship*

Estimations of the length-weight relationship by landing site for brownbanded bamboo shark are shown in Table 2. The results showed that significant differences were found only from the factor area (p-value for all landing sites were <0.001) and did not found in sex.

Table 2. Length-weight relationship parameters of brownbanded bamboo shark caught in the three landing sites from 2015 to 2016.

|     | $\alpha$ | $\beta$ | 95%C.I. | $R^2$ |
|-----|----------|---------|---------|-------|
| Sv  | $6.90 \times 10^{-6}$ | 2.87 | (2.81 – 2.95) | 0.89 |
| Sk  | $2.12 \times 10^{-6}$ | 3.15 | (3.13 – 3.17) | 0.97 |
| KK  | $1.90 \times 10^{-6}$ | 3.15 | (3.10 – 3.21) | 0.93 |

*Growth, mortality, and gear selectivity*

The initial values of $L_\infty$ were set as 78.82, 87.25, and 86.66 cm for Sv, Sk, and KK, respectively. The estimated growth parameters, mortality, and size and age at first capture were provided in Table 3. The fitted growth curves to the length-frequency data were shown in Figure 3.

Table 3. Estimated growth parameters for the three landing sites

| Landing sites | $L_\infty$ | $K$ | $t_0$ | $\Phi'$ | $Z$ | $t_{max}$ | $M$ | $F$ | $E$ | $L_{50}$ | $t_c$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sv | 81.62 | 0.37 | -0.43 | 3.39 | 0.54 | 10 | 0.25 | 0.29 | 0.54 | 39.49 | 1.36 |
| Sk | 88.09 | 0.51 | -0.29 | 3.39 | 0.64 | 10 | 0.25 | 0.40 | 0.63 | 30.41 | 0.54 |
| KK | 86.48 | 0.40 | -0.37 | 3.48 | 0.22 | 15 | 0.17 | 0.06 | 0.26 | 55.59 | 2.20 |
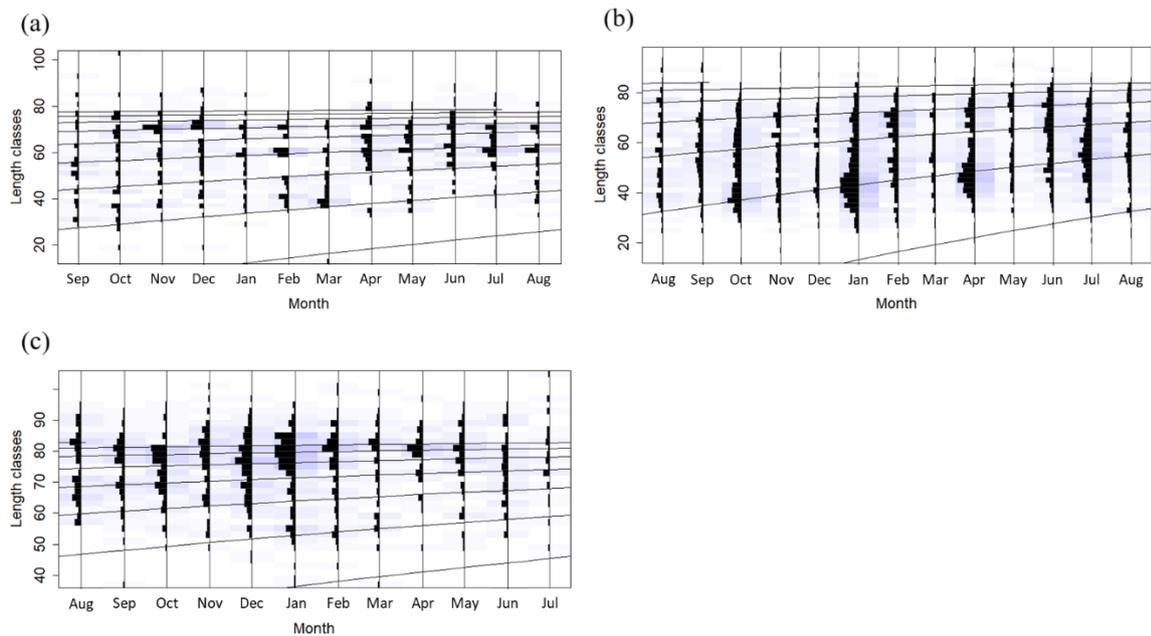


Figure 3. Fitting growth curve of brownbanded bamboo shark to the monthly length-frequency data from Sv (a), Sk (b), and KK (c).

The gear selectivity estimations were conducted separately for each of the landing sites and are listed in Table 4 and Figure 4.

Table 4. Gear selectivity of brownbanded bamboo shark from the three landing sites.

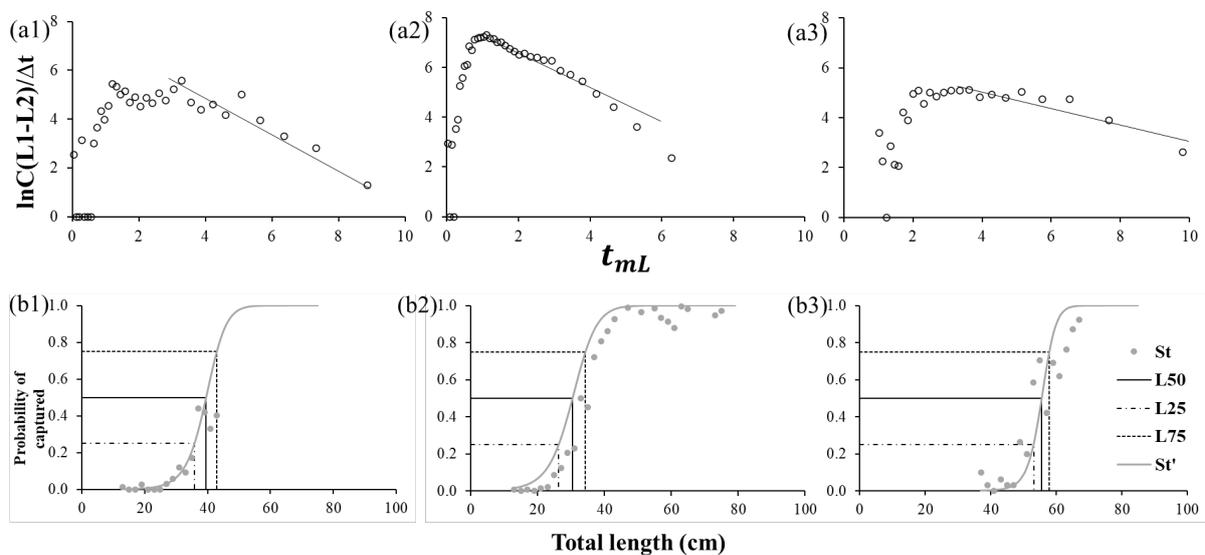|  | Sv | Sk | KK |
|---|---|---|---|
| $L_{50}$ (cm TL) | 39.49 | 30.41 | 55.59 |
| $t_{50}$ (year) | 1.36 | 0.54 | 2.20 |

Figure 4.  Catch curve of brownbanded bamboo shark by area (a) and selectivity curve of brownbanded bamboo shark by area (b) for Sv (1), Sk (2), and KK (3), where $S_t$, is the observed selection ogive and $S_t'$ is the estimated selection ogive. The regression lines on the catch curves were used for the estimation of the total mortality $Z$.

Results from gear selectivity show that the range between $L_{25}$, and $L_{75}$ of brownbanded bamboo shark from Sv and Sk were 35.78-42.89 cm for Sv, and 26.28-34.26 cm for Sk which were smaller than those caught from KK which the range was 53.10-57.90 cm. The length at first capture from Sv was slightly larger than Sk, and from KK was the largest.

The results of the sensitivity test for $F_{curr}$ by the difference of $L_\infty$, $K$, and $t_{max}$ were provided in Figure 5.
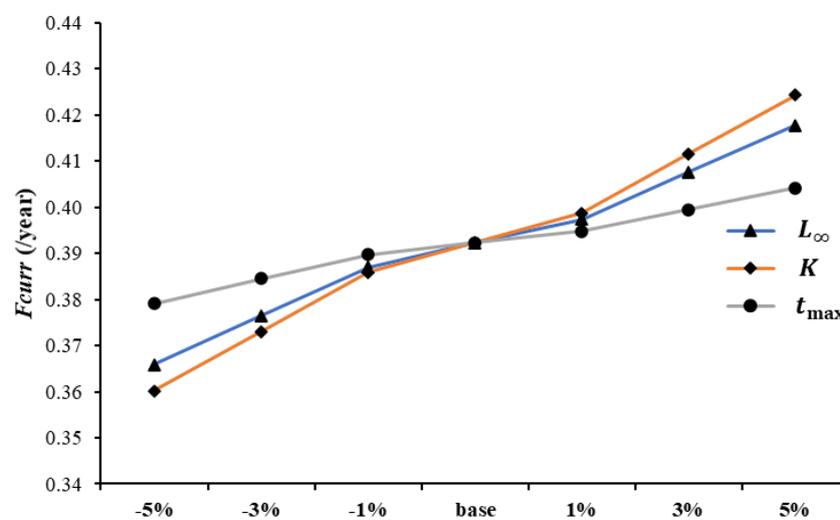


Figure 5. Sensitivity test for $F_{curr}$ varied by three parameters, $L_\infty$ and $K$, and $t_{max}$.

The sensitivity analysis shows that the $F_{curr}$ is directly varied by these three parameters. However, parameter $K$ gave the highest variation (approximately 8% for the 5% from the case) compared to other variables while $t_{max}$ gave the smallest variation (approximately 3% for the 5% from the base case).

*Per-recruit analysis and implementation*

The $t_m$ and $t_r$ were estimated from the $L_m$ from literature and $L_r$ from the smallest size caught in each area as 3.87 and 1.15 years for Sv, 2.64 and 0.00 years for Sk, and 3.11 and 0.98 years for KK, respectively. The surface plot for YPR and SPR analyses for the three landing sites were displayed in Figure 6. The results showed that the current fishing mortality has exceeded the BRPs for YPR ($F_{0.1}$) at Sv and both $F_{0.1}$ and $F_{max}$ at Sk, but not at KK. For SPR, only the current fishing mortality of KK that not exceeded any of the SPR's BRPs (20% and 30% SPR) as provided in Table 5.

Table 5. Results of yield per recruit (YPR) and spawning per recruit (SPR) analyses by the ratio between current fishing mortality ($F_{curr}$) and biological reference points ($F_{max}$, $F_{0.1}$, 20%SPR, and 30%SPR) from the three landing sites.

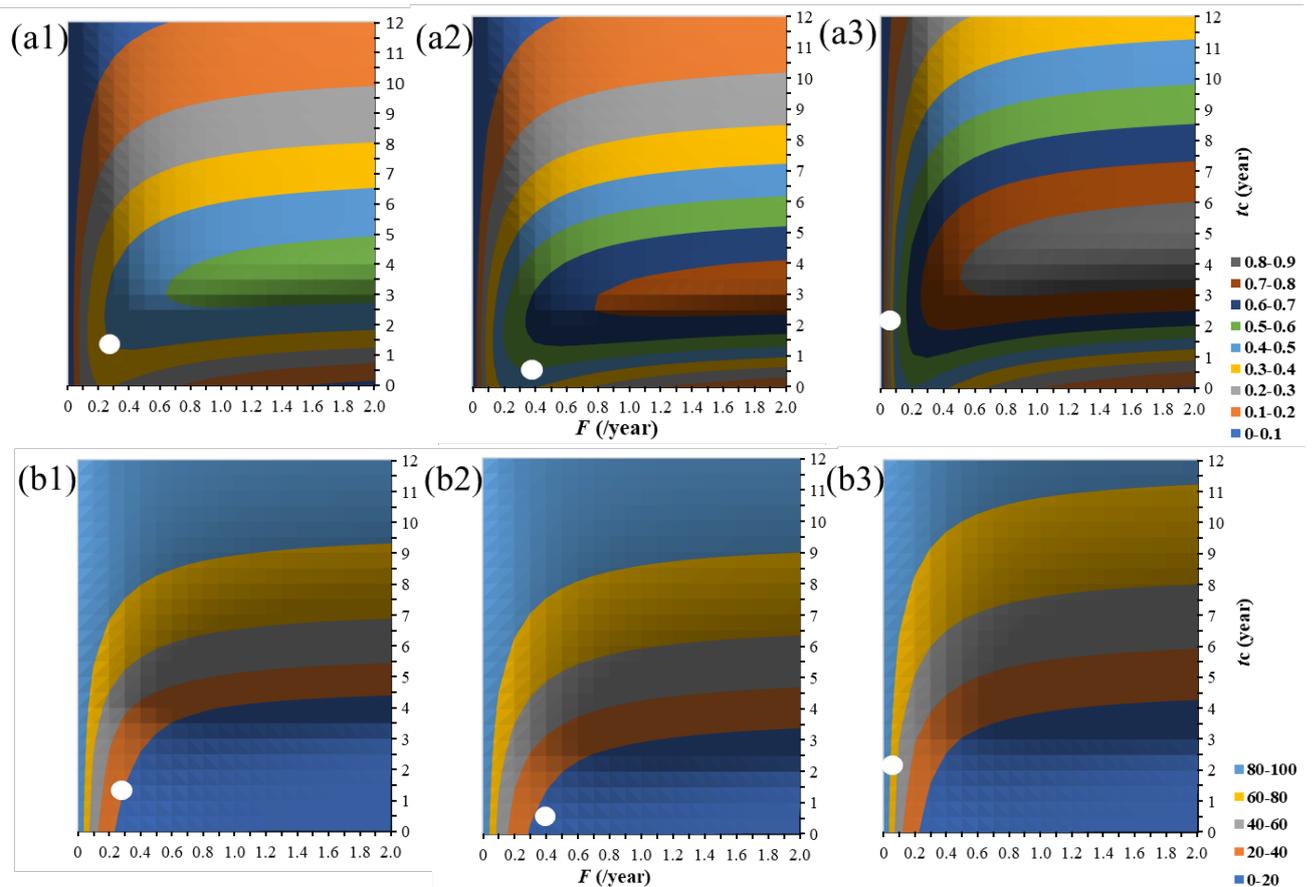|  | Sv | Sk | KK |
|---|---|---|---|
| $F_{curr}$ | 0.291 | 0.392 | 0.058 |
| BRPs |  |  |  |
| $F_{0.1}$ | 0.260 | 0.231 | 0.243 |
| $F_{max}$ | 0.438 | 0.340 | 0.487 |
| 30%SPR | 0.207 | 0.226 | 0.239 |
| 20%SPR | 0.290 | 0.319 | 0.354 |



Figure 6. Yield per recruit (a) and spawning per recruit (b) of brownbanded bamboo shark from for Sv (1), Sk (2), and KK (3). The white spots represent the current fishing situation with current $t_c$ and $F_{curr}$.

In Sv, the $F_{curr}$ was exceeded $F_{0.1}$ and both $F_{30\%}$ and $F_{20\%}$ for 11.5, 40.3, and 0.02%, respectively but, still 33.7% lower than $F_{max}$. For Sk, the $F_{curr}$ was exceeded all of the reference points, $F_{0.1}$, $F_{max}$, $F_{30\%}$, and $F_{20\%}$, for 69.8, 15.5, 73.6, and 22.8%, respectively. For KK, the results were contracted with Sv and Sk. $F_{curr}$ was smaller than all the reference points, $F_{0.1}$, $F_{max}$, $F_{30\%}$, and $F_{20\%}$, for 75.9, 88.0, 75.5, and 83.4%, respectively.

## DISCUSSIONS

*Length-weight relationship and growth parameters estimation*

The regression value, $\beta$ is recommended in the range of $2.5 < \beta < 3.5$ considering the assumption of the YPR and SPR model (Beverton and Holt, 1957; Froese, 2006; Ricker, 1975; Sparre and Venema, 1998). The result was confirmed that the length-weight relationship of brownbanded bamboo shark was fitted to the model's assumption. The significant differences in the length-weight relationships were found by area but not found by sex. Therefore, brownbanded bamboo shark data were assessed separately by area. Although sex factor may affect through the interaction terms, the analysis was not separated by sex, regarding the uncertainties from the gear selectivity and unclear life history between sex.

The growth parameters of brownbanded bamboo shark (Table 3) have never been estimated before. As a study of the related species, whitespotted bamboo shark (*Chiloscyllium plagiosum*) from Taiwan waters showed slightly larger size with slower growth rate, the $L_\infty$ and $K$ were 98.4 cm, 0.21 year$^{-1}$, and 3.31 for male and 93.12 cm, 0.22 year$^{-1}$, and 3.28 for female (Chen *et al.*, 2007).

The closer growth parameters can be observed in the tropical species. For example, for Halmahera walking shark (*Hemiscyllium halmahera*) from Indonesia and Spadenose shark (*Scoliodon laticaudus*) from eastern India, $L_\infty$, $K$, and $\Phi'$ were 81.5 cm, 0.51 year$^{-1}$, and 3.58, and 75.53 cm, 0.54 year$^{-1}$, and 3.49, respectively. According to the criteria of Branstetter (1987), brownbanded bamboo shark was the fast-growing with higher resilience as same as Halmahera walking shark, spadenose shark, and whitespotted bamboo shark (Branstetter, 1987; Liu *et al.*, 2015).

The $\Phi'$ was compared with Hemiscyllidae sharks such as brownbanded bamboo shark *Chiloscyllium punctatum*, whitespotted bamboo shark *Chiloscyllium plagiosum*, and Halmahera walking shark *Hemiscyllium halmahera*. The difference of $\Phi'$ was smaller between brownbanded bamboo shark and Halmahera walking shark than whitespotted bamboo shark for $0.08 - 0.20$, and $0.05 - 0.14$, respectively.

*Mortality estimation, gear selectivity, and sensitivity test*

The results of the gear selectivity show that Sk has the smallest size at first captured comparing to Sv and KK. These were the results of the selected relative age of the catch curve (Figure 4a2) which the usable slope can be observed between age 1 to 4 years. The older relative age in the catch curve can cause the overestimation for $Z$ and $L_{50}$ which should be avoided (Sparre and Venema, 1998).

For the natural mortality, $M$, several empirical relationships were proposed and widely used, including life-history parameters such as growth parameters and longevity (Pauly, 1980; Hoenig, 1983; Then *et al.*, 2015). The Tanaka model (Tanaka, 1960) was selected for this study considering the simplified equation and wide applications especially in Japanese official stock assessments, which incorporates a maximum age, $t_{max}$.

In this study, the $t_{max}$ was assumed for brownbanded bamboo shark according to the maximum age estimated from the length-converted catch curve by areas, such as $t_{max}$ 10 years for Sv and Sk, and $t_{max}$ 15 years for KK. The $t_{max}$ of brownbanded bamboo shark can be reached to 16–25 years in captivity (Chen *et al.*, 1990; Harahush *et al.*, 2007; Dudgeon *et al.*, 2016). However, the specific longevity may vary depending on the distribution of the populations with different environmental condition. therefore, the brownbanded bamboo shark in the natural habitat should have longevity shorter than 16 years. Also, the assumption of $t_{max}$ for determining $M$ was the $t_{max}$ in the situation without fishing pressure (Tanaka, 1960). Therefore, the decided $t_{max}$ for this study was shorter than in previous report.

The sensitivity test showed that the estimated $F_{curr}$ will be increased by the increase of the growth parameters and age at the endpoint with moderate sensitivity. For SPR, $L_m$ affects the results because it directly affects the spawning stock biomass (Goodyear, 1993).

*Per-recruit analysis*

One of the input parameters for SPR is the age at first maturity, $t_m$, which was estimated by converting from the size at first maturity, $L_m$. The range of $L_m$ for brownbanded bamboo shark in Southeast Asia was ranged between 63 – 84 cm. In this study, the possible $L_m$ for male and female were selected as the size that was covered by the $L_m$ range of both sexes (Yano et al., 2005; Krajangdara, 2017).

The results from Sv and Sk were indicated that fisheries for brownbanded bamboo shark in this area are almost inefficient and has no room to increase fishing mortality for sustainability. In KK, the stock status was still in acceptable condition compared to Sv and Sk with a lower $F_{curr}$ comparing to the target reference points. This probably due to the difference is in the implementation of fishing ground zonation of Malaysia (Department of Fisheries, 2015; Ramli, 2015). The major fishing ground was up to 8 nautical miles from the shoreline in KK, but approximately 5 nm in Sv and Sk. Brownbanded bamboo shark and other several elasmobranchs use the coastal shallow area as nursery areas (Heupel *et al.*, 2007; Davy *et al.*, 2015; Dudgeon *et al.*, 2016). The proper zoning will be effective for protecting small brownbanded bamboo shark and increase $t_{50}$.

*The suggested management measures*

The landing of brownbanded bamboo shark has been reported as a bycatch in the region alongside other elasmobranchs with a higher percentage (SEAFDEC, 2006). In Southeast Asia, the fishing situation is far more complexed by the multi-species fishery together with the data-poor situation (Harlyan *et al.*, 2019). In such situations, the species-specific regulation may not be fully effective.

The age or size at first captured, as well as the other management options, of this species, can be simply increased with several approaches. The first approach was to improve the fishing gear design such as using the "Trawling Efficiency Device, TED" as the options to reduce the elasmobranch bycatch (Watson *et al.*, 1986; Brčić *et al.*, 2015). The second approach was the zonation which has the potential to conserve the small size brownbanded bamboo shark as the larger shark can be found with higher density in the deeper water than in the shore area (Speed *et al.* 2010). The third option will be the establishment of a Marine Protected Area (MPA) to conserve the juvenile shark and other fishery resources (Heupel *et al.*, 2007; 2018; Arai and Azri, 2019). Several previous studies identifying the hot spot area may be useful for establishing the MPA (Pennino *et al.*, 2013; Giménez *et al.*, 2020).

**CONCLUSIONS**

Regarding the study, the fisheries for brownbanded bamboo shark in Kota Kinabalu in Malaysia was efficient and sustainable with the $F_{curr}$ smaller than the BRPs but in Sihanoukville, Cambodia, and Songkhla, Thailand, it was almost inefficient and has no room to increase fishing mortality for sustainability with the $F_{curr}$ exceeded the BRPs.

Considering the bycatch issue and multi-species fishery situation in the region, the management options should be considered such as fishing gear improvement, fishing zonation, and MPA.

## ACKNOWLEDGEMENTS

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