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**Stock assessment of elasmobranch in Southeast Asia using yield per recruit
and spawning per recruit analyses**

(東南アジアにおける板鰐類の YPR・SPR 解析を用いた資源評価)

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Abstract

Background and Objectives

The subclass Elasmobranchii comprises cartilaginous fishes that have a long history of evolution and adaptation that dates back to the early Devonian (400 million years ago). Because of their low resilience life histories with relatively long lifespans and slower growth rates than teleosts, elasmobranch biology and stock assessment have been studied worldwide. Despite the susceptibility of elasmobranchs to modern fishing methods, catch data of elasmobranchs, especially sharks and rays, are limited in many regions including Southeast Asia. As a result, stock assessment using data collected at the regional levels is limited. To develop a reliable data collection process, the Southeast Asian Fisheries Development Center (SEAFDEC) conducted a project during 2015-2016 called “Regional sharks, rays and skates data collection” at 11 pilot sites in 6 member countries. During the project, 163 tons of sharks and 253 tons of rays were landed. Using the data collected from the project, this study aimed to determine the stock status of elasmobranchs in Southeast Asia by conducting stock assessment with yield per recruit (YPR) and spawning per recruit (SPR) analyses.

Materials and Methods

The target species for the stock assessment were selected based on the availability and reliability of monthly length-frequency data, which should be continuous with at least 200 samples per year. The length-weight relationship of each species selected was analysed, and outliers were omitted. Length-frequency data were used to estimate growth parameters, such as average maximum length (L_{∞}), growth rate (K), and growth performance index (Φ'), using four methods namely K -Scan, Response Surface Analysis (RSA), ELEFAN combined with Simulated Annealing (ELEFAN_SA), and ELEFAN combined with Genetic Algorithm (ELEFAN_GA). Four sets of provisional results were finalised based on the goodness of fit score (R_n), which was calculated from the number of peaks of monthly length-frequency and the number of peaks that were selected for fitting the growth curve. The score was provided along with the results. Total mortality (Z) and gear selectivity (L_c) were estimated using a length-converted catch curve. Natural mortality (M) was estimated based on the maximum age (t_{max}), which was estimated from various methods and summarised by the median of those results. Fishing mortality (F_{curr}) was determined

from the difference between Z and M . The growth parameters, mortality parameters, and length at first capture were used as inputs for the YPR and SPR analyses. Finally, biological reference points (BRPs) were derived from YPR and SPR analyses. They included target reference points, $F_{0.1}$ and $F_{30\%}$ for YPR and SPR analyses, respectively, and limit reference points $F_{\max}$ and $F_{20\%}$ for YPR and SPR analyses, respectively.

Results and Discussion

A total of 32 stocks of sharks and rays were selected from 6 landing sites in 4 countries. All of the selected species showed isometric growth pattern based on the criteria of Froese (2006) except for the spadenose shark (*Scoliodon laticaudus*) from Myanmar, which resulted from a data collection error. The growth parameter estimation showed that 27 stocks had rapid growth rates, 4 stocks had average growth rates, and 1 stock of female whitespotted whiptail (*Maculabatis gerrardi*), the largest stingray found in this study, had a slow growth rate. The maximum age ($t_{\max}$) estimated for the natural mortality (M) estimation showed that elasmobranchs in this study, $t_{\max}$ varied widely from 3.16 years in male sharpnose stingray (*Telatrygon zugei*) from Malaysian waters in the South China Sea to 53.22 years in female *M. gerrardi* from Malaysian waters in the Andaman Sea. However, these results were estimated from empirical equations, therefore, the true $t_{\max}$ of these species may have differed from these results. A sensitivity test showed that L_{∞} had the highest effect on changing the current fishing mortality, F_{curr} , ($\pm 3\text{-}17\%$) while $t_{\max}$ had the smallest effect ($\pm 0.3\text{-}1.8\%$). The results of both YPR and SPR showed that in 7 stocks (22%), F_{curr} exceeded the limit BRPs, while in 10 stocks (31%), F_{curr} was below the BRP. For the selected stocks, the sub-region with the lowest exploitation rate was the South China Sea which was represented by only one country with a specific fishing ground. Based on the study results, the suggested management measures were fishing gear adaptation, establishment of marine protected areas, and zonation improvement.

Table of contents

	Page
Abstract.....	i
Table of contents.....	iii
List of tables.....	v
List of figures.....	vi
Acknowledgements.....	viii
1. Introduction.....	1
1.1. Elasmobranchs.....	1
1.2. The role of elasmobranchs in the marine ecosystem.....	3
1.3. The current study of elasmobranch stock status and management measures.....	4
1.4. Fish stock assessment.....	7
1.5. Shark and ray management in Southeast Asia.....	10
1.5.1. Indonesia.....	12
1.5.2. Malaysia.....	12
1.5.3. Thailand.....	13
1.6. SEAFDEC shark and ray data collection project.....	13
2. Study objectives.....	15
3. Materials and methods.....	16
3.1. Data collection.....	16
3.2. Length-weight relationship.....	18
3.3. Estimation of growth parameter.....	21
3.4. Estimation of mortality, selectivity, and size and age at first maturity.....	21
3.5. Per recruit analysis.....	23
3.6. Biological reference points (BRPs).....	24
3.7. Sensitivity test.....	25
4. Results.....	26
4.1. Length-weight relationship and statistical tests.....	27
4.2. Growth parameter estimation.....	29
4.3. Mortality estimation.....	30
4.3.1. Total mortality (Z).....	30
4.3.2. Natural mortality (M).....	36
4.3.3. Fishing mortality (F) and exploitation ratio (E).....	37
4.3.4. Gear selectivity.....	38
4.4. Yield per recruit analysis and spawning per recruit analysis.....	44
4.4.1. Sharks.....	45
4.4.1.1. Bamboo shark (Family Hemiscyllidae).....	45
4.4.1.2. Catshark (Family Scyliorhinidae).....	51
4.4.1.3. Requiem shark (Family Carcharhinidae).....	54
4.4.2. Rays.....	56
4.4.2.1. Sharpnose stingray (<i>Telatrygon zugei</i>).....	56
4.4.2.2. Bluespotted maskray (<i>Neotrygon kuhlii</i>).....	61
4.4.2.3. Dwarf whipray (<i>Brevitrygon heterura</i>).....	66
4.4.2.4. Spotted stingray (<i>Maculabatis gerrardi</i>).....	71
4.5. Sensitivity test.....	76
4.6. Shark and ray stock status by sub-regions.....	77

5. Discussion.....	79
5.1. Data selection, length-weight relationship, and growth parameters estimation.....	79
5.1.1. Data selection.....	79
5.1.2. Length-weight relationship.....	79
5.1.3. Growth parameter estimation.....	80
5.2. Mortality estimation and gear selectivity.....	81
5.3. Stock status from YPR and SPR.....	82
5.4. Suggested management measures.....	83
6. General conclusions.....	87
References.....	89
Appendices.....	105
Appendix A: Length-weight relationship of the selected elasmobranchs.....	106
Appendix B: Growth parameter of the selected elasmobranchs.....	112
Appendix C: Growth parameters comparison of the selected elasmobranchs with the literatures.....	131

List of tables

	Page
Table 1 Example of elasmobranch resource management by RFMOs and RFBs.....	5
Table 2 Data collection period in each country.....	16
Table 3 Abbreviations for area names.....	20
Table 4 Taxonomic classification for the selected species.....	26
Table 5 Catch amount of selected elasmobranch species used in this study by country by sub-region.....	26
Table 6 Statistical test for the sexual dimorphism of selected elasmobranch species using Ogle <i>et al.</i> (2020).....	27
Table 7 Length-weight relationship parameters for every selected elasmobranch species.....	28
Table 8 Growth parameter estimation, L_{∞} , K , and t_0 with the growth performance index, Φ' , and the fitting score, R_n , for each shark and ray species.....	29
Table 9 Total mortality (Z), with the 95% C.I. for each shark and ray species.....	35
Table 10 Estimated t_{max} and M for elasmobranchs.....	36
Table 11 Total mortality (Z), natural mortality (M), fishing mortality (F), and exploitation ratio (E) estimation for elasmobranchs.....	37
Table 12 Size and age at first capture (L_c , t_c).....	43
Table 13 Size at first maturity (L_m) based on Ahmad and Lim (2012), Ahmad et al. (2014), and Krajangdara (2017), and estimated age at first maturity (t_m) based on L_m	44
Table 14 F_{curr} and BRPs for bamboo shark (Family Hemiscylliidae).....	45
Table 15 F_{curr} and BRPs for catshark (Family Scyliorhinidae).....	51
Table 16 F_{curr} and BRPs for requiem shark (Family Carcharhinid).....	54
Table 17 F_{curr} and BRPs for sharpnose stingray (<i>Telatrygon zugei</i>).....	56
Table 18 F_{curr} and BRPs for bluespotted maskray (<i>Neotrygon kuhlii</i>).....	61
Table 19 F_{curr} and BRPs for dwarf whipray (<i>Brevitrygon heterura</i>).....	66
Table 20 F_{curr} and BRPs for whitespotted stingray (<i>Maculabatis gerrardi</i>).....	71
Table 21 Stock status of shark and ray in Southeast Asia divided into sub-region. Green shows that the F_{curr} was smaller than BRPs and red shows that F_{curr} was equal to or larger than the BRPs	75
Table 22 Percentage of variation in the sensitivity test of F_{curr} varied by each scenario of three observed parameters.....	77
Table 23 Stock status of elasmobranchs where L (low exploitation): $F_{curr} < F_{target}$ and F_{limit} , M (medium exploitation): $F_{target} < F_{curr} < F_{limit}$, and H (high exploitation): $F_{curr} > F_{target}$ and F_{limit}	78

List of figures

	Page
Figure 1 Diversity of sharks (modified from Krajangdara, 2017).....	1
Figure 2 Diversity of rays (modified from Krajangdara, 2017).....	2
Figure 3 Comparison of resilience between Osteichthys and elasmobranchs. The resilience levels were converted from the intrinsic rate of population increasing (r) (applied from Froese et al., 2017). Trophic level by species was collected from FishBase.....	7
Figure 4 Catch amount statistics of sharks and rays of Indonesia, Malaysia, and Thailand from area 71 in Western Central Pacific, and area 57 in the Indian Ocean (SEAFDEC, 2020).....	11
Figure 5 Eleven landing sites (stars) in 6 countries selected for the project, 1 in Cambodia, 2 in Indonesia, 2 in Malaysia, 2 in Myanmar, 2 in Thailand, and 2 in Vietnam.....	16
Figure 6 Comparison between length-frequency with no continuous monthly length- frequency and not cover all the length classes (left) and the usable length- frequency data (right).....	17
Figure 7 Six landing sites (stars) selected for this study, 1 in Cambodia, 2 in Malaysia, 1 in Myanmar, and 2 in Thailand.....	18
Figure 8 Length measurements for sharks and rays used in this study according to the standard operation procedure (after SEAFDEC, 2017).....	19
Figure 9 Maritime area covered in this study.....	20
Figure 10 Length-converted catch curve for shark species. M: male, F: female.....	31
Figure 11 Length-converted catch curve for ray species. M: male, F: female.....	33
Figure 12 Gear selectivity for shark species. M: male, F: female	39
Figure 13 Gear selectivity for ray species. M: male, F: female.....	41
Figure 14 YPR surface plots for C_p (a1: CM/GT, a2: TH/GT, a3: ML/SC, a4: ML/AM), C_l (b1: male, b2: female from ML/AM), and C_h (c: ML/AM).....	46
Figure 15 YPR line plot at constant t_c for C_p (a1: CM/GT, a2: TH/GT, a3: ML/SC, a4: ML/AM), C_l (b1: male, b2: female from ML/AM), and C_h (c: ML/AM).....	47
Figure 16 %SPR surface plot for C_p , C_l , and C_h . a1, a2, a3, and a4 for C_p (a1: CM/GT, a2: TH/GT, a3: ML/SC, a4: ML/AM), C_l (b), and C_h (c).....	48
Figure 17 %SPR line plot at constant t_c for C_p (a1: CM/GT, a2: TH/GT, a3: ML/SC, a4: ML/AM), C_l (b), and C_h (c).....	50
Figure 18 YPR surface plot for A_m at TH/GT (a1: male, a2: female), ML/AM (b1: male, b2: female).....	52
Figure 19 YPR line plot at constant t_c for A_m at TH/GT (a1: male, a2: female), ML/AM (b1: male, b2: female).....	53
Figure 20 %SPR surface plot for A_m at TH/GT (a), and ML/AM (b).....	53
Figure 21 %SPR line plot at constant t_c for A_m at TH/GT (a), and ML/AM (b).....	54
Figure 22 YPR surface plot (a) and %SPR surface plot (b) for and S_l from MY.....	55
Figure 23 YPR line plot at constant t_c (a) and %SPR line plot at constant t_c (b) for S_l from MY.....	55
Figure 24 YPR surface plot for T_z at TH/GT (a1: male, a2: female), ML/SC (b1: male, b2: female), and ML/AM (c).....	57

Figure 25 YPR line plot at constant t_c for Tz at TH/GT (a1: male, a2: female), ML/SC (b1: male, b2: female), and ML/AM (c).....	58
Figure 26 %SPR surface plot for Tz at TH/GT (a), ML/SC (b), and ML/AM (c).....	59
Figure 27 %SPR line plot at constant t_c for Tz at TH/GT (a), ML/SC (b), and ML/AM (c).....	60
Figure 28 YPR surface plot for Nk at ML/SC (a1: male, a2: female), TH/AM (b1: male, b2: female), and ML/AM (c1: male, c2: female).....	62
Figure 29 YPR line plot at constant t_c for Nk at ML/SC (a1: male, a2: female), TH/AM (b1: male, b2: female), and ML/AM (c1: male, c2: female).....	63
Figure 30 %SPR surface plot for Nk at ML/SC (a), TH/AM (b), and ML/AM (c).....	64
Figure 31 %SPR line plot at constant t_c for Nk at ML/SC (a), TH/AM (b), and ML/AM (c).....	65
Figure 32 YPR surface plot for Bh at TH/GT (a1: male, a2: female), TH/AM (b1: male, b2: female), and ML/AM (c1: male, c2: female).....	67
Figure 33 YPR line plot at constant t_c for Bh at TH/GT (a1: male, a2: female), TH/AM (b1: male, b2: female), and ML/AM (c1: male, c2: female).....	68
Figure 34 %SPR surface plot for Bh at TH/GT (a), TH/AM (b), and ML/AM (c).....	69
Figure 35 %SPR line plot at constant t_c for Bh at TH/GT (a), TH/AM (b), and ML/AM (c).....	70
Figure 36 YPR surface plot for Mg at ML/SC (a) and ML/AM (b1: male, b2: female)....	72
Figure 37 YPR line plot at constant t_c for Mg at ML/SC (a) and ML/AM (b1: male, b2: female).....	73
Figure 38 %SPR surface plot for Mg at ML/SC (a) and ML/AM (b).....	73
Figure 39 %SPR line plot at constant t_c for Mg at ML/SC (a) and ML/AM (b).....	74
Figure 40 Sensitivity test for F_{curr} varied by three parameters, L_∞ and K , and t_{max}	76
Figure 41 Malaysian's fishing zonation from the shoreline (Zone A) to high sea (Zone C3) (applied from DoF, 2016).....	85

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Sincerely yours

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1. INTRODUCTION

1.1. Elasmobranchs

The subclass Elasmobranchii is a group of cartilaginous fish including sharks and rays, that evolved from 400 million years ago (Krajangdara, 2017). The long-time evolution has allowed them to adapt to various aquatic ecosystems. The evolution of elasmobranchs is unique compared to jawed fishes. Over 1,250 species of elasmobranchs are found globally (Ebert et al., 2017; Marramà et al., 2018; Stein et al., 2018). The long history of evolution has resulted in various kinds of sizes and habitats. Which were range from freshwater stingrays in the family Potamotrygonidae to several species of deep-sea elasmobranchs found in every ocean, and from the smallest sharks such as the smalleye pygmy shark, *Squaliolus aliae*, (20 cm, TL) to the largest like the whale shark, *Rhincodon typus*, (20 m, TL) (Kyne and Simpfendorfer, 2010; Liu et al., 2015; Lovejoy et al., 1998; Nelson, 2006; Rosa et al., 2008).

Most elasmobranchs are top predators in the marine ecosystem (Kiszka et al., 2014). Their important role is evident in their high trophic level at the range between 3.0-4.5 (Colman, 1997; Lindeman and Lindeman, 1942; Navia et al., 2017; Rastgoo and Navarro, 2017).

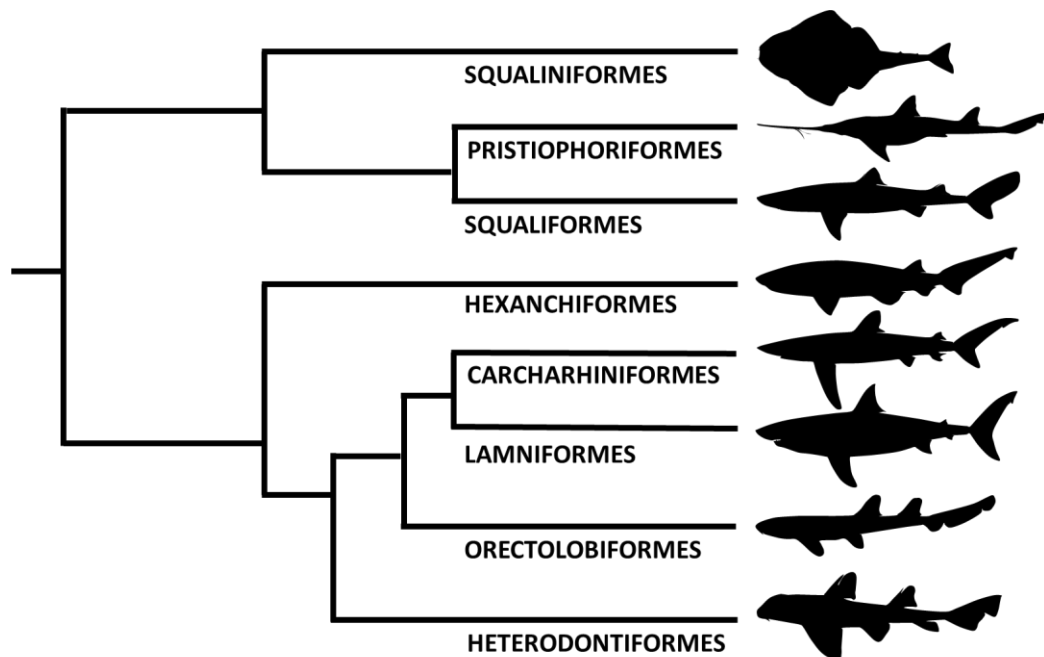


Figure 1. Diversity of sharks (modified from Krajangdara, 2017)

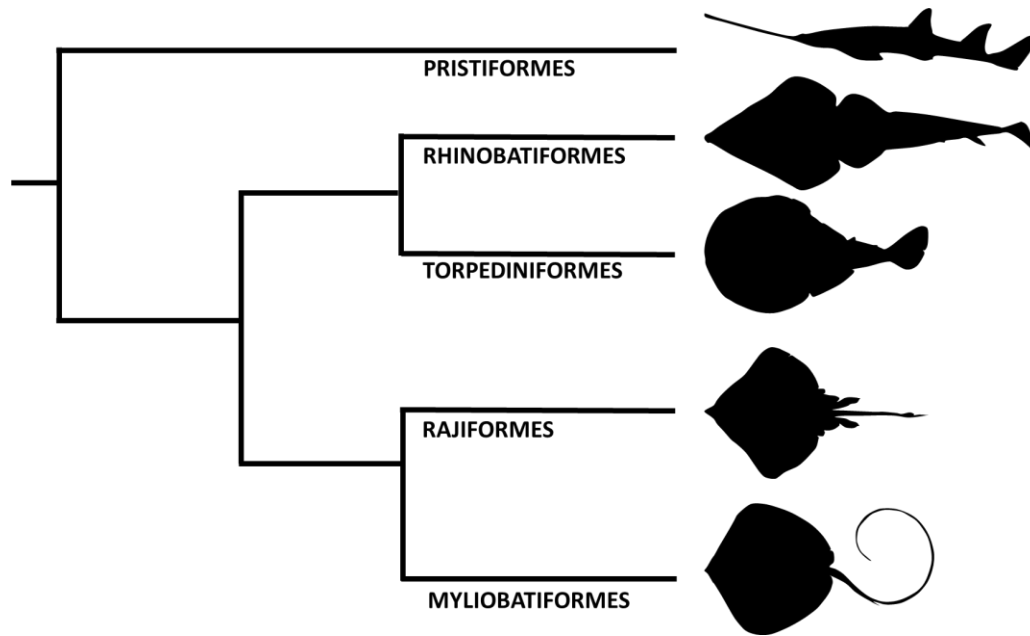


Figure 2. Diversity of rays (modified from Krajangdara, 2017)

Elasmobranchs prey on various kinds of food. The prey includes small invertebrates such as zooplankton for the whale shark, *Rhincodon typus*, marine mammal such as the seals for the great white shark, *Carcharodon carcharias*, and even seagrass for juvenile bonnethead shark, *Sphyrna tiburo* (Bornatowski et al., 2014; Leigh et al., 2018; Navia et al., 2017, 2007; Vaudo and Heithaus, 2011). The feeding behaviour, in some ways, can defy how elasmobranchs utilize the feeding ground as well. Several elasmobranch species have developed a deep relationship with coastal and estuarine habitats. A case study from the Caribbean Sea shows that shark species in the families Ginglymostomatidae and Carcharhinidae, and ray species in the families Dasyatidae and Myliobatidae often utilize coastal areas, especially several coral reefs, as a feeding ground (Bruns and Henderson, 2020). Several elasmobranchs use mangrove forests as the spawning ground, especially in the families Carcharhinidae, Hemiscyllidae, Dasyatidae, and Urotrygonidae (Davy et al., 2015; Every et al., 2017; Speed et al., 2016; Vaudo and Heithaus, 2011).

The reproductive strategies of elasmobranchs are a key factor in determining the diversity of life history. Elasmobranchs display three kinds of reproductive patterns namely oviparity, viviparity, and ovoviviparity (Parsons et al., 2008). Regarding sexual reproduction, elasmobranchs are sexually dimorphic, displaying differences in body size and genital organs (Cortés, 2000). However, recent studies show that parthenogenesis, (i.e. asexual reproduction without fertilization

by sperm) occur in some requiem shark species such as blacktip shark, *Carcharhinus limbatus* (see Chapman et al., 2008).

The life history of elasmobranchs is unique and, in some ways, closer to marine mammals than to teleosts (Cortés, 1998; Liu et al., 2015). This kind of life history can be explained as the *K*-selected species, the species that mature late and live long, according to the *r/K* selection theory (Hoenig and Gruber, 1990). These populations are susceptible to overfishing, especially if monitoring has not been conducted (Cailliet, 2015). The lack of assessment for elasmobranchs raises concern about possible stock collapses for these top predators (Carvalho et al., 2018; Cortés and Brooks, 2018; Ferretti et al., 2010; Navia et al., 2017; Nur-Farhana et al., 2013).

1.2. The role of elasmobranchs in the marine ecosystem

Elasmobranchs play an important role in the marine ecosystem including the role of mesopredator and apex predator, this role can be observed from the small coastal species until the long-range for the migratory species (Block et al., 2011; Kiszka et al., 2014; Wallach et al., 2015). Kiszka et al. (2014) suggested that apex predators are important because they control the number of lower trophic level species, including the meso-predators. Therefore, the absence of an apex predator can have a large effect on the ecosystem. One of the well-known case studies for the absence of the apex predator was the case study from Yellowstone national park in the United State of America where the population of an apex predator, the grey wolf (*Canis lupus*), declined due to hunting increase (Ripple and Beschta, 2006; Smith et al., 2003). This led to a significant increase of their prey, elk deer (*Cervus canadensis*), and the mesopredator Coyote (*Canis latrans*).

Similar effects can also be observed in the ocean (Heithaus et al., 2008; Rizzari et al., 2014). The large decline of top predators in the marine ecosystem such as sharks, alongside other large teleosts such as billfishes and tunas, resulted in a trophic level shift to the mesopredators (Heithaus et al., 2008). For the coral reef shark, Rizzari et al. (2014) and Roff et al. (2016) suggested that coral reef sharks are mesopredators that adjust the ecological balance in sensitive ecosystems such as coral reefs. Considering the sophisticated relationship between meso and apex-predators in the ecosystem, the absence of sharks can cause a weakening of the ecosystem, such as the coral reef ecosystem (Matich et al., 2017; Vaudo and Heithaus, 2011; Wallach et al., 2015). This result is supported by the narrower trophic level position of the adult sharks than in juveniles (Matich et al., 2017).

The global landing of the elasmobranchs reported by FAO declined by almost 20% from 2003 to 2012, due to the population decreasing despite several management measures were conducted (Davidson et al., 2016). Liu et al. (2015) suggest that the life history of the elasmobranchs is more like marine mammals than teleosts with a longer life span and slow growth rate. Stein et al. (2018) suggested that the negative effect on the population size should be cautious and put priority for further stock management because of the unique evolution and life history of elasmobranchs compared to other fishery resources (Dulvy et al., 2014; Stein et al., 2018).

Concern about the declining population of elasmobranchs has reached national and international organizations, such as the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), which is considering listing elasmobranchs as an endangered species (Friedman et al., 2018). Therefore, stock assessment is necessary to decide the appropriate management measures.

1.3. The current study of elasmobranch stock status and management measures

Elasmobranchs are caught alongside other target fish species in many fisheries around the world such as commercial longline, trawl, and gillnet (Oliver et al., 2015). However, the study about the elasmobranch biology and population dynamic is limited in several regions around the world. In the 20th century, some countries such as the United States of America conducted studies related to elasmobranchs which led to rapid development of stock assessment. The major inspirations can be identified as 4 issues namely, 1) the study of shark biology led by the U.S. Navy for military purpose, 2) the rise of shark game fishery, which later helped the tagging study for shark population, 3) The shark fin market in China for sharks caught in U.S. waters, and 4) the popularity of the movie “Jaws” (Castro, 2016).

From biological and resource management perspectives, the stock status of elasmobranchs has been of concern worldwide considering their slow growth rates and long-life spans. They have been recognized as one of the most threatened taxa after Amphibian (Prince, 2005; Sandoval-Castillo, 2019). Several studies were conducted to determine elasmobranch stock status worldwide. The methods ranged from the catch abundance index observed from CPUE standardization with the mixed model (Baum and Blanchard, 2010) to more sophisticated methods such as the size-sex-age structure model (Cortés, 2018; Punt et al., 2013).

The stock status of elasmobranchs in tropical areas, including the West Pacific (Australia and Southeast Asia, SEA), where the main issue for elasmobranchs is bycatch or unreported catch from various fishing activities (Cortés, 1998; Stobutzki et al., 2002). Punt et al. (2000) suggested that the stock status is closely related to the number of pups produced per stock biomass that remain on the fishing ground. A study from the same region also indicates that the migratory pattern of the concerned species should be observed together with fishing gear adaptation (Prince, 2005). In Central and South America, the impact of fishing activities on elasmobranchs was clarified. Several possible studies and management measures, such as the diversity, stock structure, and genetic identification of elasmobranchs were suggested (Clarke et al., 2016; Doherty et al., 2014; Sandoval Laurrabaquio-A et al., 2019). In the Mediterranean Sea, gear selectivity was observed for the appropriate size at first capture for several elasmobranch species (Echwikhi et al., 2014).

Recent studies indicated the population status of elasmobranchs around the globe using two types of indices namely 1) Living Planet Index, LPI, as abundance changing index, and 2) Red List Index, RLI, as extinction risk index (Pacoureau et al., 2021). The results indicate that elasmobranchs have declined in abundance approximately 70% during the past 50 years, which led to increased global extinction risk. This study was provided with the population status without stock assessment conducted. Since the 2010s, the stock assessment for elasmobranchs has been conducted for some species in many areas as showed in Table 1. To handle such a situation, stock management for elasmobranchs were operated by various Regional Fisheries Management Organization (RFMOs) and Regional Fisheries Bodies (RFBs). The recent study and management measures conducted by RFMOs are shown in Table 1 and the trophic level with resilience, the ability for each species to be recovered from the fishing activities, to fishing activities are provided in Figure 3.

Table 1. Example of elasmobranch resource management from RFMOs and RFBs.

Organization	Year	Target species	Management plan	Remarks
IOTC	2010	Mobulidae rays	Development of species identification guide and data collection process	Evgeny (2010)
IOTC	2016	Pelagic sharks	Study of catch composition and species diversity of	Novianto et al. (2016)

CITES	2013-2016	All sharks and rays with concerned stock status	pelagic shark species Up listing of concerned species for international trade prohibition or become transparent as much as possible	Friedman et al. (2018)
WCPFC	2012	Silky shark (<i>Carcharhinus falciformis</i>)	The first stock assessment conducted for <i>C. falciformis</i> bycatch from tuna fisheries	Rice and Harley (2012)
WCPFC	Until present	All sharks bycatch fishing activities	The fishery report from member country including bycatch species such as elasmobranch	Kim et al. (2019); Rice and Harley (2012); WCPFC (2019, 2010)
Western Pacific Regional Fishery Management Council	2007	Sharks	Reduce shark bycatch from pelagic longline	Gilman et al. (2007)
IUCN	2009	All concerned pelagic elasmobranchs	Up to date the stock status and identify the risk of being violated by fishery	Camhi et al. (2009)
SEAFDEC	2015-2016	Elasmobranchs in Southeast Asia	To observe the species diversity and catch of bycatch elasmobranch in the region	SEAFDEC (2017); Wanchana et al. (2020)

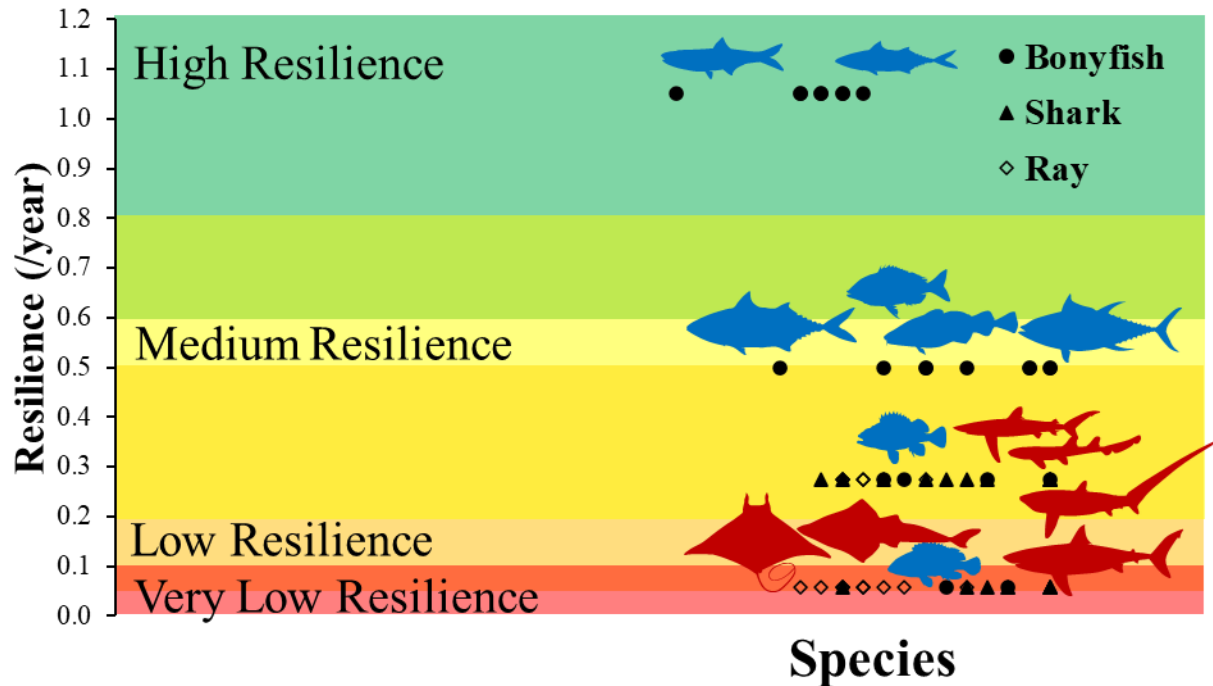


Figure 3. Comparison of resilience between Osteichthys and elasmobranchs. The resilience levels were converted from the intrinsic rate of population increase (r) (applied from Froese et al., 2017). Trophic level by species was collected from FishBase.

The elasmobranchs have been worried worldwide even though many management measures were established and implemented in several regions. Despite the various management measures conducted, the stock statuses of several concerned elasmobranch species in several regions still be concerned internationally because of the low resilience life history in Figure 3 (Froese et al., 2017). Closing or banning a fishery is a difficult choice because of the huge negative effect on fishers and various business involved, especially, for countries in which the fishing sector is an important income. The stock assessment is required to estimate the appropriate reference point for elasmobranch exploitation.

1.4. Fish stock assessment

The basic concept of stock assessment can be explained by the equation proposed by Russell (1942) which explains the relationship between biomass, growth, recruitment, natural mortality, and fishing activities at each period so-called population dynamics which can be explained as following equation (1)

$$B_{t+1} = B_t + (R + G) - (D + Y) \quad (1)$$

where

B_t	=	Biomass at time = t
B_{t+1}	=	Biomass at time = t+1
R	=	Weight gained from recruitment at time = t
G	=	Weight gain from growth at time = t
D	=	Weight loss from natural mortality at time = t
Y	=	Weight loss from fishing activities at time = t

In a normal situation, fish will usually have a high amount of recruitment to compensate for natural mortality. The amount of weight gained less the weight lost by natural mortality known as “surplus”, which can be utilized by fishing activity (Ricker, 1975).

According to equation (1), the only parameter we can control is the amount of catch, Y , which further reference points were developed according to this concept. To maintain the sustainable utilization of fishery resources, stock assessment can provide an essential reference point as a target or limited reference point. Such advice can be very useful for fishery managers and policymakers (Sparre and Venema, 1998).

Several methods and aspects have been conducted worldwide during the past decades. To maximize the usable resource, the basic concept known as Maximum Sustainable Yield (MSY) has been implemented worldwide by the United Nations since the 1930s. Its practice has become the world stock assessment standard practice until today for many countries and regions (Mace, 2001). Most models require population dynamics parameters and other relevant fisheries data (Cope and Punt, 2009) which are based on data availability. The results give an optimum fishing mortality which leads the population at the MSY level, so-called F_{MSY} .

The range of the definition of the word “non-target” was wide from the “different valuable species from the main catch (for example, the sea bass caught from the crab gillnet) until the discard, the unused product from each fishing operation. Several elasmobranch species can be applied for all of this category as the lower market price than teleost which causing the poor data collected known as data-limited (Davies et al., 2009; Harry et al., 2016; Liu et al., 2015; Reuter et al., 2010; Yaglioglu et al., 2015; Zhou and Griffiths, 2008). The term “data-limited” generally explains the stocks in situations in which data collection is impossible or lack of time-series data, and the utilization of the data set should be conducted carefully considering these limitations (Arnold and Heppell, 2015; Honey et al., 2010; Smith et al., 2009).

Gulland and Boerema (1973) suggested that for the species with a complex biological system, the concept of MSY may not be appropriate for many biological factors involved. They also suggest that for some data-poor fisheries, the management of yield in a sustainable situation can be challenging in the current-heavily exploitation of marine resources. However, the management of the yield based on biological factors can be effective. Several elasmobranch species were suggested that have a closer biological aspect to a marine mammal than other bony fish, therefore, the management measure focusing mainly on yield can be effective (Cortés, 1998; Gulland and Boerema, 1973; Liu et al., 2015).

To respond to the data-limited situation which causes difficulties to apply F_{MSY} as a reference point, an alternative reference points proxy to F_{MSY} was established and applied (Horbowy and Luzeńczyk, 2012). Regarding the suggestion by Gulland and Boerema (1973) on the yield-focusing model, the model such as Yield per Recruit, YPR, can be a good candidate focusing on the yield that can be obtained per unit of recruitment under the current age selectivity by fishing gear (Beverton and Holt, 1957; Chen et al., 2007; Goodyear, 1993; Sparre and Venema, 1998). Another merit of YPR is to give both targets and limit reference point ($F_{0.1}$ and F_{max} , respectively). The limit references are based on the biological limitation that can the fishing pressure larger than this reference point can be harmful to the stock. The target reference points which based on the precautionary approach are far more negotiable (Heino et al., 2013; Ortiz et al., 2010).

The Yield per Recruit, YPR, analysis is based on the amount of potential yield fishers can get at each fishing mortality. However, YPR can address only the appropriate fishing mortality providing the maximum yield not for the biomass directly. To addressing the status of biomass, Spawning per Recruit, SPR, analysis was developed (Goodyear, 1993). SPR is suitable for observing the effect of fishing pressure on a stock with density dependence situations when the exploited population is caught at the early maturity age (Rochet, 2000). Moreover, the %SPR is a suitable reference point to be utilized as both target and limit reference points.

Davidson et al. (2016) suggested that the decline of elasmobranchs from fishing can be observed from various countries with huge populations living in the coastal area including Southeast Asian Countries (Dulvy et al., 2014; Ferretti et al., 2010; Holmes et al., 2012; Roff et al., 2018). However, stock assessments for elasmobranch populations in those countries are

limited or unavailable. Therefore, stock assessments for elasmobranchs are strongly required to assess the population and determine the appropriate measures.

1.5. Shark and ray management in Southeast Asia

Southeast Asia is rich in marine bioresources including elasmobranchs (Bonfil, 2008; Wanchana et al., 2016). The rich species diversity leads to the diverse species in several fishing activities, for example, 51 elasmobranch species have appeared in the Australian trawl fishery (Zhou and Griffiths, 2008). Studies of elasmobranchs in Southeast Asia have been carried out since the 18th century, and the current record shows that Indonesia, the Philippines, Malaysia, and Thailand have the highest biodiversity of elasmobranch in the region (Ahmad and Lim, 2012; Krajangdara, 2017).

Another issue in Southeast Asia is the complex fishery condition known as ‘the multi-species fishery situation’ where several species of fish can be caught by the same gear at the same time. This has made species-specific management approaches difficult (Harlyan et al., 2019). Elasmobranchs also have been recognized as minor species from the regional point of view, so the data collected for this particular group are limited (SEAFDEC, 2006).

Elasmobranchs in Southeast Asia have been caught by various kinds of fishing gear such as demersal trawlers and gillnets for local consumption and also the aquarium trade (Dharmadi et al., 2015; Dudgeon et al., 2016; Krajangdara, 2017). However, information on the diversity, distribution, and life history of elasmobranchs in the Southeast Asia region is limited (Arai and Azri, 2019). The limited information leads to limited stock status assessment, which makes the situation of elasmobranchs in the region unclear.

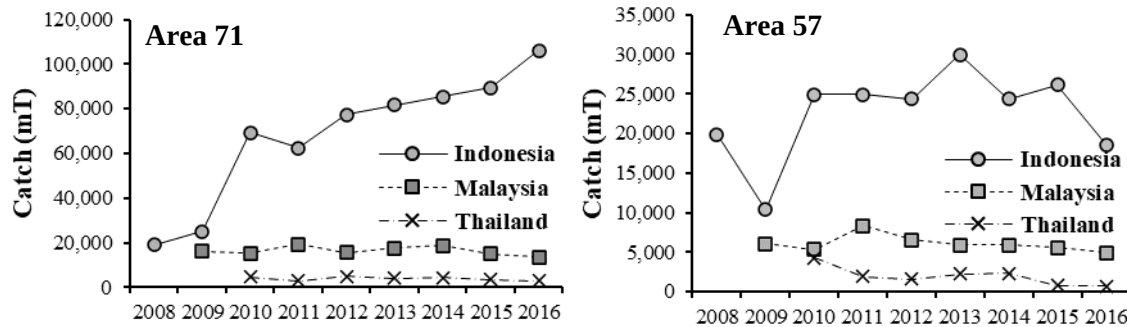


Figure 4. Catch amount statistics of sharks and rays of Indonesia, Malaysia, and Thailand from area 71 in Western Central Pacific, and area 57 in the Indian Ocean (SEAFDEC, 2020).

Countries in Southeast Asia have been working on the improvement of shark and ray management since the agreement from the COFI meeting in 1998 under the scope of “International Plan of Action for Conservation and Management of Shark” or IPOA-Shark. IPOA-Shark has become the guideline for establishing the National Plan of Action (NPOA) of shark management for ASEAN member countries known as NPOA-Shark under the preview of FAO (SEAFDEC, 2006). A study by the Southeast Asian Fishery Development Center, SEAFDEC, in 2006 was confirmed that sharks and rays in Southeast Asia are minor species, caught mostly on a small scale. Regarding the supplementary catch besides other main target species, local communities in the region use elasmobranchs for only meat consumption, while finning is completely an “alien concept” (SEAFDEC, 2006).

Even though the value of elasmobranchs is lower than teleost caught from the same fishing activity, data recording for sharks and rays is considered a necessary process (Liu et al., 2015; SEAFDEC, 2006). Since the meeting of CITES-CoP16 in March 2013, a data collection project has been conducted by SEAFDEC by targeting the major species listed in the CITES appendix (Chamsai et al., 2013). The species proposed by CITES in 2013 included 5 species of sharks namely oceanic whitetip (*Carcharhinus longimanus*), porbeagle shark (*Lamna nasus*), scalloped hammerhead (*Sphyrna lewini*), great hammerhead (*S. mokarran*), and smooth hammerhead (*S. zygaena*), and one genus of manta ray which is recently known as *Mobula* spp. (White et al., 2018). The SEAFDEC member countries established the NPOA-Shark in response. However, direct stock assessment or biological-parameter estimation for a particular area or stock have never been

conducted. For example, the stock status and some biological parameters for large-pelagic shark species such as thresher shark, silky shark, blue shark, etc. were obtained from the annual assessment of each RFMOs (Chamsai et al., 2013; Wanchana et al., 2020). Here the NPOA-Shark from three countries namely Indonesia, Malaysia, and Thailand are summarised as follows.

1.5.1. Indonesia

About 221 spp. of sharks and rays occurred in Indonesian's waters with about 10% having a high economic value such as large-pelagic sharks and guitarfishes. Shark meat is an important resource for local consumption in several areas. In the past decades, the catch and landing of sharks in Indonesia have increased alongside India, Spain, Taiwan, and Mexico, which has raised concern about finning.

Indonesia has 11 Fishery Management Areas (FMAs), of which some are believed to be hot spots of elasmobranch biodiversity, such as FMA 572 (Western Sumatra). Recently Indonesia established international and national laws and regulations related to shark and ray management and conservation such as the Indian Ocean Tuna Commission (IOTC), Western Central Pacific Fisheries Commission, Commission for the Conservation of Southern Bluefin Tuna (CCSBT), Inter American Tropical Tuna Commission (IATTC), and Convention on International Trade in Endangered Species (CITES).

The management plan for Indonesia during 2016-2020 aimed to be a sign of the commitment of the government of Indonesia to its ratified international commitments. The national laws were considered to support the RFMOs regulations such as Government regulation number 7/1999 for protection species listed under CITES appendices and for supporting the data collection development process such as Ministerial Regulation of Marine Affairs and Fisheries Number PER.18/MEN/2010 (Sadili et al., 2015).

1.5.2. Malaysia

Malaysia is endowed with a rich biodiversity of sharks and rays. At least 147 spp. of elasmobranchs that inhabit in Malaysian waters should be properly managed to minimize the impact on the marine ecosystem.

The NPOA-Shark of Malaysia was focused on the sustainable utilization of elasmobranch resources including the assessment and protection of stocks based on scientific information and

aimed to minimize the unutilized incidental catches of sharks and rays. The status of vulnerable species based on the international categorization was also involved and applied.

The two NPOA-Shark plans were established as follows.

Plan 1: The assessment should be conducted to determine the effectiveness of NPOA at least once a year. Five key issues were evaluated, namely 1) Biological information on sharks and related habitats, 2) Socio-economic information of fishers and traders, 3) Utilization, 4) Marketing and trade information, and 5) Coordinated research and expertise on shark and inadequate management measures.

Plan 2: Plan two was simply developed to review, evaluate, and strengthen plan one in several points, for example, the data deficient obstacle from plan one. However, the presented action plan is to conserve, rehabilitate and sustain the shark and ray resource in Malaysia (Department of Fisheries Malaysia, 2014).

1.5.3. Thailand

The NPOA-Shark of Thailand was established in 2005 and includes capacity building for shark and ray identification and data collection. However, the involvement of each concerned stakeholder is low and must be increased. Also, a recreational project was conducted with the Royal Thai Navy, a private aquarium, and a scuba diving club for releasing juvenile bamboo shark (*Chiloscyllium* spp.) and blacktip reef shark (*Carcharhinus melanopterus*). The limitation of NPOA-Shark implementation has been identified and suggested for further actions (Krajangdara, 2014).

1.6. SEAFDEC shark and ray data collection project

During 2015 – 2016, the Southeast Asian Fisheries Development Center (SEAFDEC) conducted a data collection project with appropriate measurement and species identification known as “Regional sharks, rays and skates data collection” (Ahmad et al., 2013; Wanchana et al., 2020, 2016). The one-year data collection was conducted at 11 landing sites under the cooperation of 6 member countries, namely Cambodia, Indonesia, Malaysia, Myanmar, Thailand, and Vietnam, with financial support from CITES and the Japanese Trust Fund, JTF. In the project, the SEAFDEC’s Standard Operation Procedure, SOP, was used as a field process guideline (SEAFDEC, 2017).

A total of 18,907 tons of fish was landed in Southeast Asia in 2015-2016, which was composed of 0.9%, 1.4%, and 0.1% of sharks, rays, and skates, respectively. Regarding the recommendation by the national and regional level, fishery management measures should provide appropriate BRPs to process the scientific-based reference points for fishery management (Edwards, 2015; Froese et al., 2019, 2017, 2014; Prager, 1994; Sainsbury, 2008; SEAFDEC, 2003). The availability of this information is essential for researchers to evaluate the appropriate Biological Reference Points (BRPs) of target stocks.

To utilize the data obtained from the project, the YPR and SPR are important tools to determine fish stock status. Regarding the small input data required (only the biological and mortality), YPR and SPR analyses have been selected as appropriate stock assessment models to determine the status of the target species. This study aims to do first determine the stock status of elasmobranchs inhabiting Southeast Asia waters using YPR and SPR as the growth and recruitment overfishing threshold, respectively. The results are expected to be the reference points for further regional elasmobranch management.

2. STUDY OBJECTIVES

The aim of this study was to assess the stock status of the elasmobranchs in Southeast Asia. The study was conducted by analysing elasmobranch data obtained from Southeast Asia using YPR and SPR with two research objectives:

- (1) To assess the stock status of elasmobranchs in Southeast Asia and identify stocks with healthy and unhealthy status
- (2) To discuss possible management measure for elasmobranch in Southeast Asia based on the stock assessment results

3. MATERIALS AND METHODS

3.1 Data collection

Shark and ray specimens were collected in the “Regional Sharks, Rays and Skates Data Collection” program during 2015 – 2016 at 11 landing sites in 6 countries including the Gulf of Thailand sub-region, and Sabah Sea (FAO area 71) and Andaman seas, and Indonesian’s fisheries management area 573 (FAO area 57) (Figure 5). Data were collected from mid-2015 – mid-2016 (Table 2). A total of 60 species of shark, 78 species of ray, and 8 species of skates were collected.

Table 2 Data collection period in each country

Country	Number of landing sites	Data collection period	
		Start	End
Cambodia	1	September 2015	August 2016
Indonesia	2	August 2015	July 2016
Malaysia	2	August 2015	July 2016
Myanmar	2	July 2015	June 2016
Thailand	2	August 2015	August 2016
Vietnam	2	September 2015	August 2016

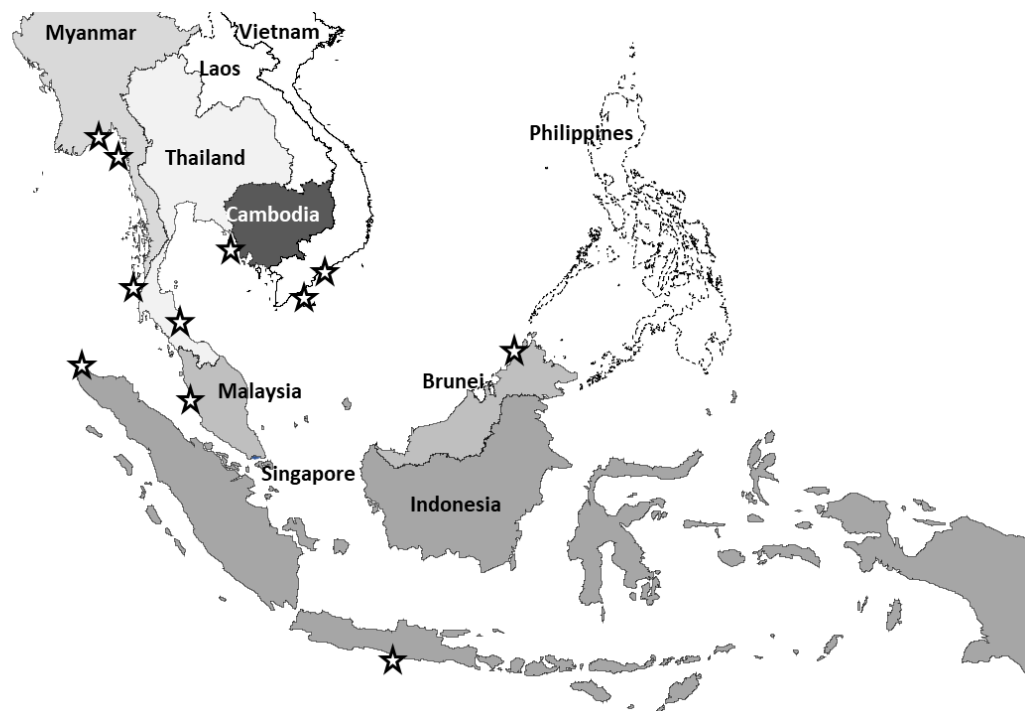


Figure 5. Eleven landing sites (stars) in 6 countries selected for the project, 1 in Cambodia, 2 in Indonesia, 2 in Malaysia, 2 in Myanmar, 2 in Thailand, and 2 in Vietnam.

From the 146 elasmobranch species, the species were selected using the criteria follower:

1. The individual length-weight data is continuous for at least 8 of 12 months.
2. Length-frequency should cover all (or almost) the size range. (Figure 6)
3. To obtain a reliable growth parameter, the sample size should have at least 200 individuals (Thorson and Simpfendorfer, 2009).
4. Data record quality such as miss typing, miss-spelling, and the outlier of the data.

The data that passed all 4 criteria are selected for further analysis.

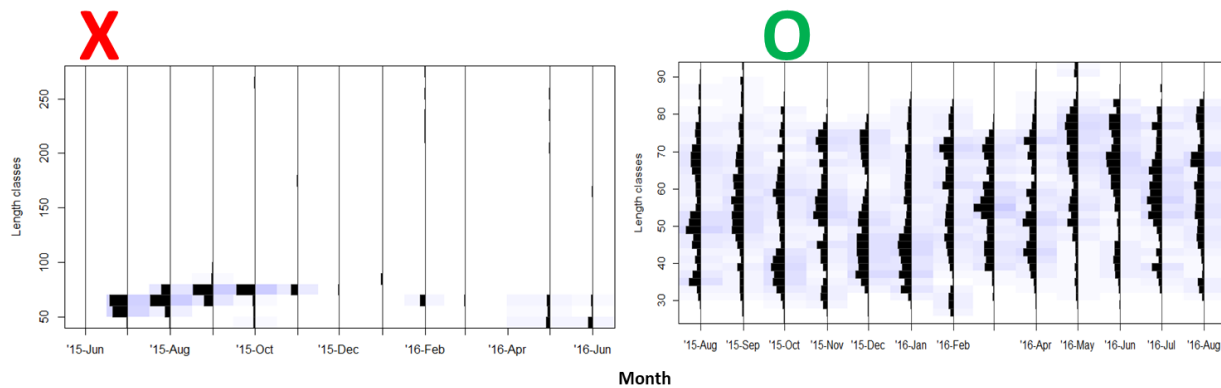


Figure 6. Comparison between length-frequency with no continuous monthly length-frequency and not cover all the length classes (left) and the usable length-frequency data (right).

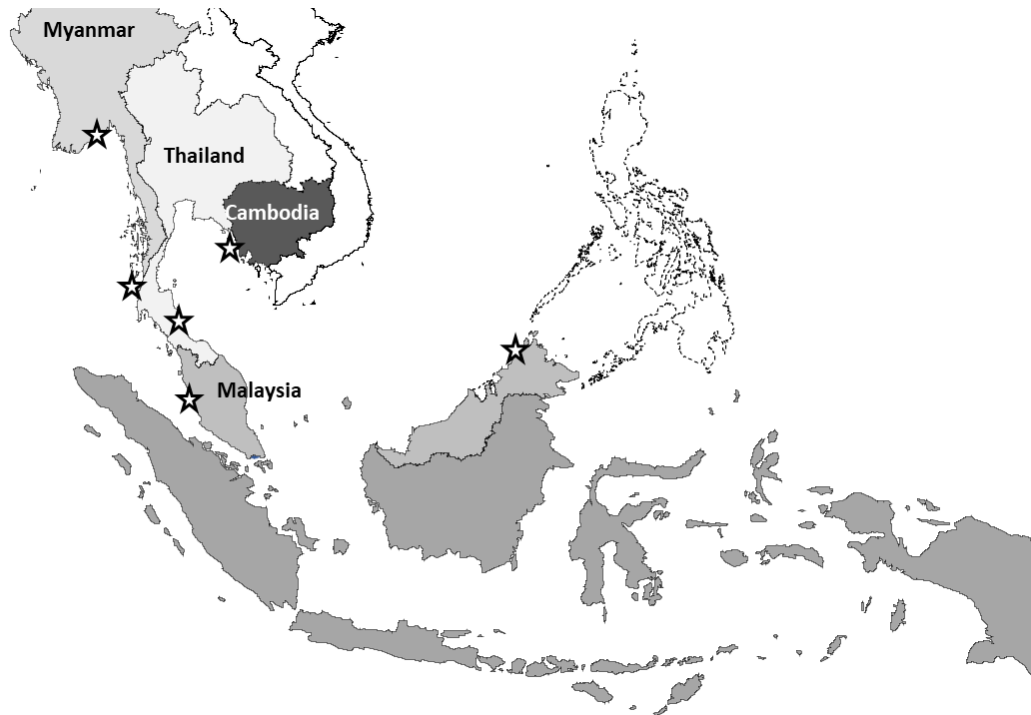


Figure 7. Six landing sites (stars) selected for this study, 1 in Cambodia, 2 in Malaysia, 1 in Myanmar, and 2 in Thailand.

Total 6 from 11 landing sites were selected using shark and ray length-frequency data that met all 4 criteria. The landing sites including 1 in Cambodia, 2 in Malaysia, 1 in Myanmar, and 2 in Thailand.

3.2. Length-weight relationship

The length-weight relationship can provide essential biological information of species growth patterns. Two length measurements were used for the sharks as pre-caudal length (PCL), the length between the tip of the snout until the beginning of the caudal fin, for thresher shark and total length (TL), the length between the tip of the snout until the end of the upper caudal fin lobe for other shark species. The length measurement used for the ray was the disc length (DL), the length between the tip of the snout until the edge of the pectoral fin. This method followed SEAFDEC's Standard Operation Procedure, SOP, as shown in Figure 8 (SEAFDEC, 2017).

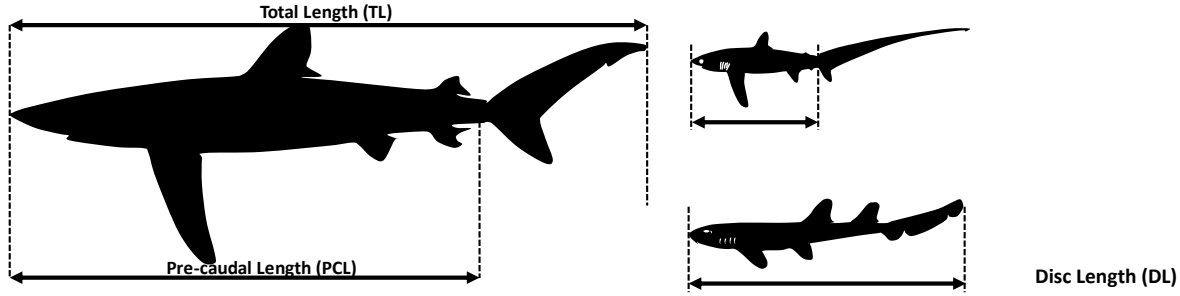


Figure 8. Length measurements for sharks and rays used in this study according to the standard operation procedure (after SEAFDEC, 2017).

The parameters of the length-weight relationship shown in Equation (2) (Ricker, 1975) were estimated by linear regression after logarithmic conversion. The equation is

$$W = qL^b \quad (2)$$

where W is the weight of specimen (kg), L is the length (total or disc length, cm), b is a regression factor, and q is a condition factor.

The populations of elasmobranchs in this study were assumed to differ between areas (the Gulf of Thailand, the Andaman Sea, the South China Sea, and the Indian Ocean) (Figure 9). Differences in a length-weight relationship due to different compositions of age, size, and sex. A significant test was conducted by area for population differences and by sex for sexual dimorphism.

The length-weight relationship of a species can vary depending on two factors, namely sex and population. Froese (2006) suggested that environmental conditions can affect the condition factor, q . In addition, the difference in body shape between males and females can affect the regression factor, b , (Froese and Palomares, 2000; Gerritsen and McGrath, 2007).

The length and weight were transformed using the log-linear transform of Equation (1) using the statistical test for the shape difference by sex (Ogle et al., 2020). The differences were assumed to occur between sexes and among areas. For sexual dimorphism, the relationship was tested by the method provided by Ogle et al. (2020) for the difference in shape and t -test for the difference in size.

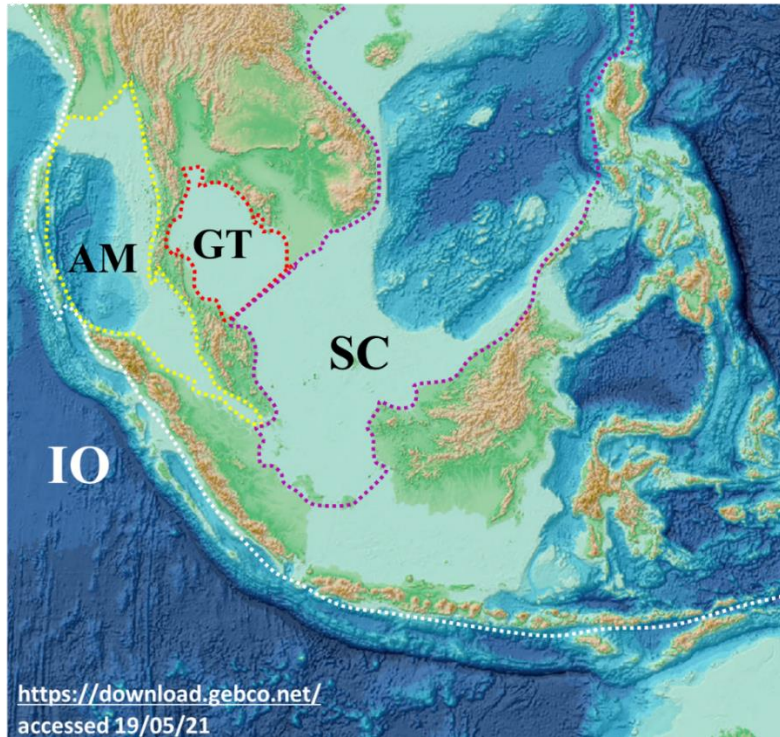


Figure 9. Maritime area covered in this study.

The areas were presented by the abbreviation as shown in Table 3

Table 3. Abbreviation for area names

Area	Abbreviation
<i>Region and sub-region</i>	
Andaman Sea	AM
Gulf of Thailand	GT
South China Sea	SC
Southeast Asia	SE
<i>Landing Sites</i>	
Cambodia	CM
Kota Kinabalu, Malaysia	KK
Indonesia	IN
Malaysia	ML
Myanmar	MY
Thailand	TH

3.3. Estimation of growth parameter

Growth curve parameter of the von Bertalanffy's growth equation (Equation 3) were estimated using Electronic Length-Frequency Analysis (ELEFAN) which was provided in the TropFishR package (Mildenberger et al., 2017). The equation is

$$L_t = L_\infty (1 - e^{-K(t-t_0)}) \quad (3)$$

where t is age (year); L_t is length (cm) at age t ; L_∞ , K , and t_0 are parameters of the growth curve.

Inversed von Bertalanffy's growth function (Mackay and Moreau, 1990) was used for the age estimation as follows,

$$t_L = t_0 - \left(\frac{1}{K}\right) \ln \left(1 - \frac{L}{L_\infty}\right) \quad (4)$$

where L (cm) is body length; t_L (year) is the estimated age from the length.

The growth performance index, Φ' , was estimated by the growth parameters from von Bertalanffy's growth equation (Pauly and Munro, 1984)

$$\Phi' = \log K + 2 \log L_\infty \quad (5)$$

The monthly length-frequency data were analysed using four methods, namely K scan, Response Surface Analysis (RSA) (both from the original ELEFAN), the ELEFAN incorporated with simulated annealing (ELEFAN_SA), and the ELEFAN incorporated with genetic annealing (ELEFAN_GA) (Brey and Pauly, 1986; Gayanilo et al., 2005; Mildenberger et al., 2017; Taylor and Mildenberger, 2017). The growth parameters fitting score (R_n) is the goodness of fit index. It can be determined as shown in Equation 6.

$$R_n = 10^{(ESP/ASP)/10} \quad (6)$$

where ESP is the estimated sum of peaks crossed by the estimated growth curves; ASP is the available sum of peaks, the best value from the available peaks (Gayanilo and Pauly, 1997; Taylor and Mildenberger, 2017). To confirm the precision, the highest R_n provided from each result observed with the Φ' was used for comparison with the literature.

3.4. Estimation of mortality, selectivity, and size and age at first maturity

The length-converted catch curve (Pauly, 1984, 1983), was applied to estimate total mortality and catch selectivity. For the total mortality (Z) estimation, the following equation was used,

$$\ln \frac{C_{L1,L2}}{\Delta t_{L1,L2}} = c - Z \times t_{mL} \quad (7)$$

where Z is total mortality; $C_{L1, L2}$ is the number of fish caught in each length interval; t_{mL} can be estimated by Equation 3, where mL is the middle length between lower and upper length intervals. The mL was calculated using Equation 8

$$mL = \frac{L_1 + L_2}{2} \quad (8)$$

where L_1 is the length at the lower interval, and L_2 is the length at the upper interval.

The parameter $\Delta t_{L1, L2}$ was calculated using Equation 9

$$\Delta t_{L1, L2} = \frac{1}{K} \ln \left(\frac{L_{\infty} - L_1}{L_{\infty} - L_2} \right) \quad (9)$$

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

$$M = \frac{2.5}{t_{\max}} \quad (10)$$

where M is natural mortality; and $t_{\max}$ is the maximum age. The $t_{\max}$ of Tanaka (1960) is the maximum age without fishing pressure. For this study, $t_{\max}$ for several fish species was estimated using various methods, the median was determined. $t_{\max}$ was estimated as follows:

- 1) The maximum age estimation using the mid-length from length-converted catch curve
- 2) The maximum age using inversed von Bertalanffy's Equation 3. However, the maximum length, $L_{\max}$, can be estimated by the method used by Froese and Binohlan (2000) as follow

$$\log L_{\max} = \frac{\log L_{\infty} - 0.044}{0.9841} \quad (11)$$

- 3) The maximum age using Taylor (1958)

$$t_{\max} = t_0 + \frac{2.996}{K} \quad (12)$$

- 4) The maximum age using by Pauly (1983) assuming that the size of the oldest fish was 95% of L_{∞}

$$t_{\max} = \frac{3}{K} \quad (13)$$

Fishing mortality (F) was estimated using the relationship between total and natural mortality in Equation 14

$$F = Z - M \quad (14)$$

The exploitation ratio E was estimated by Equation 15

$$E = \frac{F}{Z} \quad (15)$$

The observed selection ogive, S_t , was estimated using Equation 16

$$S_t = \frac{C}{\Delta t_{L1, L2} e^{a - Z t_{mL}}} \quad (16)$$

and estimated selection ogive, S_t' , was estimated using Equation 17

$$S_t' = \frac{1}{1+e^{a+bt}} \quad (17)$$

The selectivity was parameterized by size at first captured, L_c , which is equivalent to L_{50} , L_{25} , and L_{75} . The L_{25} and L_{75} were the lengths of individuals caught for 25 and 75% of the populations. The result was shown by age and converted to length using von Bertalanffy's equation. Size selection was assumed to be knife-edge for YPR and SPR.

Size at first maturity (L_m) was assumed for all species based on Ahmad and Lim (2012), Ahmad et al. (2014), and Krajangdara (2017) as provided in Table 12. L_c and L_m were converted to t_c and t_m using reversed von Bertalanffy's equation.

3.5. Per recruit analysis

YPR is the model accounting for yield obtained from each stock at each specific age and fishing pressure. The average maximum age, W_∞ , used in this equation was estimated from the length-weight relationship, Equation (2), using L_∞ as input. The result was calculated by Equation 18.

$$\frac{Y}{R} = FW_\infty e^{-M(t_c-t_r)} \times \sum_{n=0}^3 \frac{A_n e^{-nK(t_c-t_0)}}{F+M+nK} \{1 - e^{-(F+M+nK)(t_\lambda-t_c)}\} \quad (18)$$

$$\begin{cases} n &= 0, & 1, & 2, & 3 \\ A_n &= 1, & -3, & 3, & -1 \end{cases}$$

The information produced by YPR was the change in the yield of the catch, in other words, the decline of catch 'in weight'. This indicates if the stock size increased or decreased, the higher F_{curr} over YPR's BRPs indicated that the weight decreased. Beverton and Holt (1957) and Sparre and Venema (1998) suggested that the YPR's unit was "kg per recruit" or the weight per one recruitment unit or per fish recruited into the fishing ground. By this definition, the higher F_{curr} over YPR's BRPs directly reflected the smaller size of fish caught by such fishing pressure. Thus, so-called growth overfishing.

The SPR was the model accounting for the biomass of the spawning female stock which would be remained in the fishing ground at each specific age at first capture and fishing pressure. To handle the possible scenarios for the target stock, the model was divided into 2 scenarios as 1) when the age at first capture (t_c) is older than the age at first maturity (t_m), and 2) when t_c smaller than t_m . The practical utilization of SPR is the %SPR, the percentage of SPR at the current fishing condition, and the SPR at no fishing pressure ($F = 0$).

For $t_c \leq t_m$:

$$SPR = W_{\infty} e^{-M(t_c - t_r) - (F+M)(t_m - t_c)} \sum_{n=0}^3 A_n e^{-nK(t_m - t_0)} \left\{ \frac{1 - e^{-(F+M+nK)(t_{\lambda} - t_m)}}{F+M+nK} \right\} \quad (19)$$

For $t_c > t_m$:

$$\begin{aligned} SPR &= W_{\infty} e^{-M(t_m - t_r)} \sum_{n=0}^3 A_n e^{-nK(t_m - t_0)} \left\{ \frac{1 - e^{-(M+nK)(t_c - t_m)}}{M+nK} \right\} \\ &+ W_{\infty} e^{-M(t_c - t_r)} \sum_{n=0}^3 A_n e^{-nK(t_c - t_0)} \left\{ \frac{1 - e^{-(F+M+nK)(t_{\lambda} - t_m)}}{F+M+nK} \right\} \end{aligned} \quad (20)$$

$$\begin{cases} n &= 0, & 1, & 2, & 3 \\ A_n &= 1, & -3, & 3, & -1 \end{cases}$$

where W_{∞} is the average maximum weight (g), t_c is the age at first capture (year), t_r is the age at recruitment (year), t_m is the age at first maturity; t_{λ} is the age at the endpoint (years). W_{∞} was calculated by substituting L_{∞} into equation (2).

The interpretation of SPR was different. Since the equation itself was involved the maturity stage by age (t_m), the result of SPR was more focused on the stock status. Goodyear (1993) suggested that the SPR can be used to detect the potential of population growth by the maturity information involved. Thus, if the F_{curr} larger than SPR's biological reference points it was directly reflected the stock size and inform the stock status directly. This phenomenon was known as recruitment overfishing.

3.6. Biological reference points (BRPs)

Biological reference points, BRPs, are widely used as safe level benchmarks for fishery management (Collie and Gislason, 2001). For YPR, the level of fishing mortalities (F) as $F_{0.1}$ and F_{max} are used as BRPs (Beverton and Holt, 1957; Chen et al., 2007). F_{max} provides the F which maximizes the yield at a given age at first capture assuming constant recruitment. $F_{0.1}$ is a precautionary reference point of F that gives 10% of the tangent of the slope from the origin of the YPR curve at each t_c (Goodyear, 1993; Zhou et al., 2020).

For SPR, this model was suggested to provide the amount of the potential spawning stock biomass that remained after fishing activities. The results of SPR were shown by the ratio between spawning biomass remained from the total biomass at no fishing activities ($F = 0$) in percentage, unlike the spawning stock biomass which indicates the biomass of the spawning stock in the observed population (Beverton and Holt, 1957; Goodyear, 1993). The SPR was developed and implemented as the USA fishery's BRPs in the 1990s. The usage of SPR suggested that the %SPR

below 20% should be avoided to maintain stock-recruitment for the bony fish and should be higher for elasmobranchs (Goodyear, 1993; Sparre and Venema, 1998). Therefore, the target SPR reference point was set at $F_{30\%}$ and the limit point at $F_{20\%}$.

3.7. Sensitivity test

The parameters used in this study, such as growth parameters L_{∞} and K , were estimated based on the length-frequency data which contained the uncertainties as well as the $t_{\max}$ which was based on the empirical estimation and was affected by growth parameters. A sensitivity test was used to determine the effect growth parameters, L_{∞} and K , and $t_{\max}$ to the current fishing mortality, F_{curr} , by varying parameters by $\pm 1\%$, 3% , and 5% , independently.

4. RESULTS

The 12 selected species included 8 sharks in 4 families and 4 rays in 1 family (Table 4).

Table 4. Taxonomic classification for the selected species

Family	Species	Abbreviation	Sub-region	Country
Shark				
Hemiscyllidae	<i>Chiloscyllium punctatum</i>	<i>Cp</i>	GT, SC, and AM	CM, IN, ML, and TH
Hemiscylliidae	<i>Chiloscyllium plagiosum</i>	<i>Cl</i>	SC	ML
Hemiscylliidae	<i>Chiloscyllium hasseltii</i>	<i>Ch</i>	AM	ML
Scyliorhinidae	<i>Atelomycterus marmoratus</i>	<i>Am</i>	GT, SC	ML, TH
Carcharhinidae	<i>Scoliodon laticaudus</i>	<i>Sl</i>	AM	MY
Ray				
Dasyatidae	<i>Brevitrygon heterura</i>	<i>Bh</i>	GT, AM	ML, TH
Dasyatidae	<i>Maculabatis gerrardi</i>	<i>Mg</i>	SC, AM	ML
Dasyatidae	<i>Neotrygon kuhlii</i>	<i>Nk</i>	GT, AM	ML, TH
Dasyatidae	<i>Telatrygon zugei</i>	<i>Tz</i>	GT, AM	ML, TH

All the elasmobranch species in this study were caught by bottom trawls except the catch from Indonesia, which was caught by tuna longline and gillnet. The catch amount of each species was divided by area (Table 5).

Table 5. Catch amount of selected elasmobranch species used in this analysis by country by subregion

Species	Total catch amount (kg)	% in elasmobranchs	Country	Subregion
Shark				
<i>Cp</i>	7,312	52.58	CB	GT
	3,635	41.07	TH	GT
	2,201	18.76	ML	SC
	1,991	7.98	ML	AM
	1,017	8.67	ML	SC
<i>Cl</i>	2,635	10.56	ML	AM
<i>Ch</i>				
<i>Am</i>	881	6.34	TH	GT
	224	2.53	ML	AM
<i>Sl</i>	2,726	5.27	MY	AM
Ray				
<i>Tz</i>	3,466	39.16	TH	GT
	930	7.93	ML	SC

	757	3.03	ML	AM
<i>Nt</i>	253	23.30	TH	AM
	2,733	7.61	ML	SC
	5,212	20.90	ML	AM
<i>Bh</i>	685	7.74	TH	GT
	368	11.06	TH	AM
	1,015	4.07	ML	AM
<i>Mg</i>	1717	14.64	ML	SC
	7,345	29.45	ML	AM

The percentage of selected species from other elasmobranchs ranged between 3.03% for *Tz* caught from the ML/AM to 52.58% for *Cp* caught from CM/GT. Also, the *Cp* and *Tz* were found in all sub-regions (GT, SC, and AM). Only *Sl* found only in MY which the stock status was categorized as near threatened (NT) (Simpfendorfer, 2015).

4.1. Length-weight relationship and statistical tests

The significant difference test between sex was conducted for shape and size provided the results in Table 6. In the remark, the ‘shape difference’ was the difference in shape between the sexes which can be reflected by the significant difference in the length-weight relationship parameters (q , and b). Another remark was known as ‘size difference’ which stands for the difference between the size of male and female as the sex dimorphism or difference of area usage between sex.

Table 6. Statistical tests for sexual dimorphism of selected elasmobranch species using Ogle et al. (2020).

Species	Area	<i>p</i> -value Ogle et al. (2020)	<i>p</i> -value <i>t</i> -test	Significant difference
Shark				
<i>Cp</i>	CM/GT	n.s.	***	Size diff.
	TH/GT	n.s.	**	Size diff.
	ML/SC	n.s.	***	Size diff.
	ML/AM	***	n.s.	Shape diff.
<i>Cl</i>	ML/SC	n.s.	***	Size diff.
<i>Ch</i>	ML/AM	*	***	Diff.
<i>Am</i>	TH/GT	***	n.s.	Shape diff.
	ML/AM	***	n.s.	Shape diff.
<i>Sl</i>	MY/AM	***	n.s.	Shape diff.
Ray				

<i>Tz</i>	TH/GT	***	***	Diff.
	ML/SC	*	***	Diff.
	ML/AM	***	***	Diff.
<i>Nk</i>	TH/AM	n.s.	***	Size diff.
	ML/SC	n.s.	n.s.	Non sig.
	ML/AD	**	***	Diff.
<i>Bh</i>	TH/GT	***	*	Shape diff.
	TH/AM	n.s.	n.s.	Non sig.
	ML/AM	**	***	Size diff.
<i>Mg</i>	ML/SC	n.s.	n.s.	Non sig.
	ML/AM	n.s.	**	Size diff.

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, n.s. not significant

Diff.: significant difference in size and shape, Shape diff.: significant difference in shape, Size diff.: significant difference in size, and Non sig.: no significant difference between sexes.

The length-frequency data show that *Ch*, *Mg* (ML/SC), *Tz* (ML/AM), and *Sl* (MY) cannot be separated by sex due to changing length-frequency structure and small sample size (less than 200 specimens in total 12 months), which can lead to the unreliability of the growth parameters, so these 4 species were analysed after combining the sexes. The significant difference for each population using was found for the species that distributed in more than one area. The species namely *Cp*, *Am*, *Bh*, *Mg*, *Nk*, and *Tz* had a significant difference(s) in whether size or shape or both by area for every species in every area (p -value < 0.001). However, the sex separation of *Cp* cannot be used for growth parameter estimation due to the distribution of monthly length frequency. Therefore, *Cp* was analysed with sexes combined. The length-weight relationship was estimated for every species (Table 7) and the plots were shown in Appendix A.

Table 7. Length-weight relationship parameter for every selected elasmobranch species.

Species	Area	Sex	q	95% C.I.	b	95% C.I.
Shark						
<i>Cp</i>	CM/GT	Pooled	6.63×10^{-6}	4.96 – 8.86	2.88	2.81 – 2.95
	TH/GT	Pooled	2.16×10^{-6}	2.00 – 2.33	3.15	3.13 – 3.17
	ML/SC	Pooled	1.64×10^{-6}	1.34 – 2.02	3.19	3.14 – 3.24
	ML/AM	Pooled	1.70×10^{-6}	1.49 – 1.95	3.21	3.18 – 3.24
<i>Cl</i>	ML/SC	M	1.82×10^{-6}	0.98 – 3.38	3.11	2.97 – 3.26
		F	2.97×10^{-7}	1.79 – 4.91	3.55	3.43 – 3.67
<i>Ch</i>	ML/AM	Pooled	1.86×10^{-6}	1.58 – 2.19	3.21	3.17 – 3.25

Ray	Am	TH/GT	M	6.10×10 ⁻⁶	4.29 – 8.68	2.83	2.74 – 2.92
			F	2.85×10 ⁻⁶	1.60 – 5.09	3.04	2.88 – 3.19
		ML/AM	M	8.43×10 ⁻⁶	5.46 – 1.30	2.75	2.64 – 2.86
			F	3.93×10 ⁻⁶	2.45 – 6.30	2.96	2.84 – 3.08
	Sl*	MY/AM	Pooled	1.00×10 ⁻⁴	0.68 – 1.48	2.18	2.08 – 2.28
	Tz	TH/GT	M	4.13×10 ⁻⁵	3.75 – 4.56	2.86	2.82 – 2.89
			F	3.50×10 ⁻⁵	3.30 – 3.72	2.93	2.91 – 2.95
		ML/SC	M	2.14×10 ⁻⁵	0.73 – 6.29	3.07	2.73 – 3.42
			F	2.68×10 ⁻⁵	1.65 – 4.37	3.01	2.86 – 3.16
	Nk	ML/AM	Pooled	3.69×10 ⁻⁵	3.19 – 4.28	2.91	2.86 – 2.96
		ML/SC	M	5.84×10 ⁻⁵	4.42 – 7.73	3.00	2.91 – 3.09
			F	6.42×10 ⁻⁵	5.07 – 8.13	2.97	2.89 – 3.05
			TH/AM	M	7.01×10 ⁻⁵	5.25 – 9.37	2.93
	F			6.28×10 ⁻⁵	5.03 – 7.83	2.96	2.89 – 3.03
	ML/AM		M	9.34×10 ⁻⁵	7.73 – 11.30	2.89	2.83 – 2.96
			F	7.20×10 ⁻⁵	6.50 – 7.99	2.98	2.95 – 3.02
	Bh	TH/GT	M	2.88×10 ⁻⁵	2.43 – 3.43	3.04	2.98 – 3.10
			F	3.63×10 ⁻⁵	2.97 – 4.43	2.95	2.89 – 3.02
TH/AM		M	1.30×10 ⁻⁵	0.86 – 1.98	3.31	3.16 – 3.45	
		F	2.02×10 ⁻⁵	1.34 – 3.04	3.16	3.02 – 3.30	
	ML/AM	M	6.04×10 ⁻⁵	4.62 – 7.89	2.85	2.76 – 2.94	
		F	7.87×10 ⁻⁵	6.07 – 10.02	2.75	2.66 – 2.84	
	Mg	ML/SC	Pooled	3.89×10 ⁻⁵	3.45 – 4.38	3.03	3.00 – 3.07
		ML/AM	M	5.78×10 ⁻⁵	5.21 – 6.41	2.95	2.92 – 2.98
		F	6.58×10 ⁻⁵	6.01 – 7.20	2.91	2.89 – 2.94	

*Unreliable please see discussions

4.2. Growth parameter estimation

The results of growth curve parameter estimation were provided in Table 8.

Table 8. Growth parameter estimation, L_{∞} , K , and t_0 with the growth performance index, Φ' , and the fitting score, R_n , for each shark and ray species

Species	Area	Sex	L_{∞}	K	t_0	Φ'	R_n
Shark							
<i>Cp</i>	CM/GT	Pooled	75.30	0.21	-0.83	3.08	0.30
	TH/GT	Pooled	93.70	0.41	-0.33	3.55	0.19
	ML/SC	Pooled	87.12	0.25	-0.59	3.28	0.18
	ML/AM	Pooled	86.52	0.21	-0.77	3.21	0.19
<i>Cl</i>	ML/SC	M	81.13	0.21	-0.63	3.15	0.36
		F	84.30	0.18	-0.70	3.11	0.37
<i>Ch</i>	ML/AM	Pooled	90.34	0.33	-0.36	3.42	0.23
<i>Am</i>	TH/GT	M	54.99	0.53	-0.51	3.20	0.45

Ray	<i>Sl</i>	ML/AM	F	59.05	0.52	-0.48	3.26	0.50
			M	63.50	0.72	-0.32	3.46	0.18
		MY/AM	F	56.10	0.71	-0.37	3.35	0.40
			Pooled	52.54	0.86	-0.34	3.38	0.37
	<i>Tz</i>	ML/SC	M	25.04	0.89	-0.43	2.75	0.59
			F	31.14	0.51	-0.42	2.70	0.30
		TH/GT	M	32.83	0.35	-0.68	2.58	0.34
			F	28.02	0.85	-0.28	2.82	0.23
	<i>Nk</i>	ML/AM	Pooled	30.01	1.00	-0.40	2.95	0.37
			M	31.87	0.61	-0.69	2.79	0.23
		ML/SC	F	30.30	0.51	-0.88	2.67	0.21
			M	27.97	0.89	-0.56	2.74	0.48
	<i>Bh</i>	TH/AM	F	30.00	0.81	-0.56	2.86	0.23
			M	29.90	0.51	-0.90	2.66	0.33
		TH/GT	F	43.06	0.18	-1.64	2.51	0.42
			M	23.80	0.64	-0.64	2.53	0.37
	<i>Mg</i>	ML/AM	F	29.40	0.21	-1.51	2.26	0.29
			M	24.90	0.53	-0.73	2.58	0.29
		TH/AM	F	30.77	0.55	-0.55	2.72	0.28
			M	26.79	0.82	-0.43	2.77	0.43
	<i>Mg</i>	ML/SC	F	24.67	0.59	-0.66	2.55	0.39
			Pooled	73.60	0.11	-1.77	2.77	0.49
		ML/AM	M	77.97	0.13	-1.40	2.89	0.29
			F	93.86	0.06	-2.48	2.71	0.4

In Table 8, only the highest R_n is shown for each species. All values of R_n and the software have been provided in appendix B. Branstetter (1987) categorized K values as 0.05-0.10 for slow growth rates, 0.11-0.20 for average growth rates, and 0.21-0.50 for rapid growth rates. Considering these criteria, 1, 3, and 11 species of shark, and 1, 3, and 16 species of ray in this study were categorized as having slow, average, and rapid growth rate, respectively.

4.3. Mortality estimation

Mortality estimates using length-converted catch curves was separated into 3 parts, namely total mortality, natural mortality, and fishing mortality.

4.3.1 Total mortality (Z)

The total mortality was estimated based on the negative slope of the catch curve. The selected negative slope was selected by the straight line from the peak of the curve (as the age at the full exploitation) until the maximum age, which not too closed to the age at L_∞ . Age older than

the selected range was assumed to not be represented to L_c which consequently not be a good representative for Z (Sparre and Venema, 1998). Results as shown in Figure 10 and 11 which the abbreviations following Table 3 and 4.

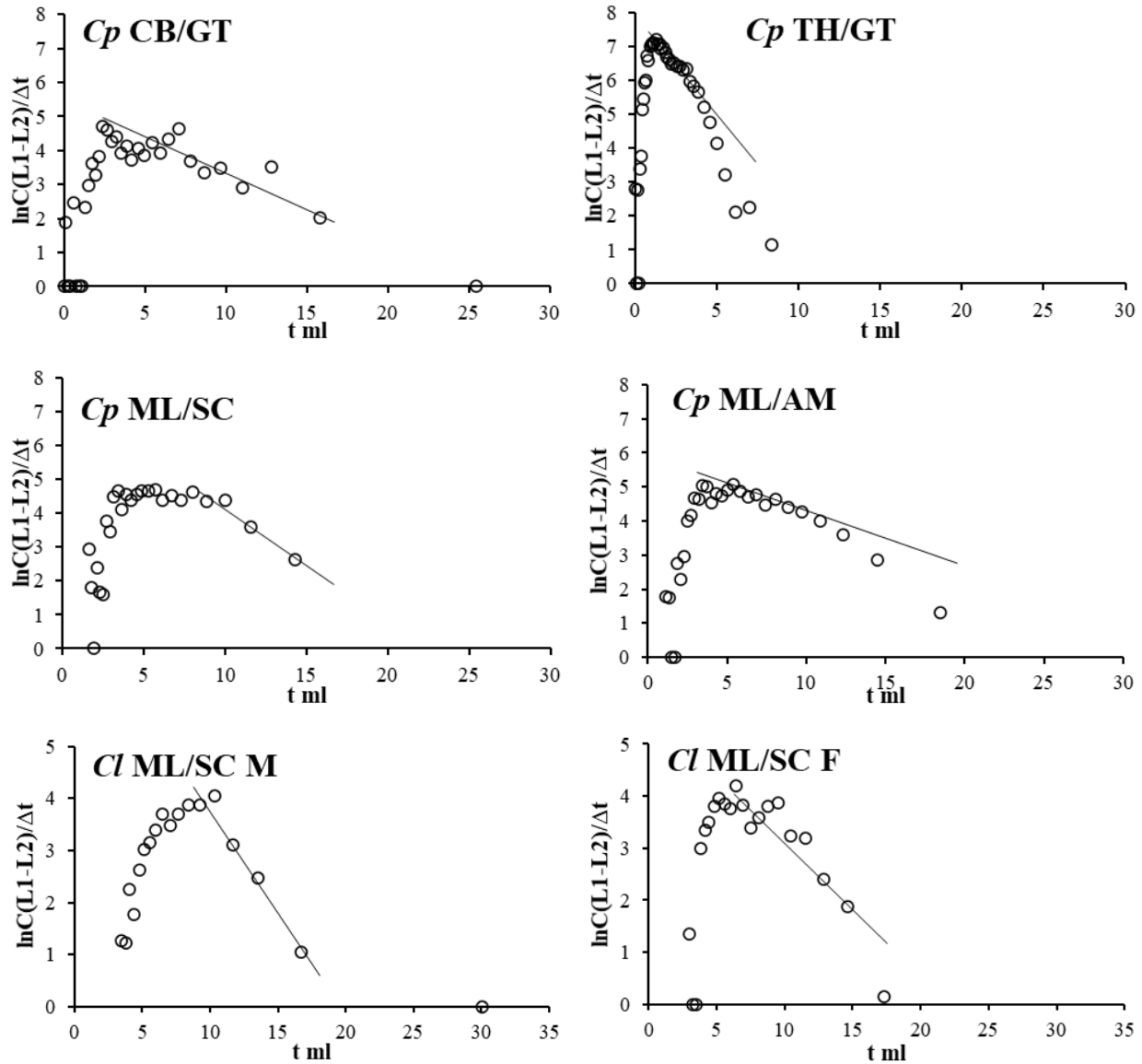


Figure 10. Length-converted catch curve for shark species. M: male, F: female.

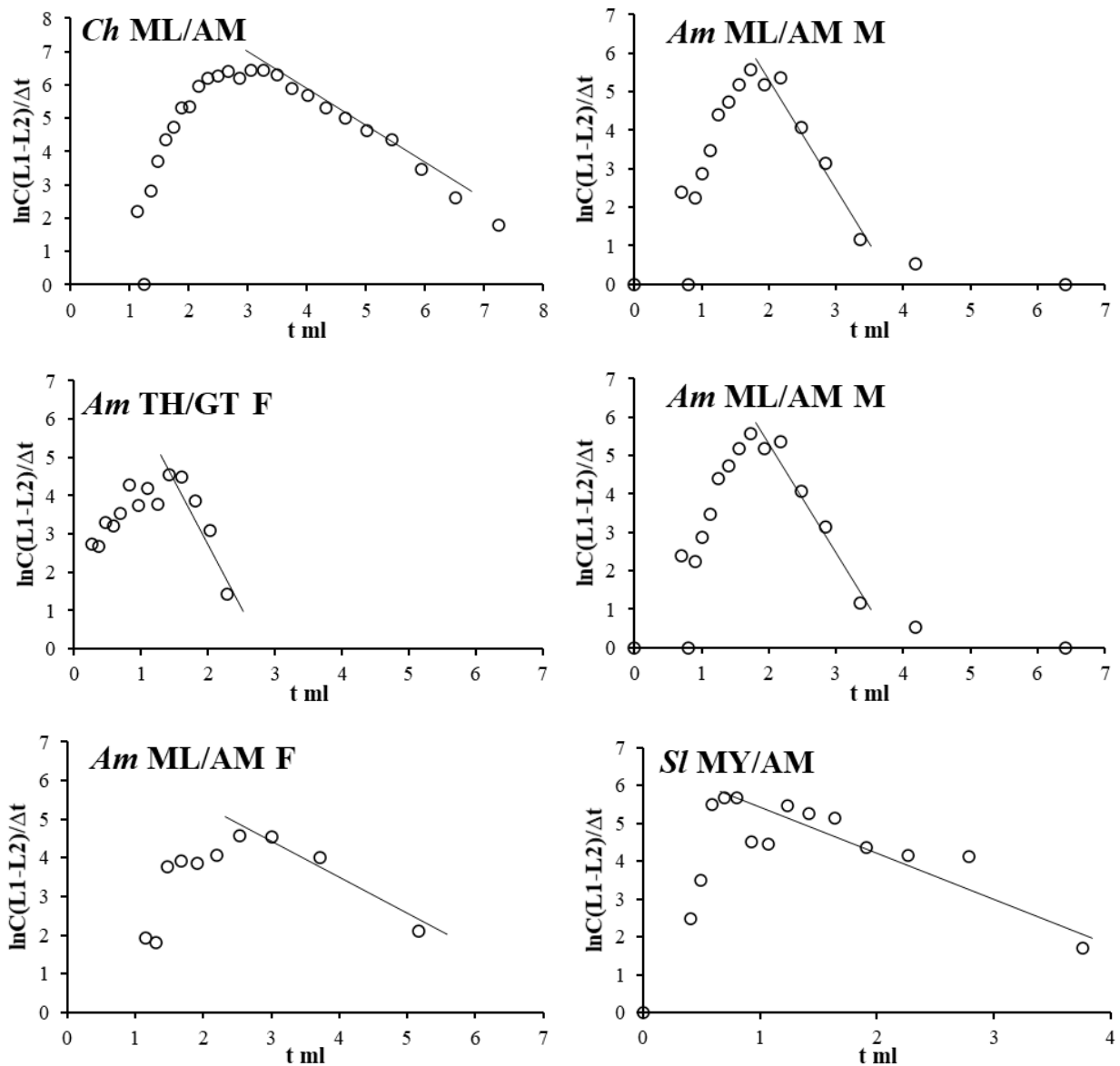


Figure 10 (continued).

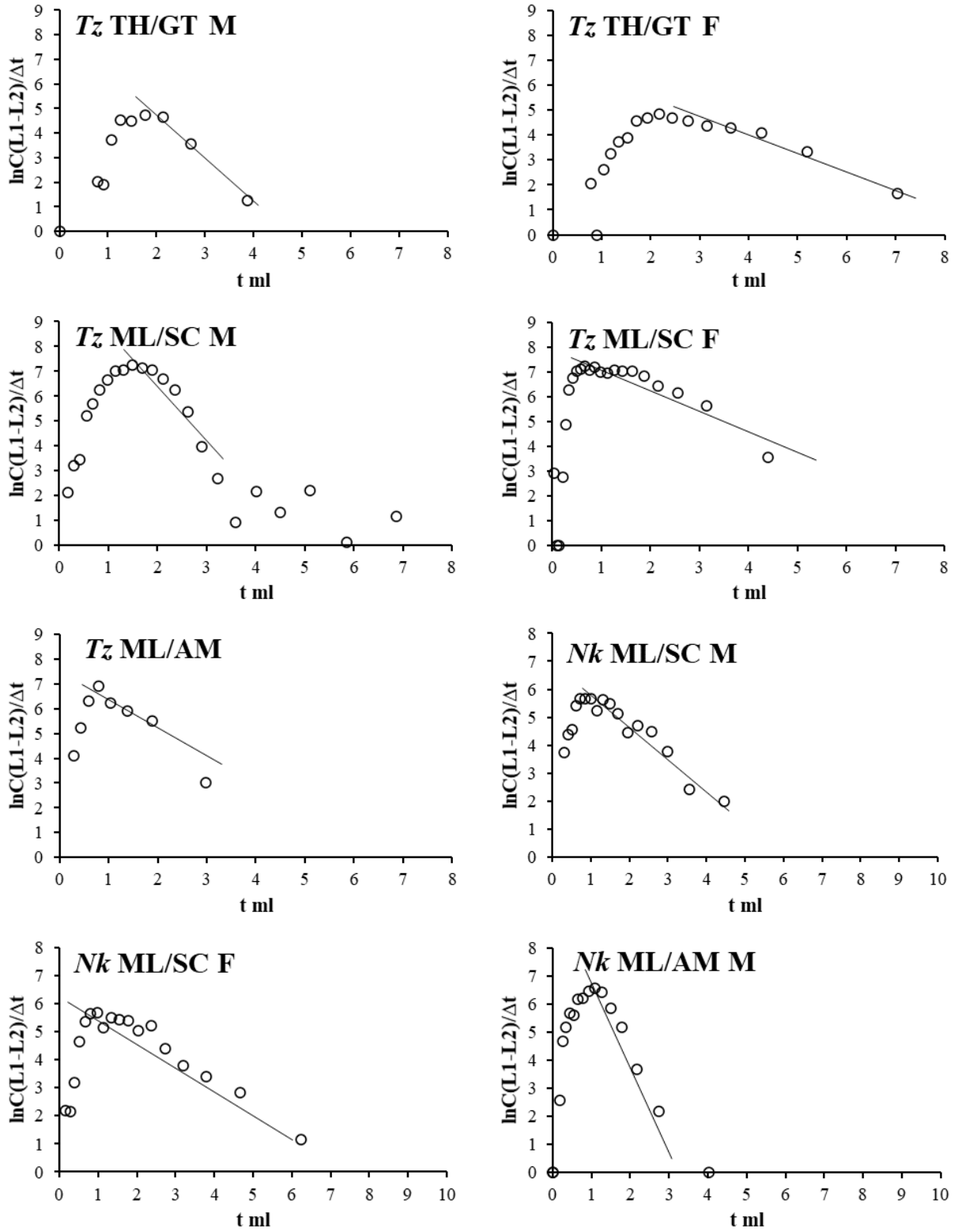


Figure 11. Length-converted catch curve for ray species. M: male, F: female.

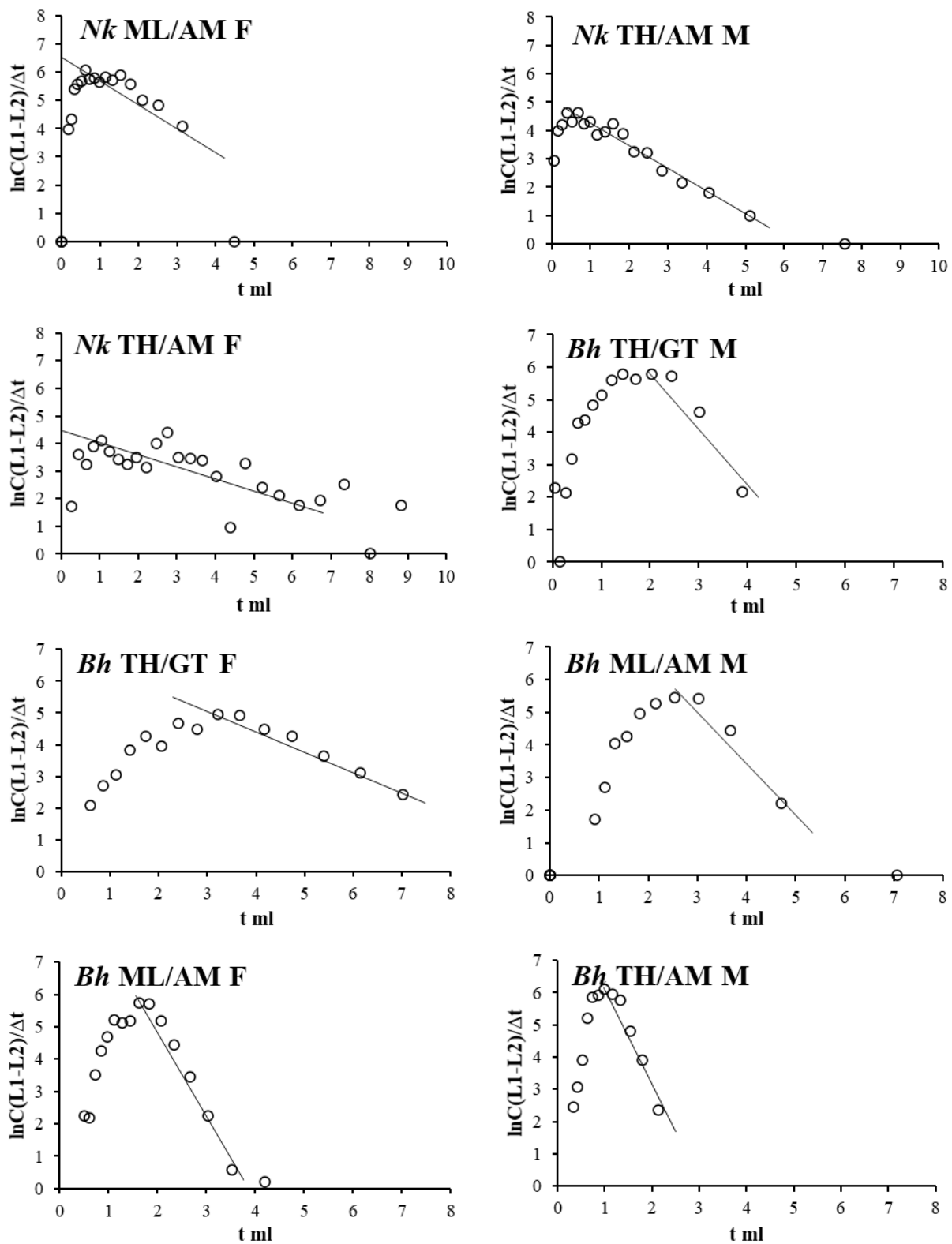


Figure 11 (continued).

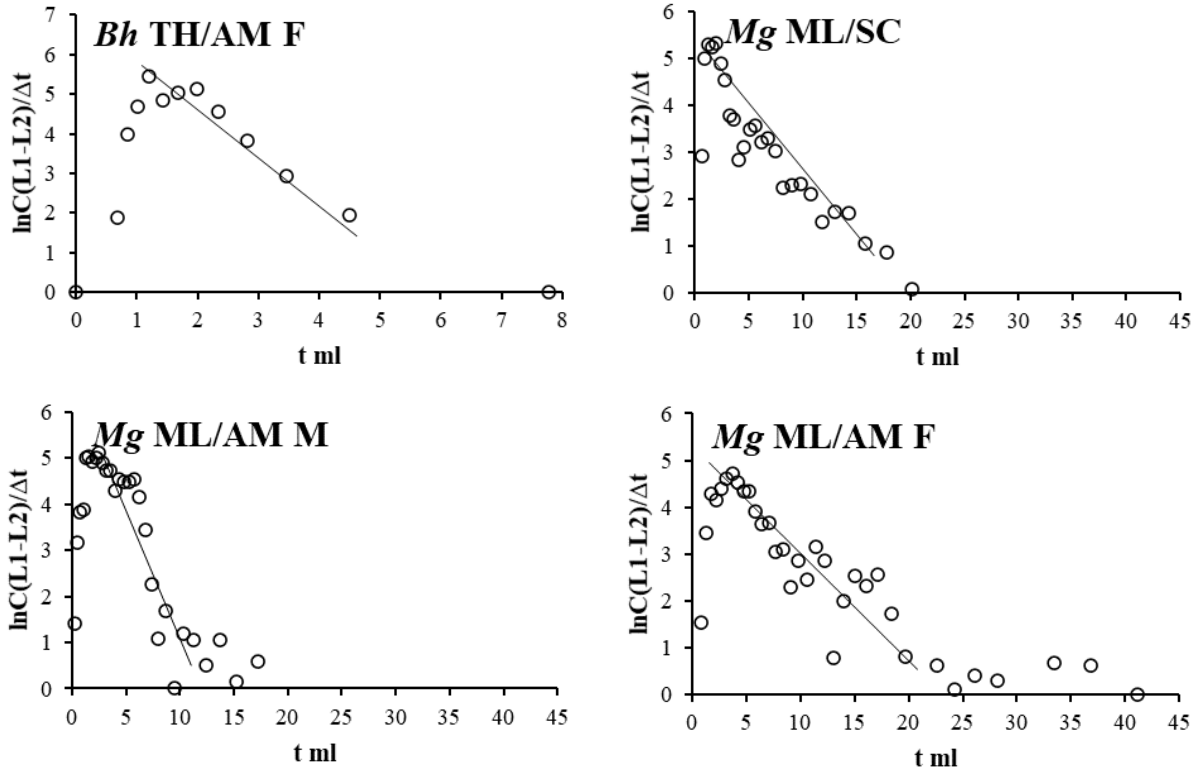


Figure 11 (continued).

The results of total mortality estimation are shown in Table 9

Table 9. Total mortality (Z) with the 95% C.I. for each shark and ray species

Species	Area	Sex	Z (year ⁻¹)	±95% C.I.
Shark				
<i>Cp</i>	CM/GT	Pooled	0.22	0.13
	TH/GT	Pooled	0.64	0.07
	ML/SC	Pooled	0.26	0.09
	ML/AM	Pooled	0.22	0.04
<i>Cl</i>	ML/SC	M	0.41	0.14
		F	0.24	0.09
<i>Ch</i>	ML/AM	Pooled	0.86	0.12
<i>Am</i>	TH/GT	M	0.93	0.36
		F	1.16	0.82
	ML/AM	M	1.84	3.26
		F	0.99	0.71
<i>Sl</i>	MY/AM	Pooled	1.04	0.23
Ray				
<i>Bh</i>	TH/GT	M	1.42	0.93

		F	0.70	0.09
	ML/AM	M	1.57	3.71
		F	1.48	0.88
	TH/AM	M	2.29	2.79
		F	1.06	0.23
<i>Mg</i>	ML/SC	Pooled	0.31	0.08
	ML/AM	M	0.46	0.17
		F	0.19	0.06
<i>Nk</i>	ML/SC	M	0.86	0.49
		F	0.80	0.18
	ML/AM	M	2.04	1.19
		F	1.09	0.34
	TH/AM	M	0.82	0.10
		F	0.40	0.23
<i>Tz</i>	ML/SC	M	1.74	0.82
		F	0.62	0.14
	TH/GT	M	1.61	0.75
		F	1.11	0.23
	ML/AM	Pooled	1.68	0.60

4.3.2. Natural mortality (*M*)

Natural mortality was estimated by the Tanaka method (Tanaka, 1960). This method requires maximum age, $t_{\max}$. The $t_{\max}$ estimates are shown in Table 10.

Table 10. Estimated $t_{\max}$ and *M* for elasmobranchs

Species	Area	Sex	$t_{\max 1}$	$t_{\max 2}$	$t_{\max 3}$	$t_{\max 4}$	<i>Med.</i>	<i>M</i>
Shark								
<i>Cp</i>	CB/GT	Pooled	15.48	13.44	14.29	25.48	14.88	0.17
	TH/GT	Pooled	8.29	6.973	7.32	11.61	7.80	0.32
	ML/SC	Pooled	13.39	11.39	12.00	25.76	12.70	0.20
	ML/AM	Pooled	15.86	13.49	14.29	18.47	15.07	0.17
<i>Cl</i>	ML/SC	M	15.85	13.64	14.29	30.02	15.07	0.17
		F	18.63	15.94	16.67	22.48	17.65	0.14
<i>Ch</i>	ML/AM	Pooled	10.30	8.72	9.091	12.40	9.69	0.26
<i>Am</i>	TH/GT	M	5.69	5.14	5.66	5.75	5.67	0.44
		F	5.89	5.28	5.77	13.13	5.83	0.43
	ML/AM	M	4.33	3.84	4.17	6.41	4.25	0.59
		F	4.27	3.85	4.22	5.17	4.24	0.59
<i>Sl</i>	MY/AM	Pooled	3.45	3.14	3.49	3.76	3.47	0.72
Ray								
<i>Tz</i>	ML/SC	M	2.94	2.93	3.37	3.88	3.16	0.79
		F	5.61	5.45	5.88	7.03	5.74	0.44
	TH/GT	M	8.14	7.87	8.57	6.87	8.01	0.31

<i>Nk</i>	ML/AM	F	3.29	3.24	3.53	4.41	3.41	0.73
		Pooled	2.65	2.59	3.00	2.99	2.82	0.89
	ML/SC	M	4.36	4.22	4.92	6.61	4.64	0.54
		F	5.12	4.99	5.88	6.24	5.50	0.45
<i>Bh</i>	ML/AM	M	2.85	2.80	3.37	4.03	3.11	0.80
		F	3.21	3.13	3.70	4.49	3.46	0.72
	TH/AM	M	5.10	4.97	5.88	7.56	5.49	0.46
		F	16.07	15.01	16.67	9.73	15.54	0.16
	TH/GT	M	4.03	4.04	4.69	6.17	4.36	0.57
		F	13.03	12.75	14.29	8.11	12.89	0.19
	ML/AM	M	4.93	4.92	5.66	7.06	5.30	0.47
		F	5.03	4.90	5.45	4.19	4.97	0.50
<i>Mg</i>	TH/AM	M	3.25	3.22	3.66	2.12	3.24	0.77
		F	4.42	4.41	5.08	7.77	4.75	0.53
	ML/SC	Pooled	29.26	25.47	27.27	41.96	28.27	0.09
	ML/AM	M	25.06	21.64	23.08	32.34	24.07	0.10
		F	56.44	47.45	50.00	75.73	53.22	0.05

4.3.3. Fishing mortality (F) and exploitation ratio (E)

The mortality estimates for elasmobranchs are shown in Table 11.

Table 11. Total mortality (Z), natural mortality (M), fishing mortality (F), and exploitation ratio (E) estimation for elasmobranchs

Species		Area	Sex	Z	M	F	E
Shark							
<i>Cp</i>		CB/GT	Pooled	0.22	0.17	0.05	0.24
		TH/GT	Pooled	0.64	0.32	0.32	0.50
		ML/SC	Pooled	0.26	0.20	0.07	0.25
		ML/AM	Pooled	0.22	0.17	0.05	0.24
<i>Cl</i>		ML/SC	M	0.41	0.17	0.24	0.59
			F	0.24	0.14	0.10	0.41
<i>Ch</i>		ML/AM	Pooled	0.86	0.26	0.61	0.70
<i>Am</i>		TH/GT	M	0.93	0.44	0.49	0.53
			F	1.16	0.43	0.73	0.63
		ML/AM	M	1.84	0.59	1.25	0.68
			F	0.99	0.59	0.40	0.41
<i>Sl</i>		MY/AM	Pooled	1.04	0.72	0.32	0.31
Ray							
<i>Tz</i>		ML/SS	M	1.74	0.79	0.94	0.54
			F	0.62	0.44	0.19	0.30
		TH/GT	M	1.61	0.31	1.30	0.81
			F	1.11	0.73	0.38	0.34
		ML/AM	Pooled	1.68	0.89	0.79	0.47

<i>Nk</i>	TH/AM	M	0.86	0.54	0.32	0.37
		F	0.80	0.45	0.34	0.43
	TH/GT	M	2.04	0.80	1.23	0.61
		F	1.09	0.72	0.37	0.34
<i>Bh</i>	ML/AM	M	0.82	0.46	0.36	0.44
		F	0.40	0.16	0.24	0.60
	TH/GT	M	1.42	0.57	0.85	0.60
		F	0.70	0.19	0.50	0.72
	ML/AM	M	1.57	0.47	1.10	0.70
		F	1.48	0.50	0.98	0.66
	TH/AM	M	2.29	0.77	1.52	0.66
		F	1.06	0.53	0.54	0.51
<i>Mg</i>	ML/SC	Pooled	0.31	0.09	0.22	0.71
	ML/AM	M	0.46	0.10	0.36	0.77
		F	0.19	0.05	0.15	0.76

The range of the natural mortality of elasmobranchs varied simultaneously with the $t_{\max}$. The largest $t_{\max}$ was 53.22 years for *Mg* from ML/AM while the smallest $t_{\max}$ was 3.16 years for male *Tz* from ML/SC. These may not be the true $t_{\max}$ values for the entire populations, but they were used for the exploited stock for each species in this study.

4.3.4. Gear selectivity

The gear selectivity estimated using the length-converted catch curve was applied to each species. L_{50} was used as the size at first capture, L_c . The observed and estimated selection ogive (St and St') with the probability of capture at 25, 50, and 75% are shown in Figures 12, and 13, and Table 12.

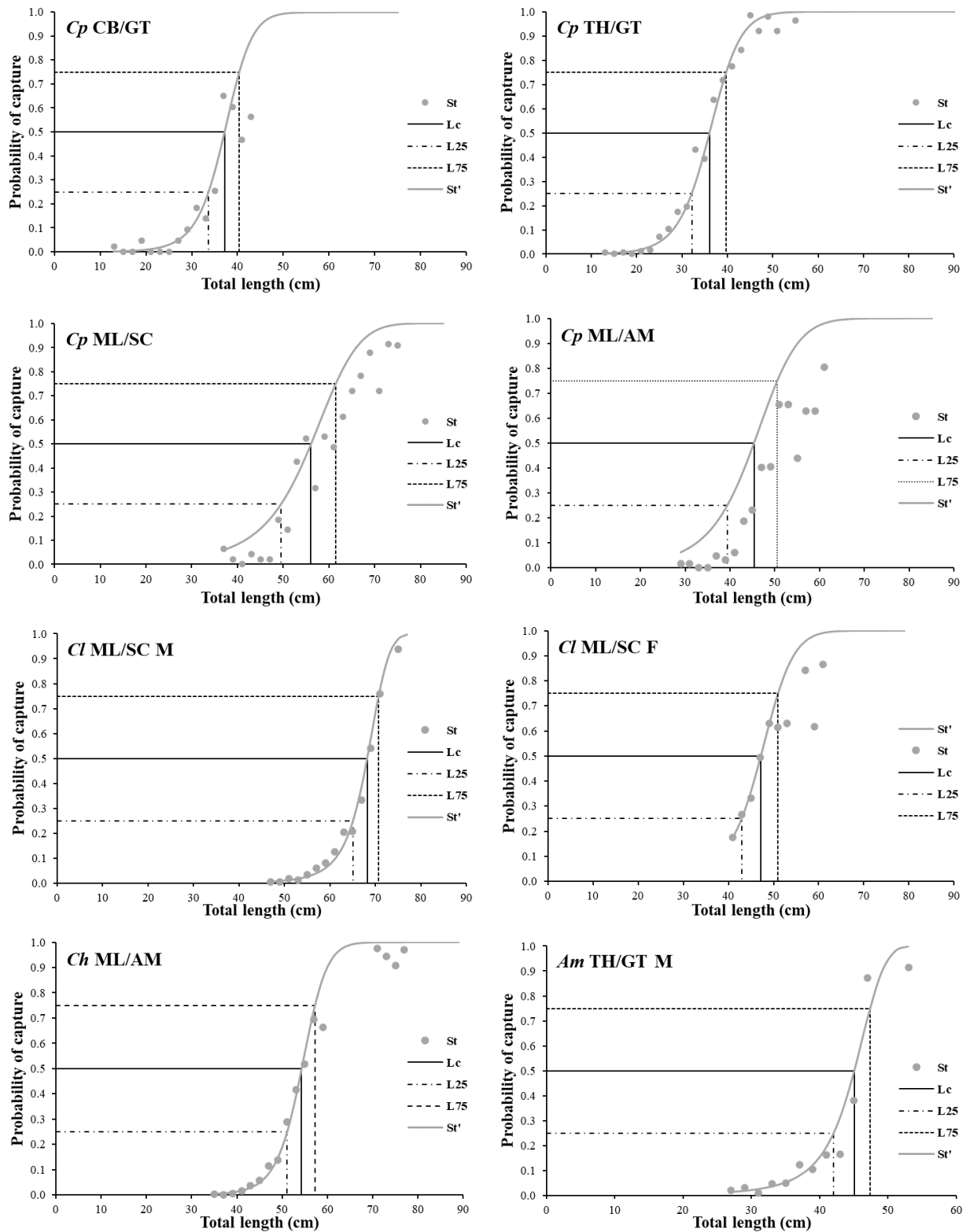


Figure 12. Gear selectivity for shark species. M: male, F: female.

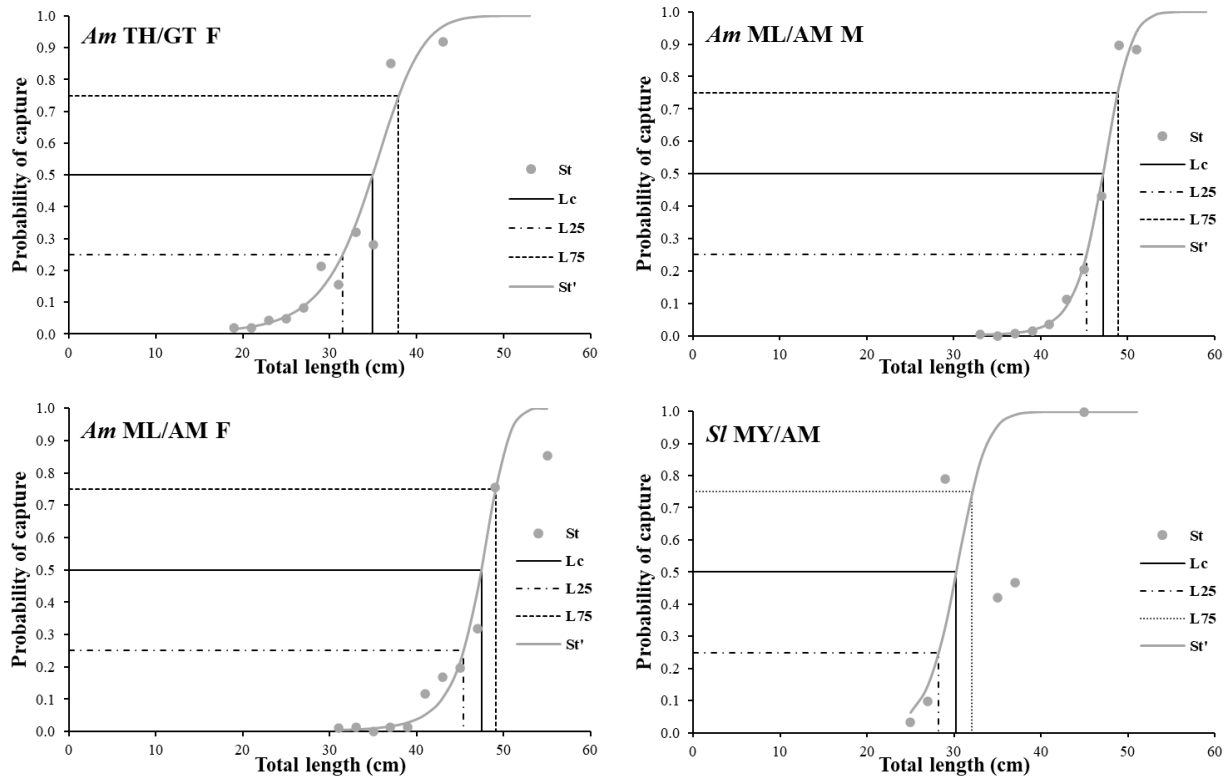


Figure 12 (continued).

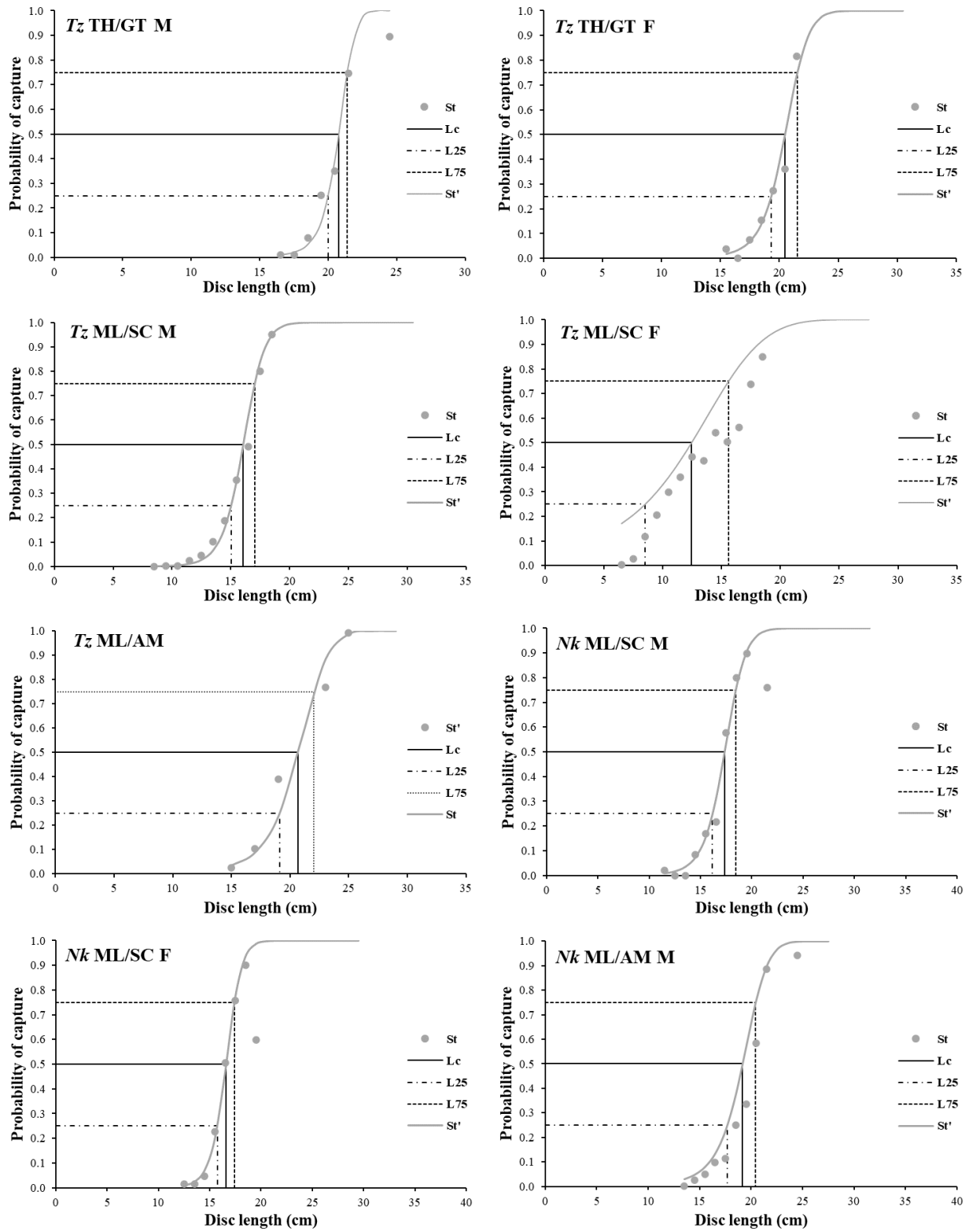


Figure 13. Gear selectivity for ray species. M: male, F: female.

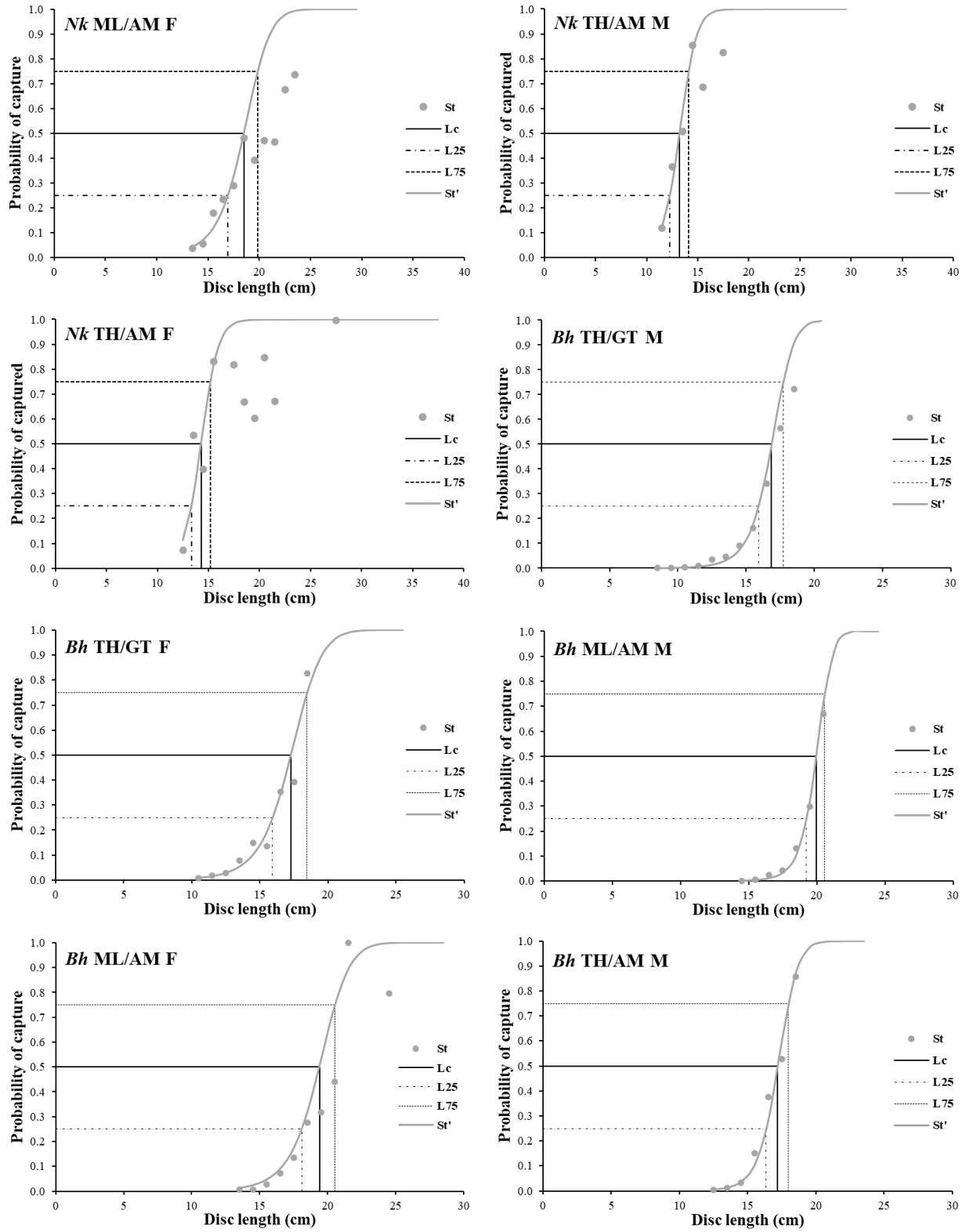


Figure 13 (continued).

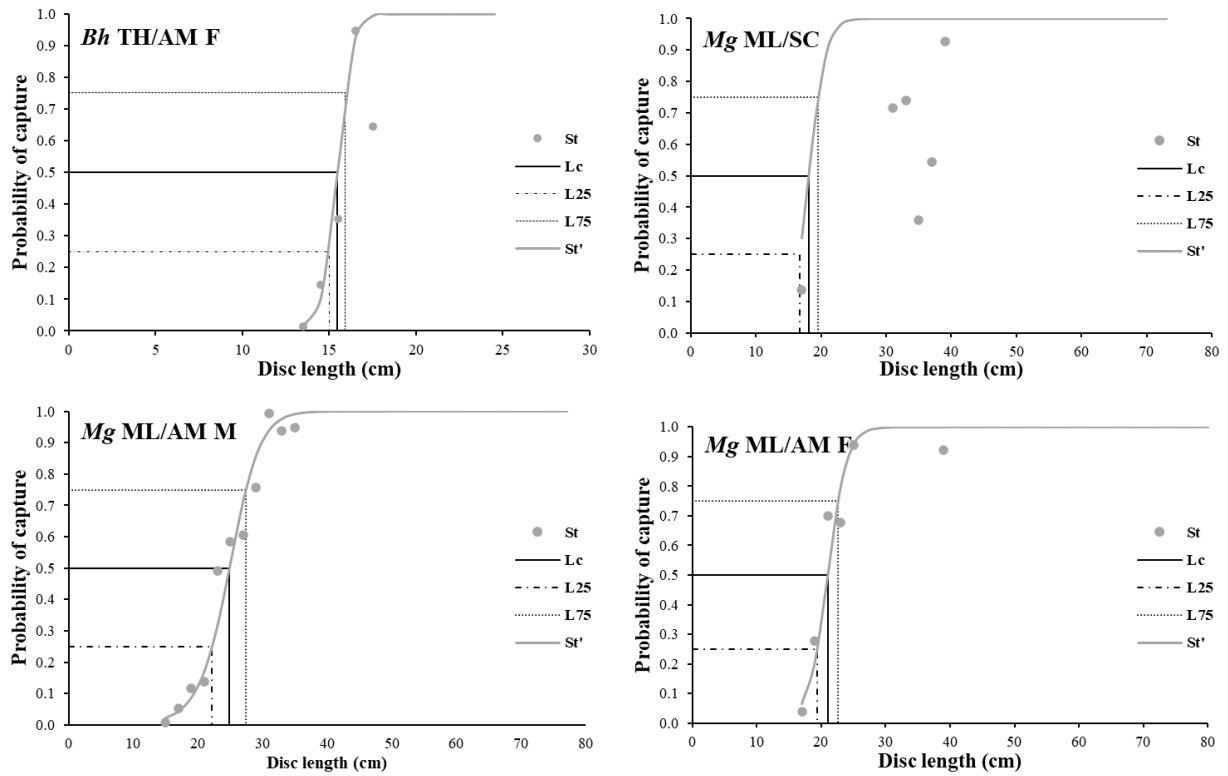


Figure 13 (continued).

Table 12. Size and age at first capture (L_c , t_c).

Species	Area	Sex	L_c	t_c
Shark				
<i>Cp</i>	CB/GT	Pooled	37.16	2.41
	TH/GT	Pooled	36.07	0.85
	ML/SC	Pooled	56.03	3.53
	ML/AM	Pooled	45.35	2.76
<i>Cl</i>	ML/SC	M	68.19	8.12
		F	47.17	3.85
<i>Ch</i>	ML/AM	Pooled	54.25	2.42
<i>Am</i>	TH/GT	M	45.06	2.72
		F	35.50	1.29
	ML/AM	M	47.17	1.57
		F	47.45	2.26
<i>Sl</i>	MY/AM	Pooled	30.25	0.65
Ray				
<i>Tz</i>	ML/SC	M	20.76	1.55
		F	20.48	0.15
	TH/GT	M	16.07	1.24
		F	12.44	0.41
	ML/AM	Pooled	20.68	0.76

<i>Nk</i>	ML/SC	M	17.35	0.59
		F	16.61	0.67
	ML/AM	M	19.16	0.74
		F	18.48	0.62
	TH/AM	M	13.20	0.21
		F	14.28	0.60
<i>Bh</i>	TH/GT	M	16.87	1.29
		F	17.27	2.70
	ML/AM	M	19.95	2.32
		F	19.39	1.26
	TH/AM	M	17.19	0.82
		F	15.46	1.01
<i>Mg</i>	ML/SC	Pooled	18.11	0.80
	ML/AM	M	24.86	1.55
		F	21.03	1.74

4.4. Yield per recruit analysis and spawning per recruit analysis

The inputs for SPR and size at first maturity (L_m) are shown in Table 13

Table 13. Size at first maturity (L_m) based on Ahmad and Lim (2012), Ahmad et al. (2014), and Krajangdara (2017), and the estimated age at first maturity (t_m) based on L_m .

Species	Area	Sex	L_m	t_m
Shark				
<i>Cp</i>	CM/GT	Pooled	65.00	8.65
	TH/GT	Pooled	67.00	2.84
	ML/SC	Pooled	68.00	4.89
	ML/AM	Pooled	56.50	3.18
<i>Cl</i>	ML/SC	M	140.00	7.70
		F	156.00	8.43
<i>Ch</i>	ML/AM	Pooled	45.00	2.62
<i>Am</i>	TH/GT	M	49.00	2.71
		F	220.00	2.91
	ML/AM	M	29.50	1.08
		F	65.00	2.54
<i>Sl</i>	MY/AM	Pooled	68.00	0.61
Ray				
<i>Tz</i>	ML/SC	M	16.00	0.71
		F	19.00	1.26
	TH/GT	M	16.00	1.22
		F	19.00	1.05
<i>Nk</i>	ML/AM	Pooled	18.50	0.55
	ML/SC	M	24.46	1.66

		F	26.13	3.44
	ML/AM	M	24.46	1.77
		F	26.13	1.93
	TH/AM	M	24.46	2.44
		F	26.13	3.55
<i>Bh</i>	TH/GT	M	15.00	0.91
		F	18.00	3.00
	ML/AM	M	15.00	1.01
		F	18.00	1.05
	TH/AM	M	15.00	0.57
		F	18.00	1.55
<i>Mg</i>	ML/SC	Pooled	60.00	16.29
	ML/AM	M	52.00	14.50
		F	63.50	16.33

Considering a large amount of information in the group figures in the previous sections, the results are presented for each family below.

4.4.1. Sharks

4.4.1.1. Bamboo shark (Family Hemiscyllidae)

All 3 species (*Cp*, *CL*, and *Ch*) were found from the GT (CM and TH), SC (ML), and AM (TH and ML). The results of YPR are shown in Figures 14 and 15 for YPR's surface plot and line plot at constant t_c . The results of SPR are shown in Figures 16 and 17 for SPR's surface plot and line plot at a constant t_c . F_{curr} and BRPs are shown in Table 14. Only the female result for SPR was provided $F_{30\%}$ and $F_{20\%}$ regarding the spawning biomass, female.

Table 14. F_{curr} and BRPs for bamboo shark (family Hemiscyllidae)

Reference points	<i>Cp</i>				<i>Cl</i>		<i>Ch</i>
	CM	TH	ML/SC	ML/AM	ML/SC		ML/AM
	Pooled	Pooled	Pooled	Pooled	M	F	Pooled
F_{curr}	0.05	0.32	0.01	0.05	0.24	0.14	0.61
$F_{0.1}$	0.22	0.31	0.29	0.29	0.31	0.22	0.40
F_{max}	0.31	0.44	0.73	0.68	1.30	0.42	0.84
$F_{30\%}$	0.12	0.25	0.23	0.28	*	0.15	0.38
$F_{20\%}$	0.16	0.35	0.34	0.42		0.20	0.60
$F_{curr}/F_{0.1}$ (%)	24.98	103.48	4.68	17.87	78.58	63.98	151.86
F_{curr}/F_{max} (%)	17.35	73.24	1.84	7.67	18.48	33.25	72.33
$F_{curr}/F_{30\%}$ (%)	44.89	128.51	5.75	18.73		95.70	161.24
$F_{curr}/F_{20\%}$ (%)	33.02	91.37	3.97	12.26		69.59	101.64

*The blanked F_{max} means that the YPR curve at the specific t_c was not providing the peak of the curve

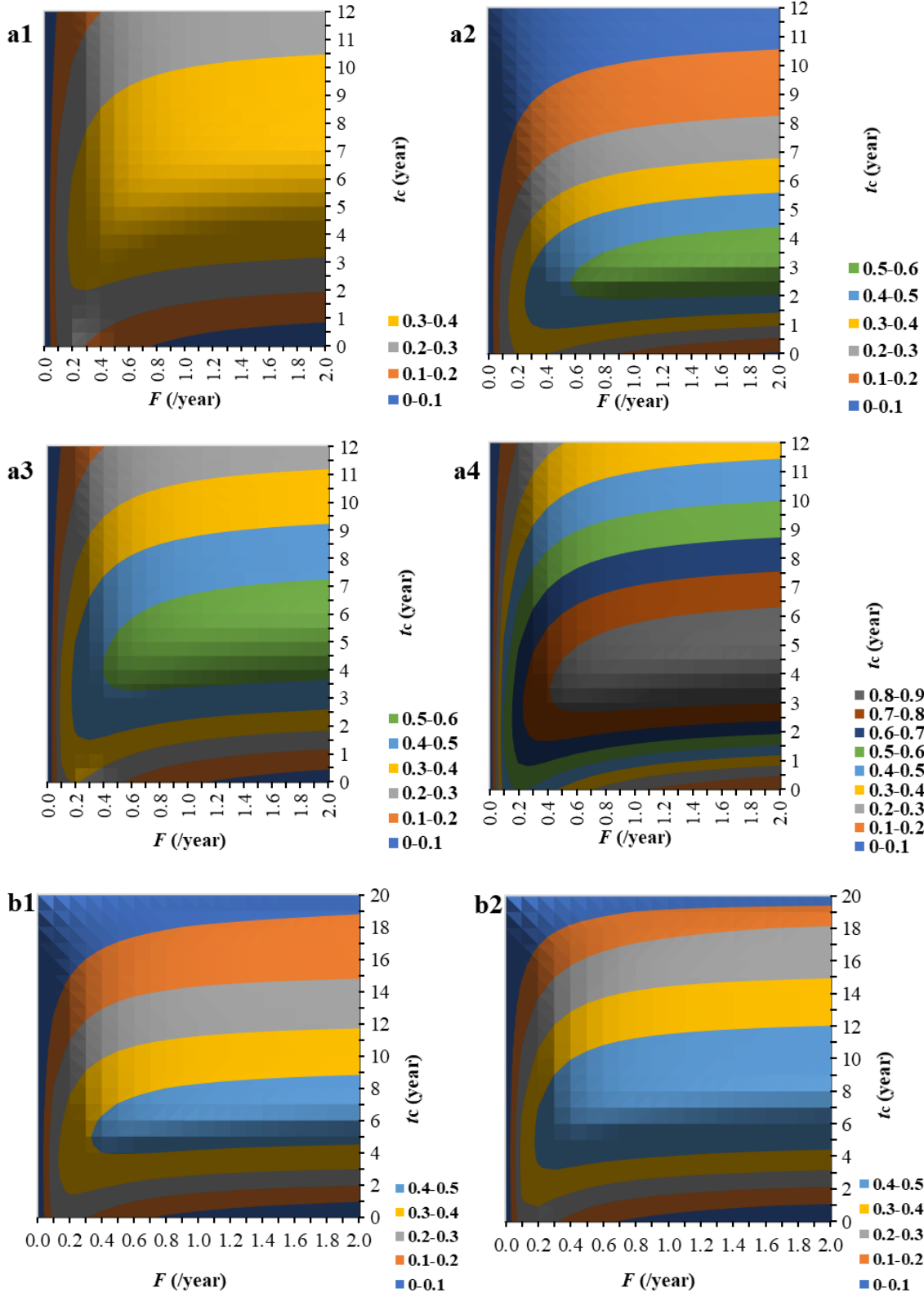


Figure 14. YPR surface plots for C_p (a1: CM/GT, a2: TH/GT, a3: ML/SC, a4: ML/AM), C_l (b1: male, b2: female from ML/AM), and C_h (c: ML/AM).

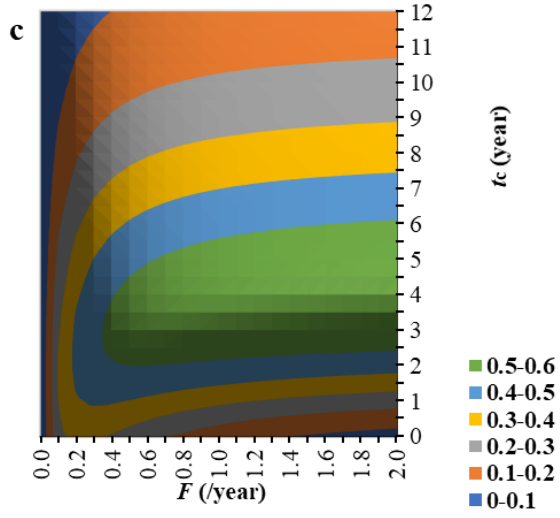


Figure 14 (continued).

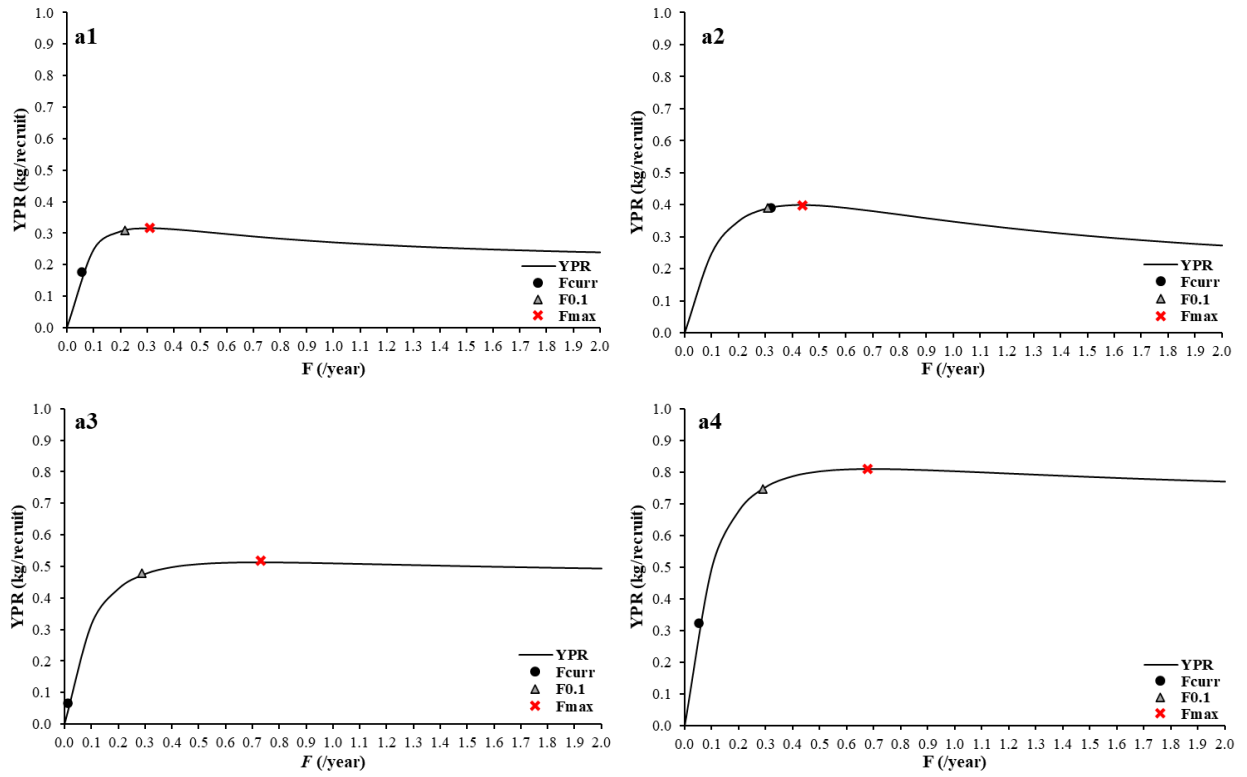


Figure 15. YPR line plots at constant t_c for (a1: CM/GT, a2: TH/GT, a3: ML/SC, a4: ML/AM), Cl (b1: male, b2: female from ML/AM), and Ch (c: ML/AM).

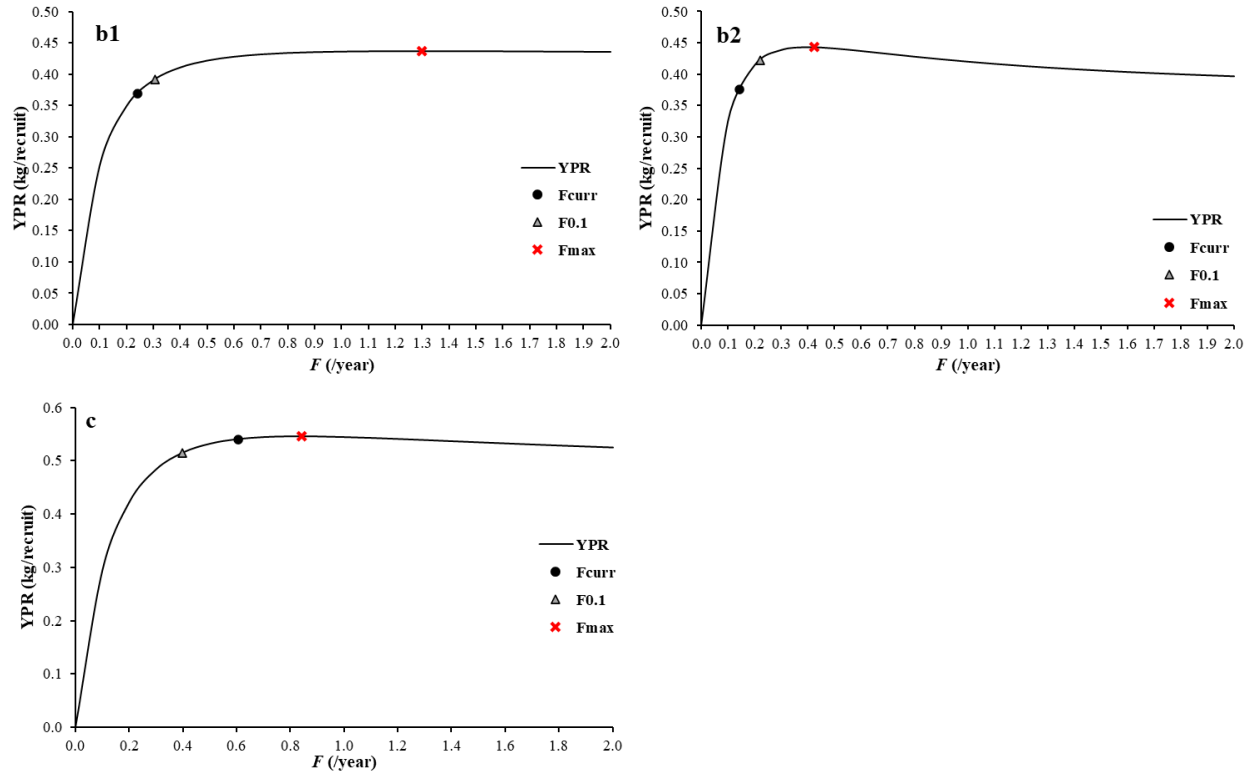


Figure 15 (continued).

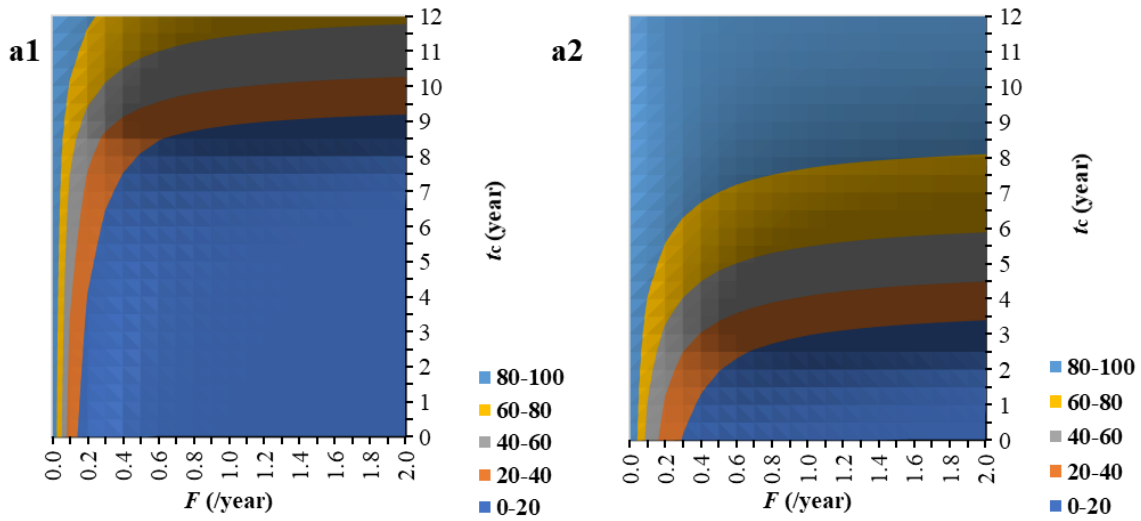


Figure 16. SPR surface plots for (a1: CM/GT, a2: TH/GT, a3: ML/SC, a4: ML/AM), Cl (b), and Ch (c).

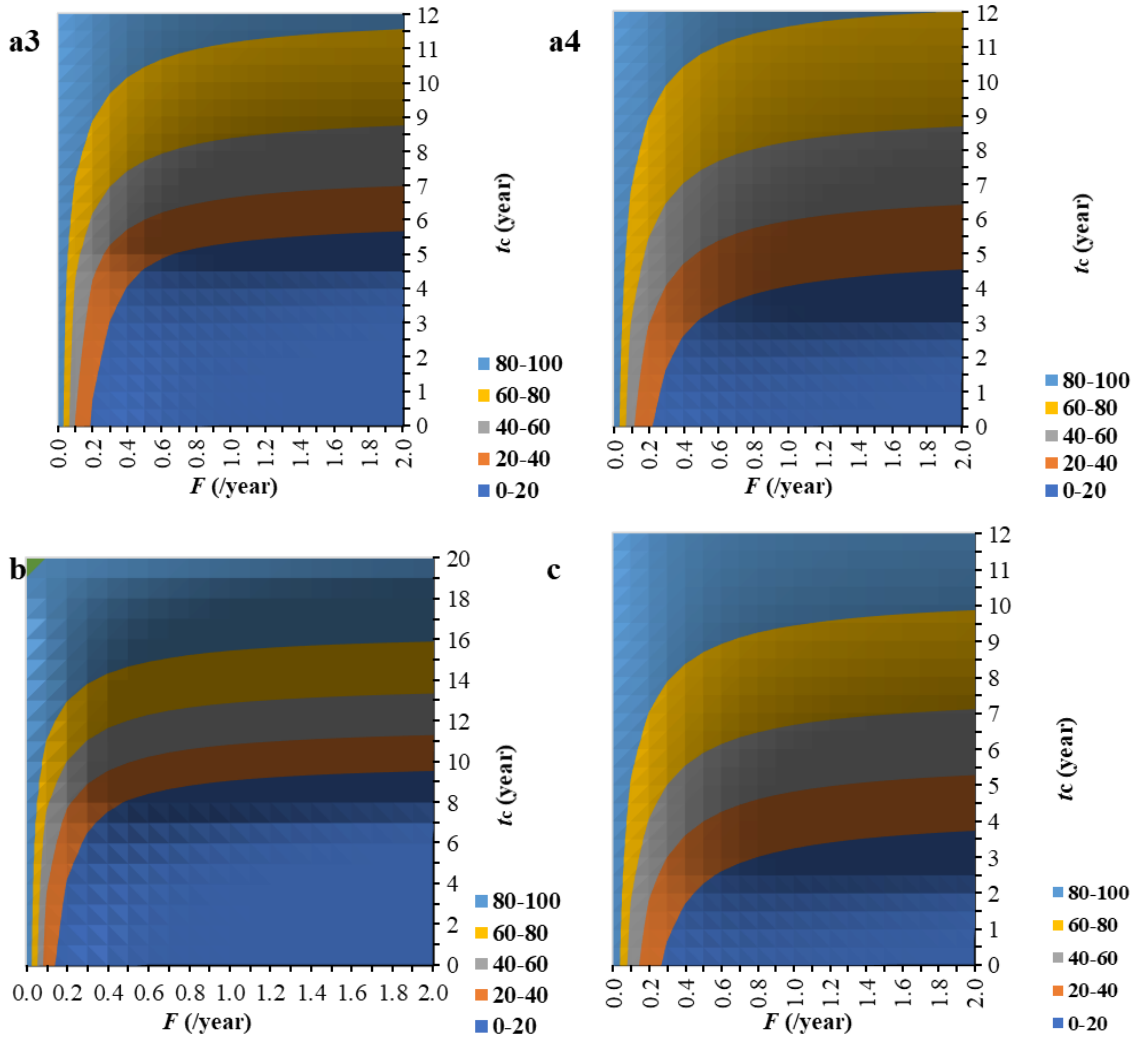


Figure 16 (continued).

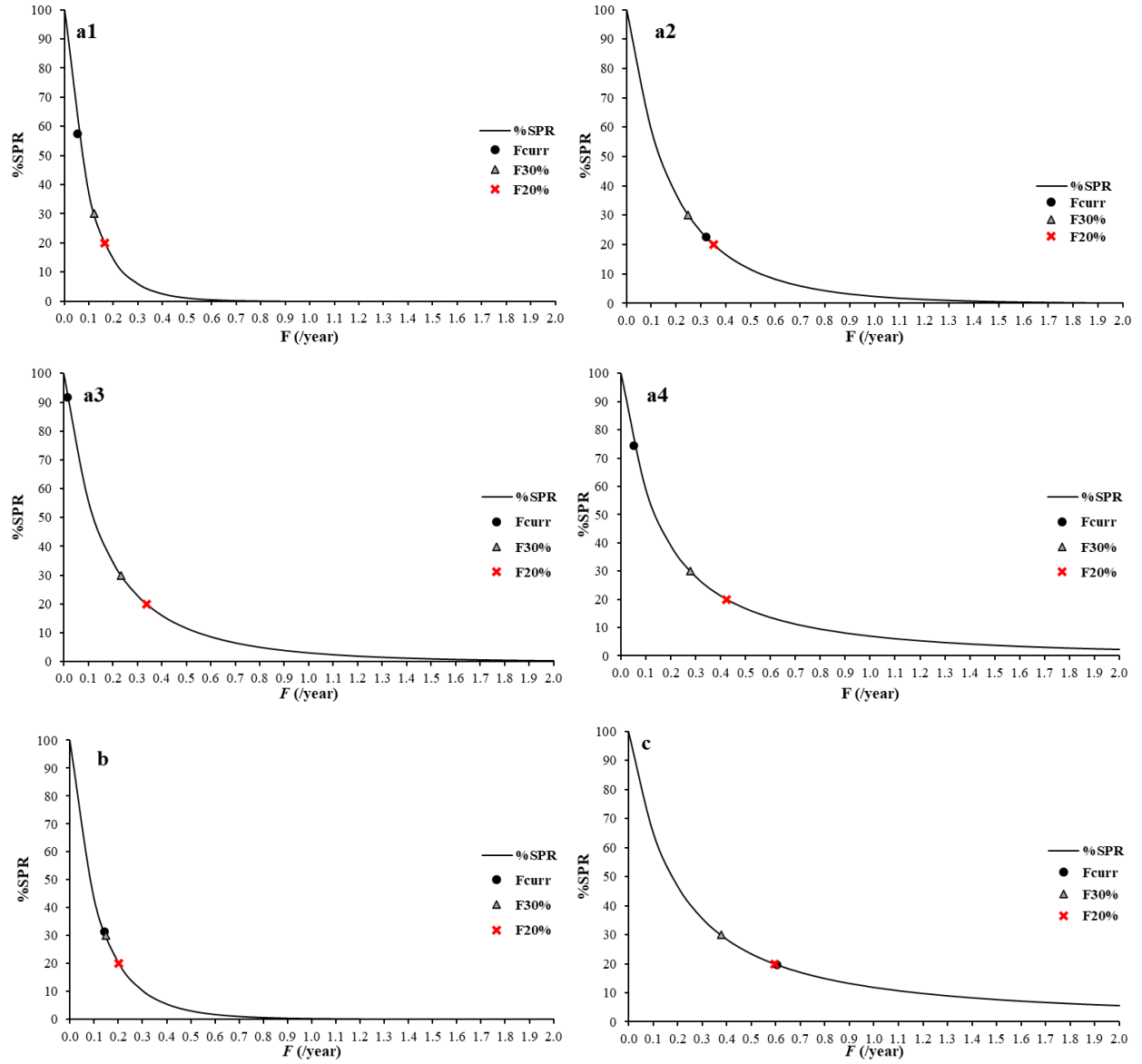


Figure 17. %SPR line plots at constant t_c for (a1: CM/GT, a2: TH/GT, a3: ML/SC, a4: ML/AM), CI (b), and Ch (c).

4.4.1.2. Catshark (Family Scyliorhinidae)

The only species of the family Scyliorhinidae selected in this study was *Am*. It was caught by trawl net and landed at TH/GT and ML/SC. The results of YPR are shown in Figures 18 and 19 for YPR's surface plot and line plot at constant t_c . The results of SPR are shown in Figures 20 and 21 for SPR's surface plot and line plot at constant t_c . The F_{curr} and BRPs were provided in Table 15.

Table 15. F_{curr} and BRPs for catshark (family Scyliorhinidae)

Reference points	<i>Am</i>			
	TH/AM		ML/SC	
	M	F	M	F
F_{curr}	0.49	0.73	1.26	0.36
$F_{0.1}$	0.82	0.55	0.93	1.24
F_{max}	*	1.25	*	*
$F_{30\%}$	**	0.35	**	0.85
$F_{20\%}$	**	0.49	**	1.28
$F_{curr}/F_{0.1}$ (%)	59.92	132.79	134.43	28.73
F_{curr}/F_{max} (%)		58.13		
$F_{curr}/F_{30\%}$ (%)		207.16		42.14
$F_{curr}/F_{20\%}$ (%)		149.09		27.96

*The blanked F_{max} means that the YPR curve at the specific t_c was not providing the peak of the curve.

** Only the female can produce $F_{30\%}$ and $F_{20\%}$ as the ability to produce the offsprings.

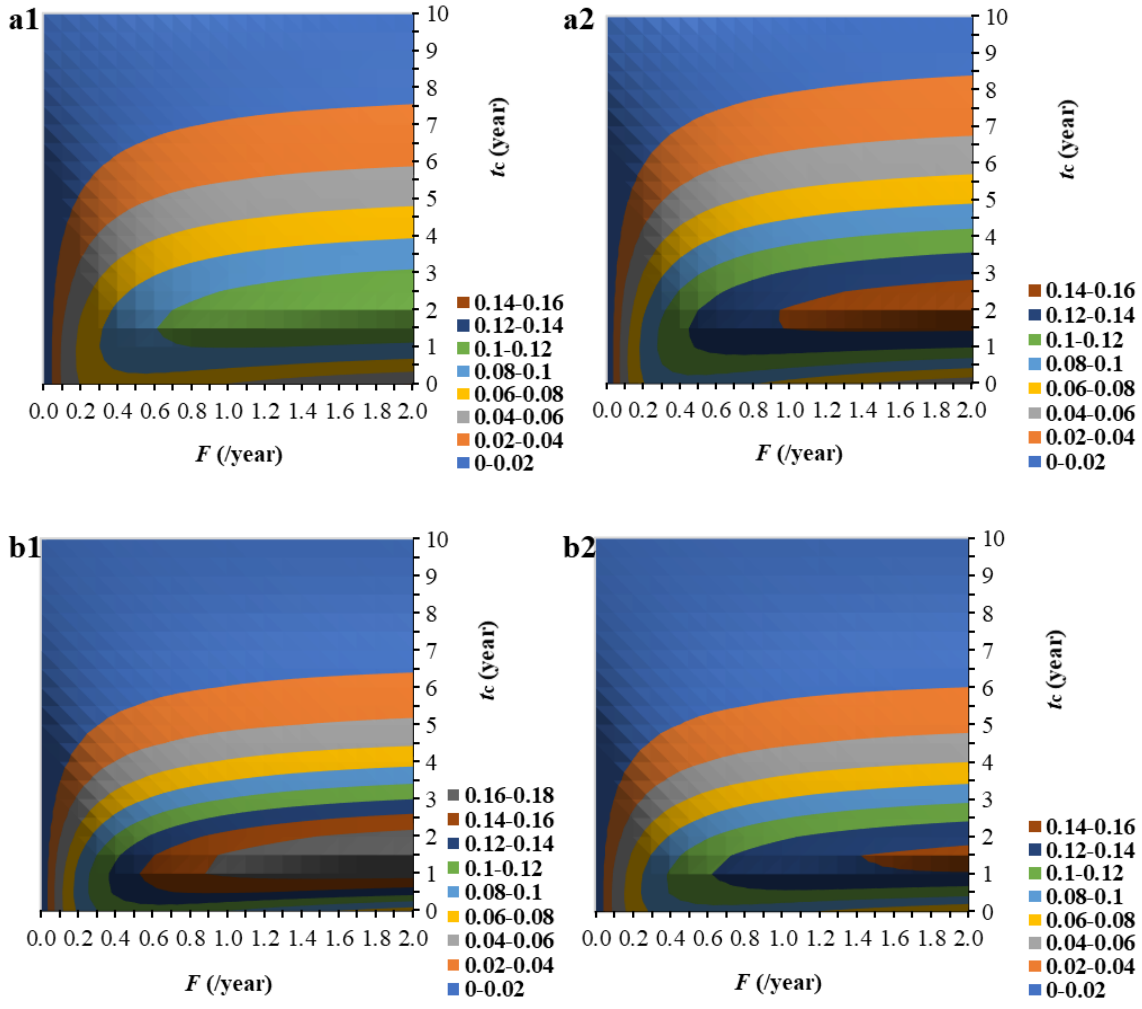


Figure 18. YPR surface plots for Am at TH/GT (a1: male, a2: female), ML/AM (b1: male, b2: female).

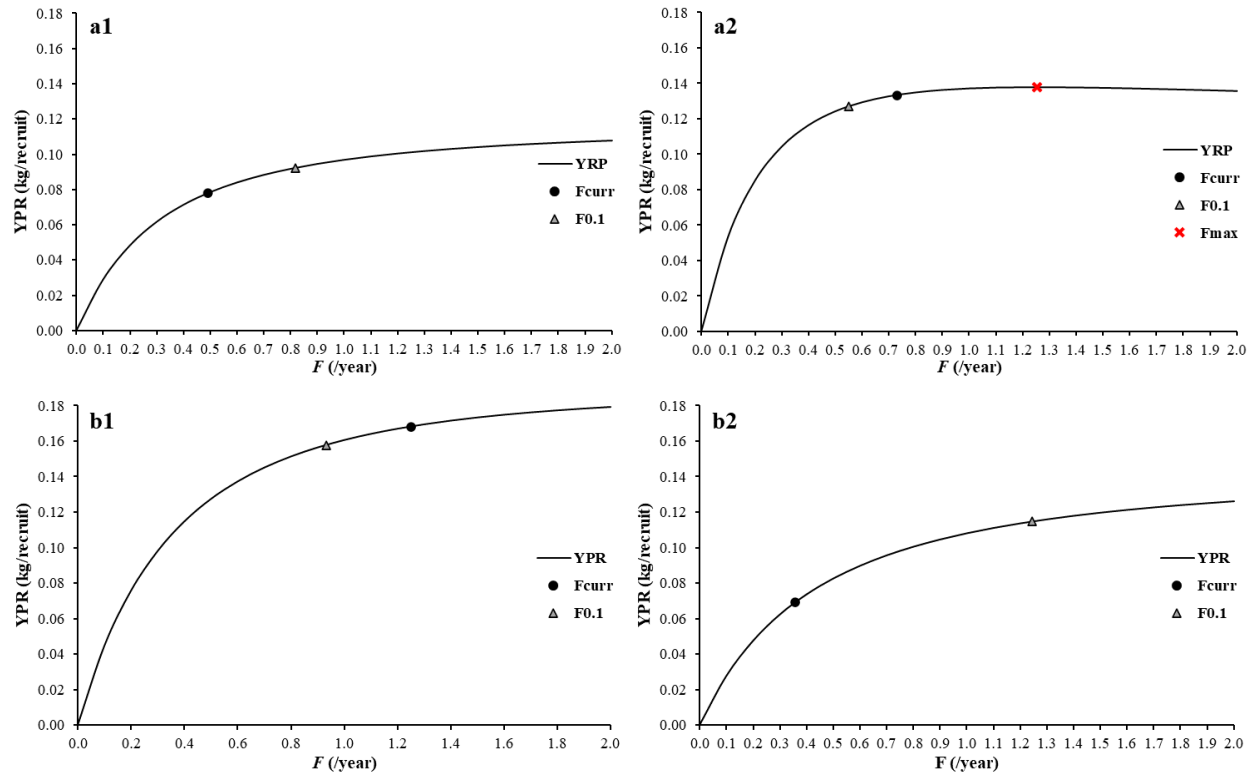


Figure 19. YPR line plots at constant t_c for *Am* at TH/GT (a1: male, a2: female), ML/AM (b1: male, b2: female).

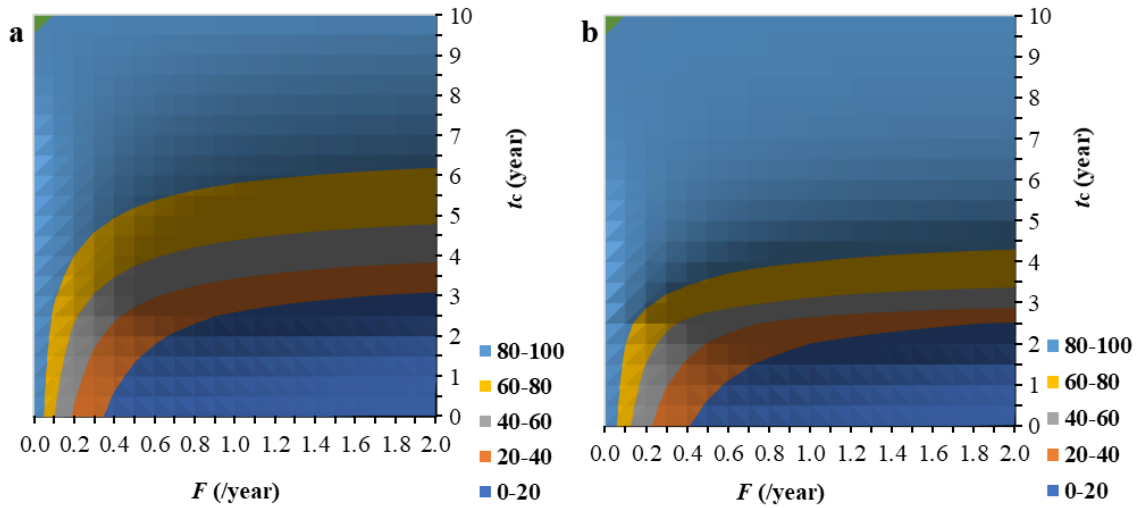


Figure 20. %SPR surface plots for *Am* at TH/GT (a), and ML/AM (b).

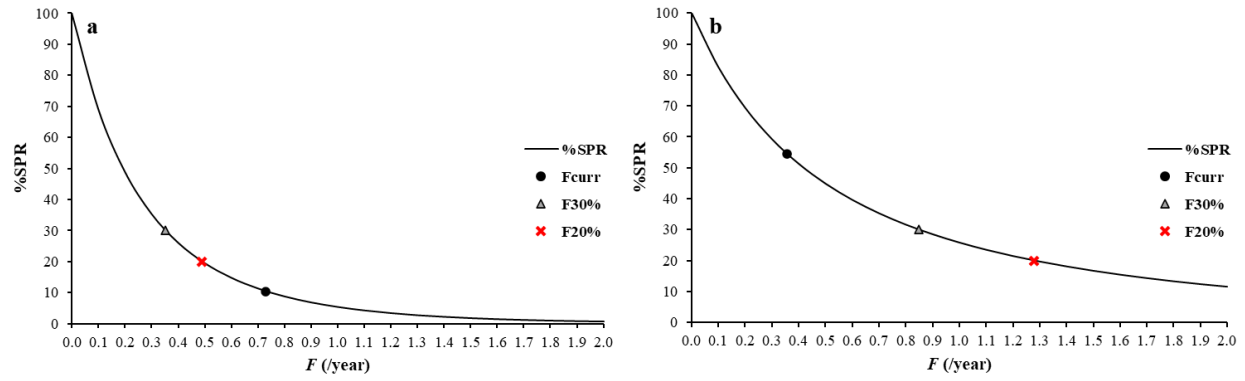


Figure 21. %SPR line plot at constant t_c for *Am* at TH/GT (a), and ML/AM (b).

4.4.1.3. Requiem shark (Family Carcharhinidae)

The Only species of the family Carcharhinidae selected in this study was *Sl*. It was caught by trawl net and landed at MY. The results of YPR and SPR were provided in Figures 22 for surface plot and 23 for line plot at constant t_c . The F_{curr} and BRPs were provided in Table 16.

Table 16. F_{curr} and BRPs

for requiem shark

(family Carcharhinid)

Reference points	<i>SL</i> MY/AM Pooled
F_{curr}	0.32
$F_{0.1}$	0.86
F_{max}	1.92
$F_{30\%}$	1.01
$F_{20\%}$	0.16
$F_{curr}/F_{0.1}$ (%)	37.13
F_{curr}/F_{max} (%)	16.61
$F_{curr}/F_{30\%}$ (%)	31.50
$F_{curr}/F_{20\%}$ (%)	19.50

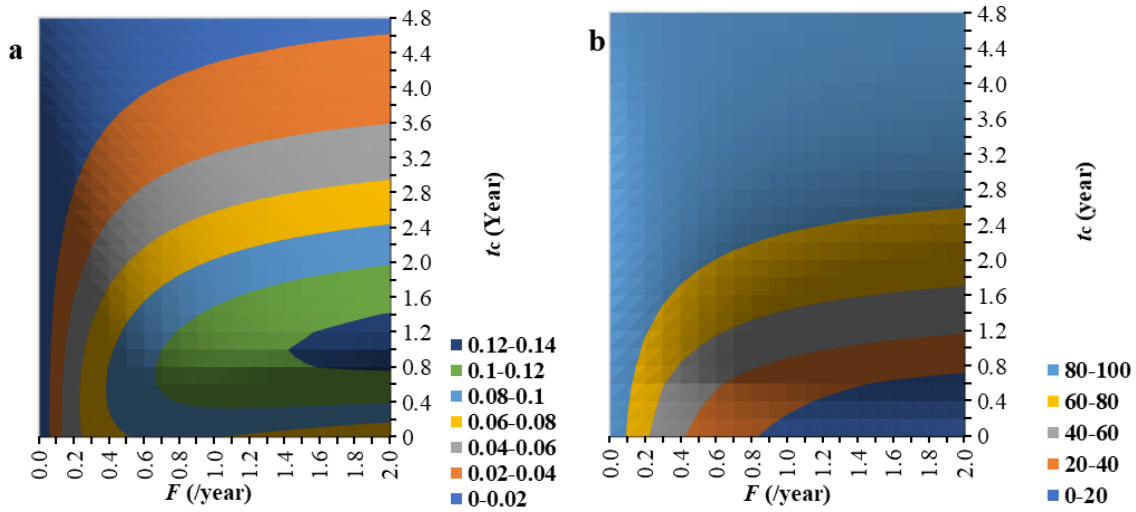


Figure 22. YPR surface plot (a) and %SPR surface plot (b) for Sl from MY.

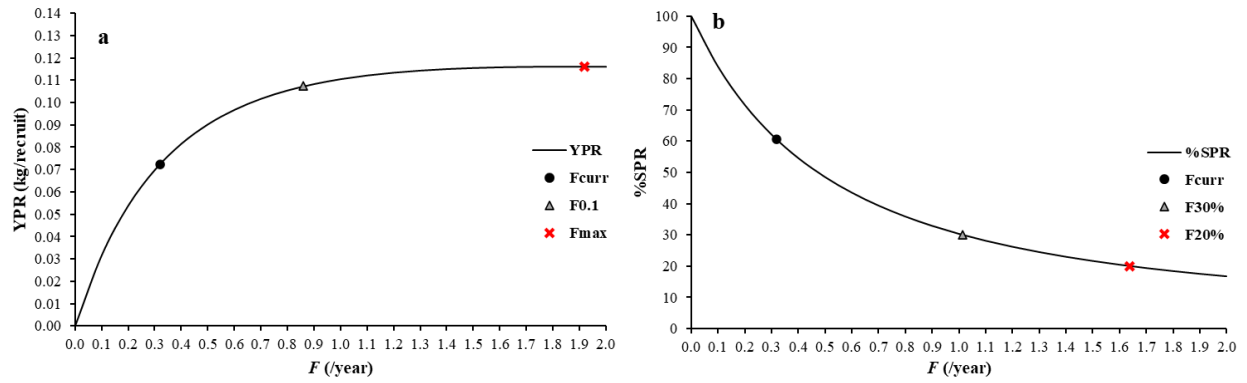


Figure 23. YPR line plot at constant t_c (a) and %SPR line plot at constant t_c (b) for Sl from MY.

4.4.2. Rays

The only family of rays analysed was Dasyatidae, the results are presented for each species.

4.4.2.1. Sharpnose stingray (*Telatrygon zugei*)

The sharpnose stingray was landed at 3 landing sites namely SK (THA/GoT), KK (MAL/SCS), and PR (MAL/ADM). The results of YPR are shown in Figures 24 and 25 for YPR's surface plot and line plot at constant t_c . The results of SPR are shown in Figures 26 and 27 for SPR's surface plot and line plot at constant t_c . The F_{curr} and BRPs are shown in Table 17.

Table 17. F_{curr} and BRPs for sharpnose stingray (*Telatrygon zugei*)

Reference points	<i>Tz</i>				
	TH/GT		ML/SC		ML/AM
	M	F	M	F	All
F_{curr}	0.94	0.19	0.91	0.38	0.79
$F_{0.1}$	1.49	0.57	0.31	0.66	1.25
F_{max}	*	1.33	0.51	1.16	*
$F_{30\%}$	**	0.60	**	0.63	>2
$F_{20\%}$	**	0.95	**	0.89	>2
$F_{curr}/F_{0.1}$ (%)	63.22	33.19	289.48	57.62	63.49
F_{curr}/F_{max} (%)		14.11	179.30	32.74	
$F_{curr}/F_{30\%}$ (%)		31.35		60.80	17.08
$F_{curr}/F_{20\%}$ (%)		19.79		42.59	0.10

*The blanked F_{max} means that the YPR curve at the specific t_c was not providing the peak of the curve.

** Only the female can produce $F_{30\%}$ and $F_{20\%}$ as the ability to produce the offsprings

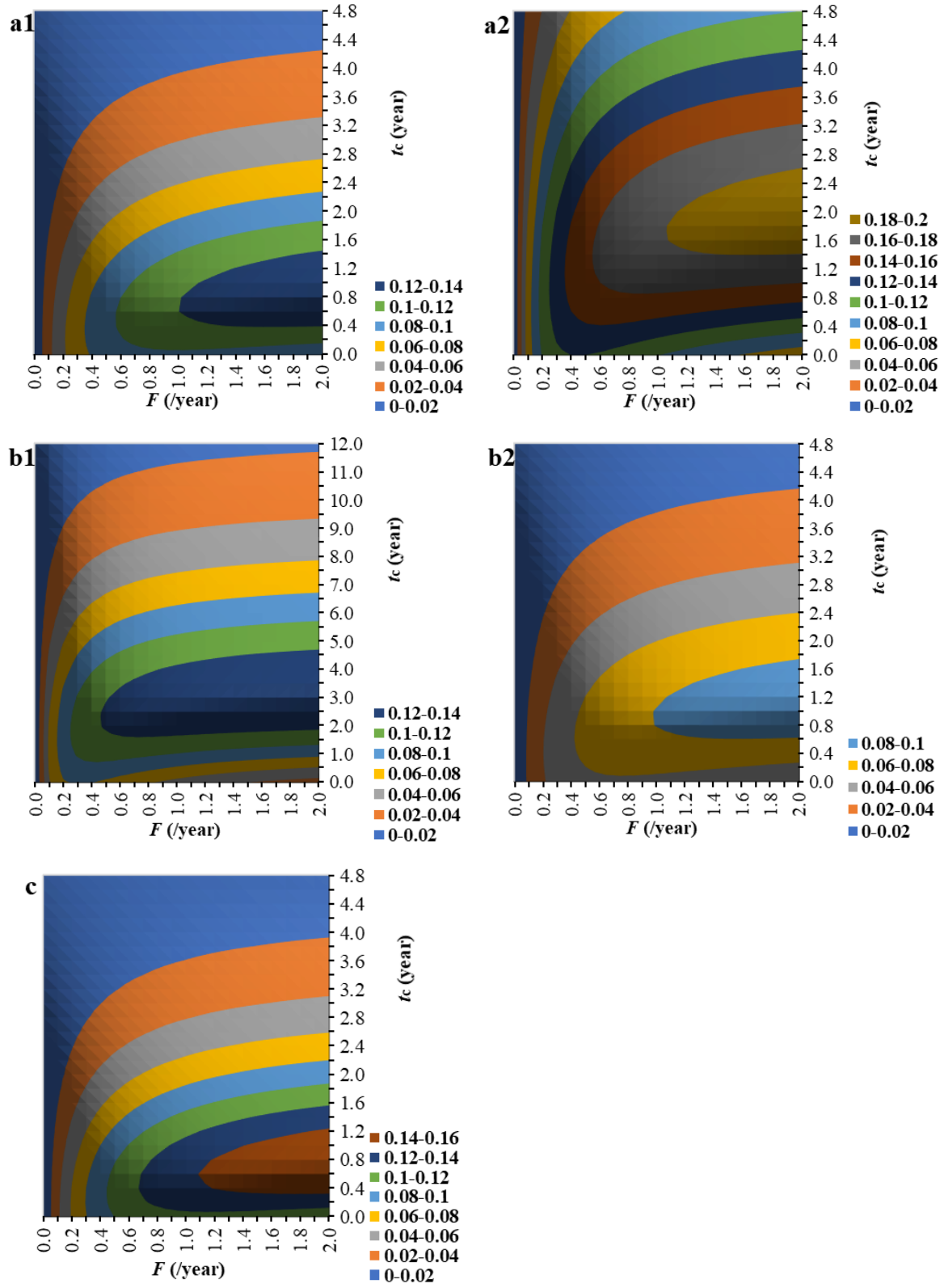


Figure 24. YPR surface plots for T_z at TH/GT (a1: male, a2: female), ML/SC (b1: male, b2: female), and ML/AM (c).

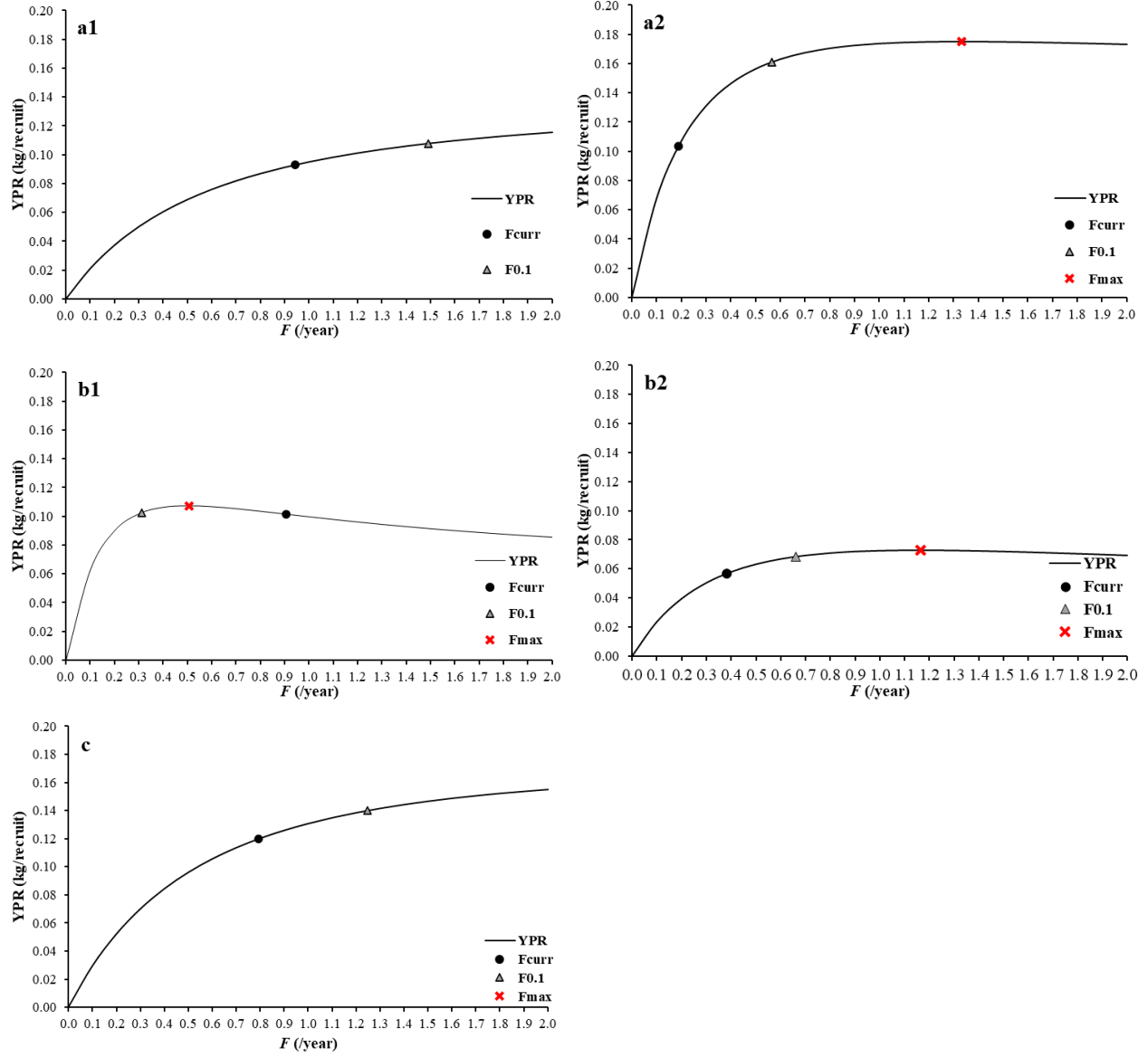


Figure 25. YPR line plots at constant t_c for Tz at TH/GT (a1: male, a2: female), ML/SC (b1: male, b2: female), and ML/AM (c).

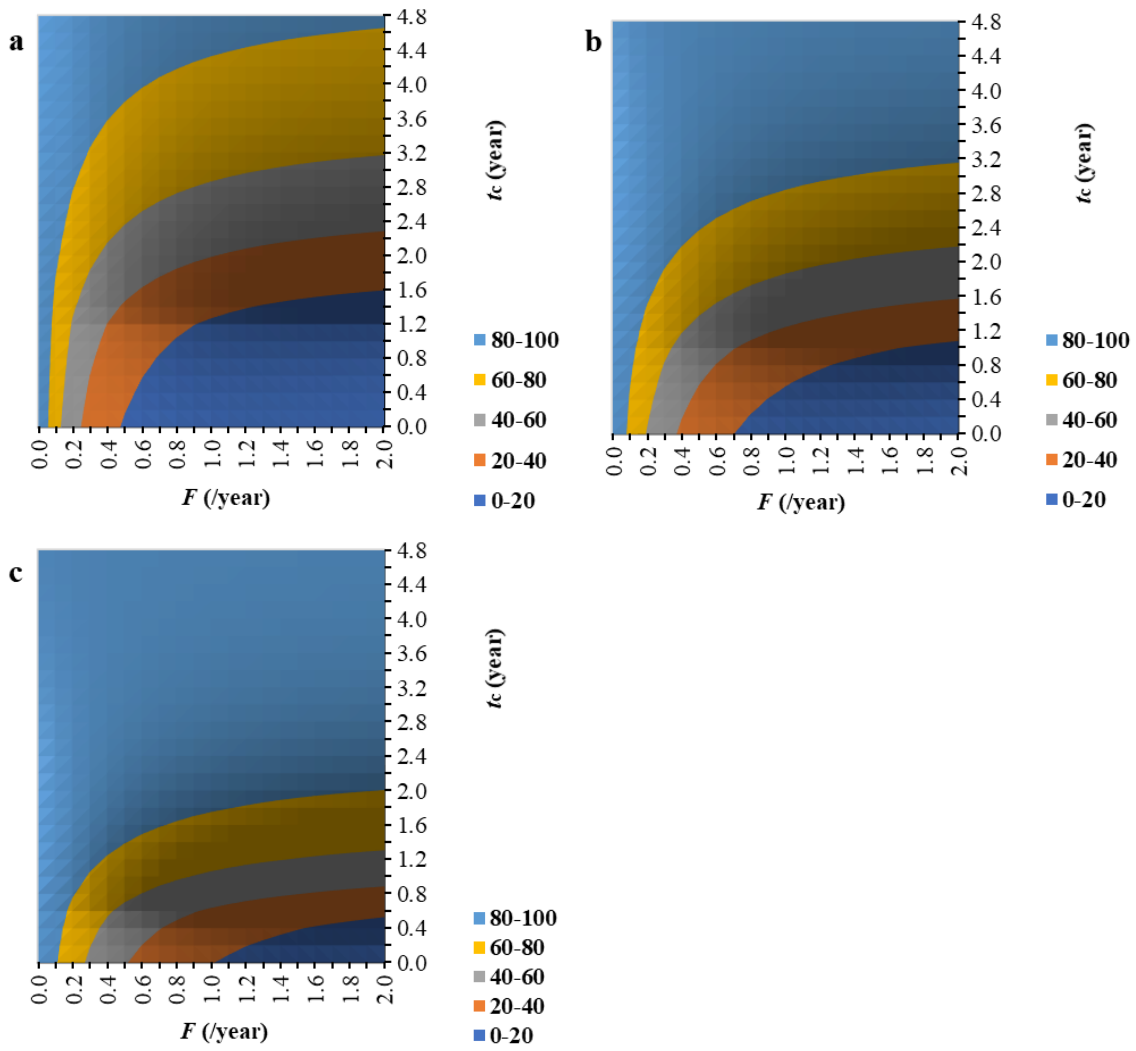


Figure 26. %SPR surface plots for T_z at TH/GT (a), ML/SC (b), and ML/AM (c).

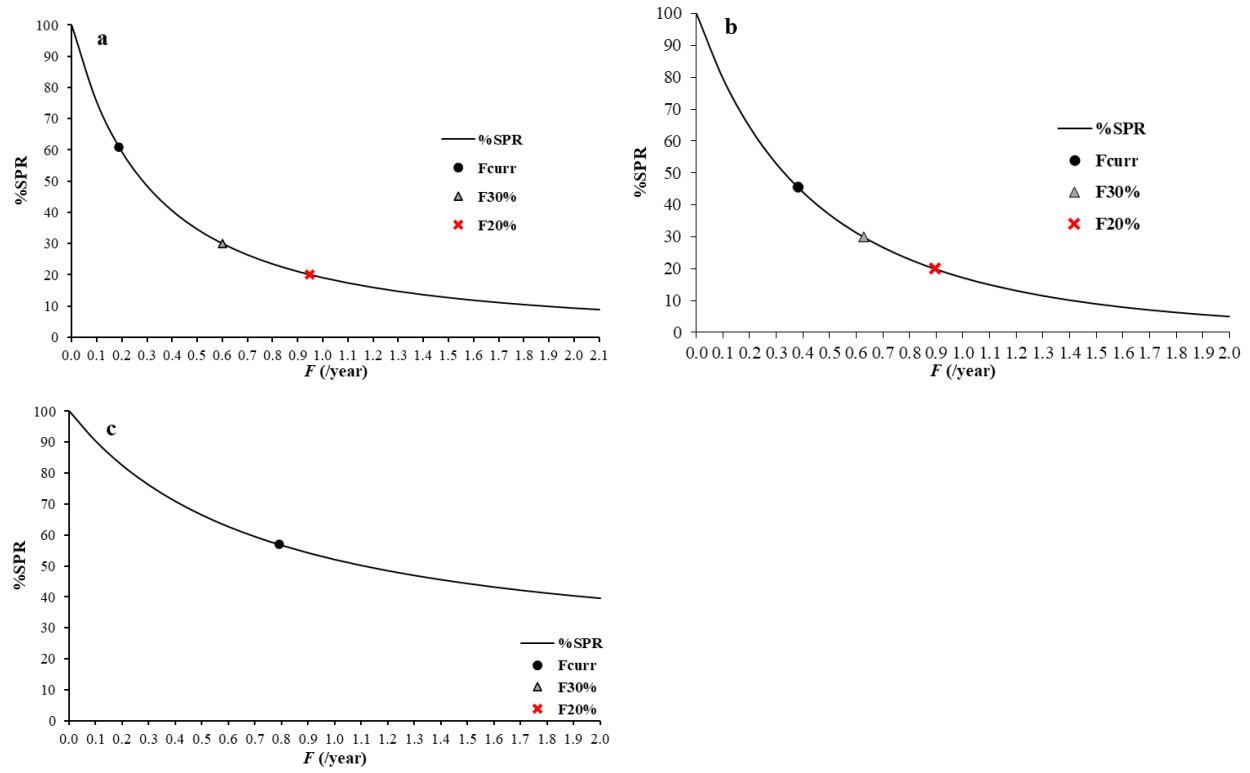


Figure 27. %SPR line plots at constant t_c for T_z at TH/GT (a), ML/SC (b), and ML/AM (c).

4.4.2.2. Bluespotted maskray (*Neotrygon kuhlii*)

The bluespotted maskray in this study was landed in ML/SC, TH/AM, and ML/AM. The results of YPR are shown in Figures 28 and 29 for YPR's surface plot and line plot at constant t_c . The results of SPR are shown in Figures 30 and 31 for SPR's surface plot and line plot at constant t_c . The F_{curr} and BRPs are shown in Table 18.

Table 18. F_{curr} and BRPs for bluespotted maskray (*Neotrygon kuhlii*)

Reference points	<i>Nk</i>					
	ML/SC		TH/AM		ML/AM	
	M	F	M	F	M	F
F_{curr}	0.32	0.34	0.36	0.24	1.23	0.37
$F_{0.1}$	0.56	0.51	0.43	0.13	1.26	1.42
F_{max}	1.20	0.95	0.71	0.21	*	*
$F_{30\%}$	**	0.25	**	1.39	**	0.86
$F_{20\%}$	**	0.35	**	1.94	**	1.27
$F_{curr}/F_{0.1}$ (%)	56.72	67.43	84.64	186.73	98.00	25.87
F_{curr}/F_{max} (%)	26.68	35.89	51.13	114.55		
$F_{curr}/F_{30\%}$ (%)		134.57		170.65		42.58
$F_{curr}/F_{20\%}$ (%)		98.13		122.28		29.01

*The blanked F_{max} means that the YPR curve at the specific t_c was not providing the peak of the curve.

** Only the female can produce $F_{30\%}$ and $F_{20\%}$ as the ability to produce the offsprings

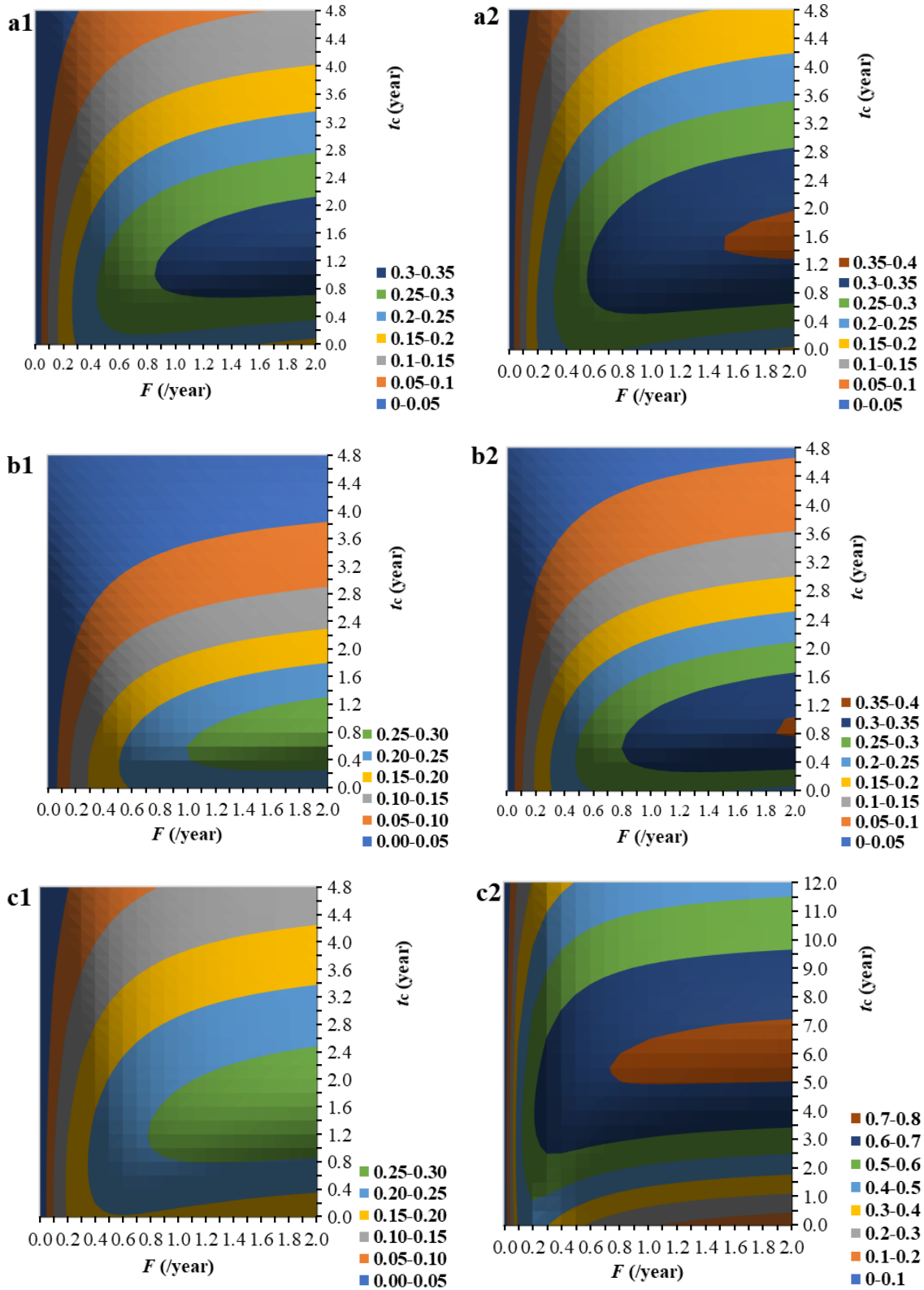


Figure 28. YPR surface plots for N_k at ML/SC (a1: male, a2: female), TH/AM (b1: male, b2: female), and ML/AM (c1: male, c2: female).

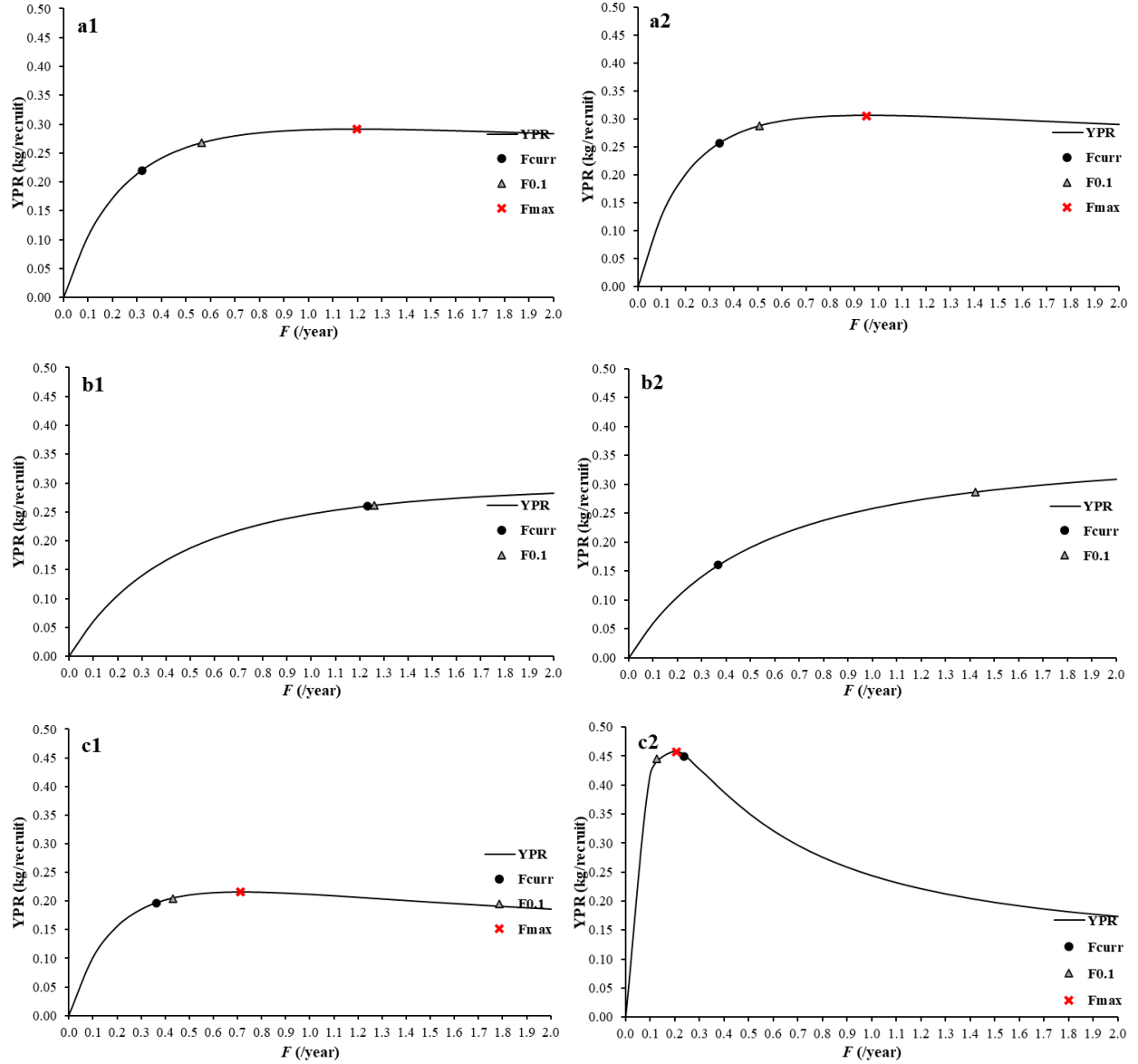


Figure 29. YPR line plots at constant t_c for N_k at ML/SC (a1: male, a2: female), TH/AM (b1: male, b2: female), and ML/AM (c1: male, c2: female).

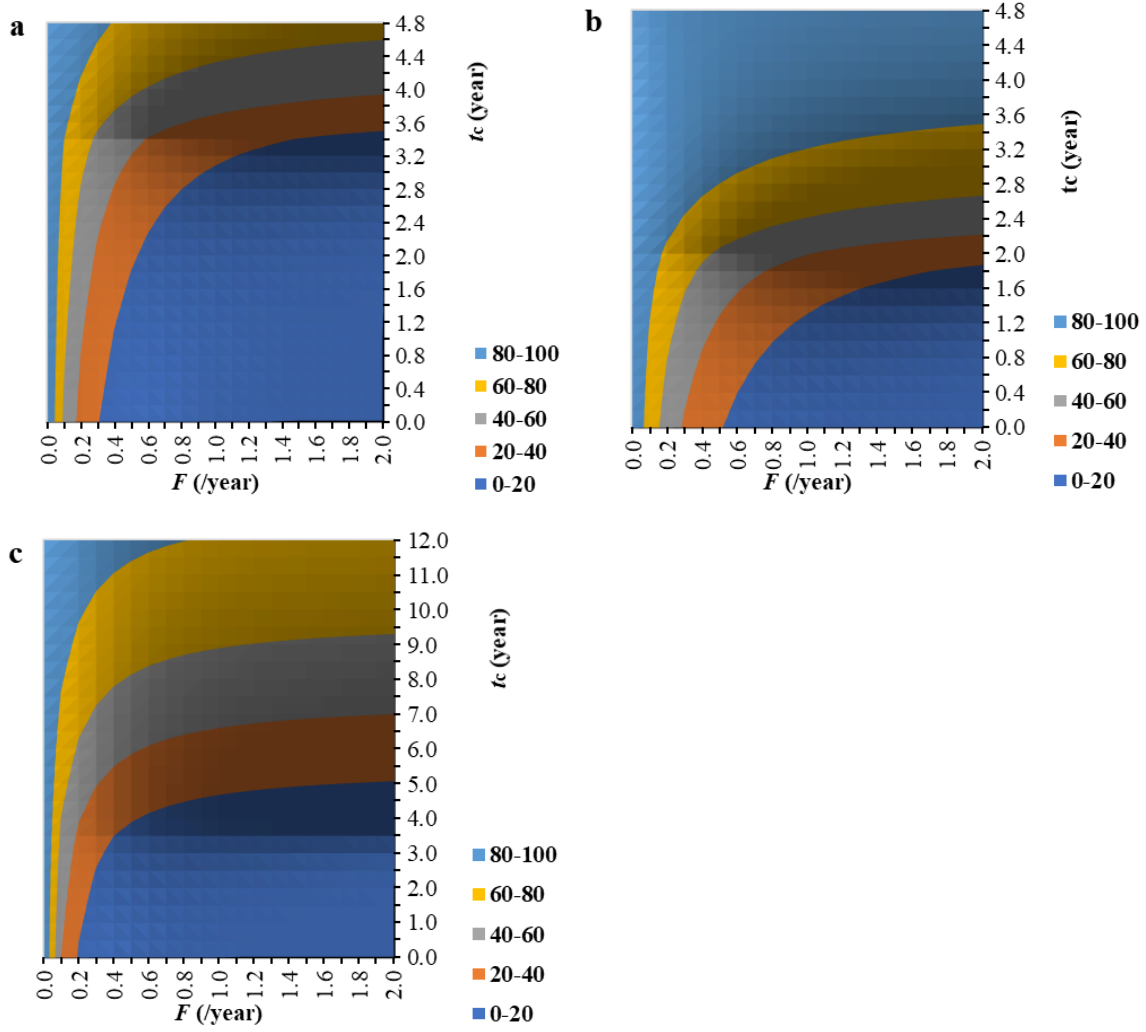


Figure 30. %SPR surface plots for Nk at ML/SC (a), TH/AM (b), and ML/AM (c).

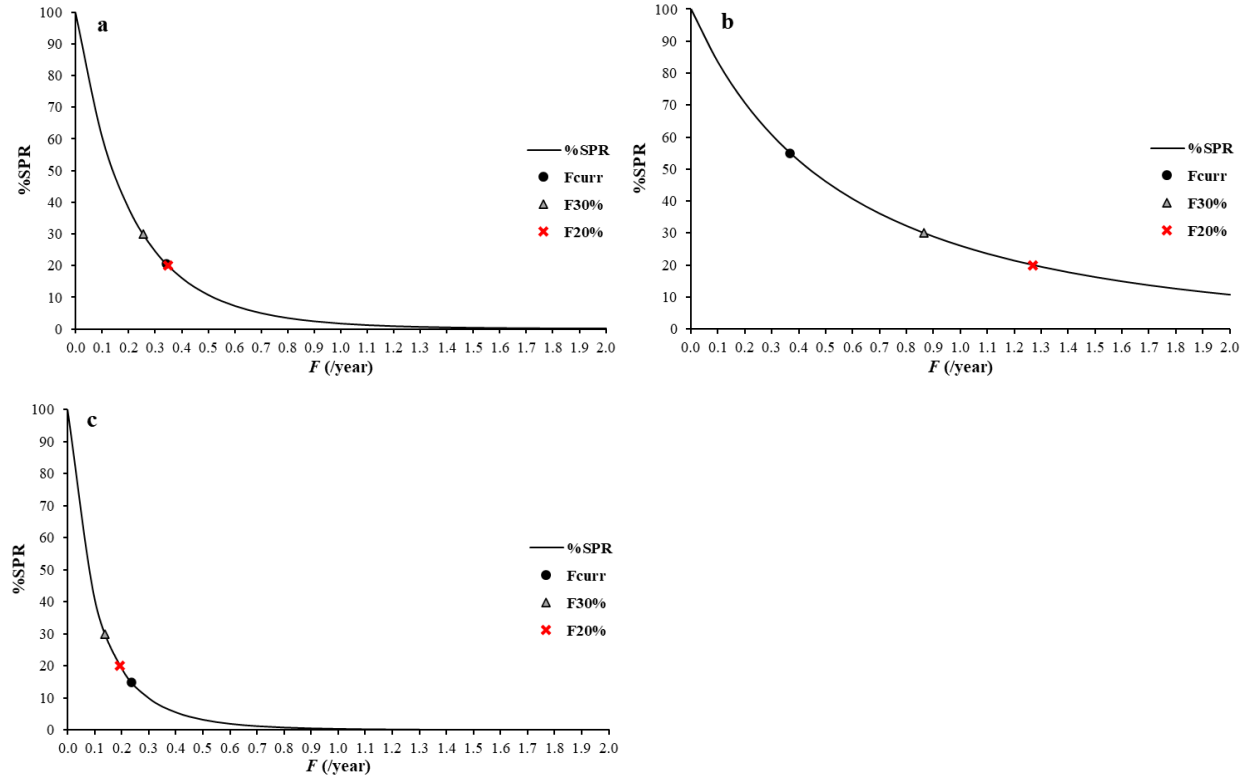


Figure 31. %SPR line plots at constant t_c for Nk at ML/SC (a), TH/AM (b), and ML/AM (c).

4.4.2.3. Dwarf whiplay (*Brevitrygon heterura*)

Data from dwarf whiplays data were collected at 3 landing sites TH/GT, and TH/AM, and ML/AM. The results of YPR are shown in Figures 32 and 33 for YPR's surface plot and line plot at constant t_c . The results of SPR are shown in Figures 34 and 35 for SPR's surface plot and line plot at constant t_c . The F_{curr} and BRPs are shown in Table 19.

Table 19. F_{curr} and BRPs for dwarf whiplay (*Brevitrygon heterura*)

Reference points	<i>Bh</i>					
	TH/GT		TH/AM		ML/AM	
	M	F	M	F	M	F
F_{curr}	0.85	0.50	1.10	0.98	1.52	0.54
$F_{0.1}$	0.87	0.27	0.85	0.79	1.02	0.68
F_{max}	*	0.57	*	*	*	1.90
$F_{30\%}$	**	0.27	**	0.69	**	0.56
$F_{20\%}$	**	0.41	**	1.04	**	0.82
$F_{curr}/F_{0.1}$ (%)	95.86	184.31	129.18	124.39	149.59	79.54
F_{curr}/F_{max} (%)		88.19				28.36
$F_{curr}/F_{30\%}$ (%)		187.70		142.62		96.27
$F_{curr}/F_{20\%}$ (%)		122.51		94.72		65.77

*The blanked F_{max} means that the YPR curve at the specific t_c was not providing the peak of the curve.

** Only the female can produce $F_{30\%}$ and $F_{20\%}$ as the ability to produce the offsprings

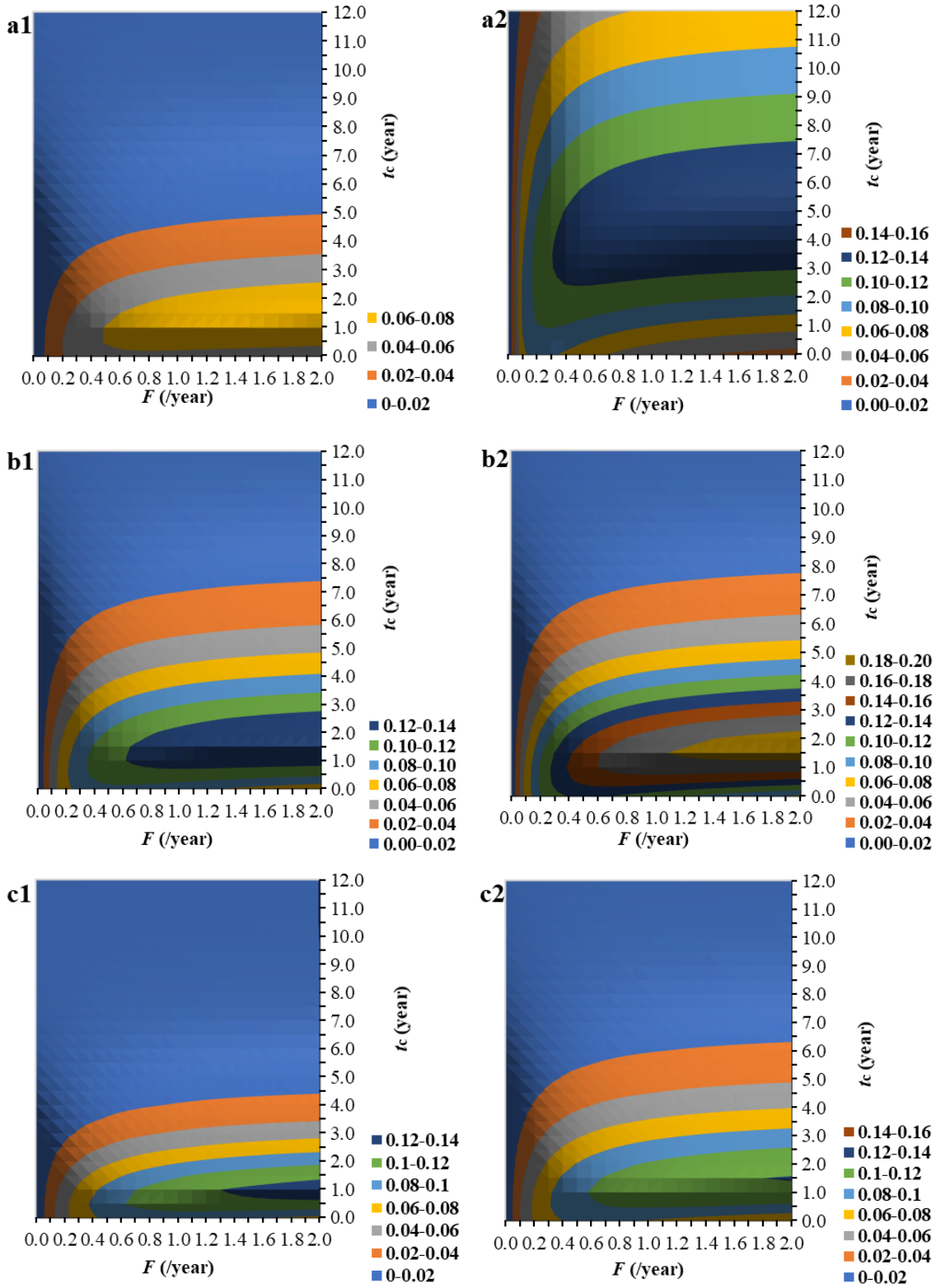


Figure 32. YPR surface plots for *Bh* at TH/GT (a1: male, a2: female), TH/AM (b1: male, b2: female), and ML/AM (c1: male, c2: female).

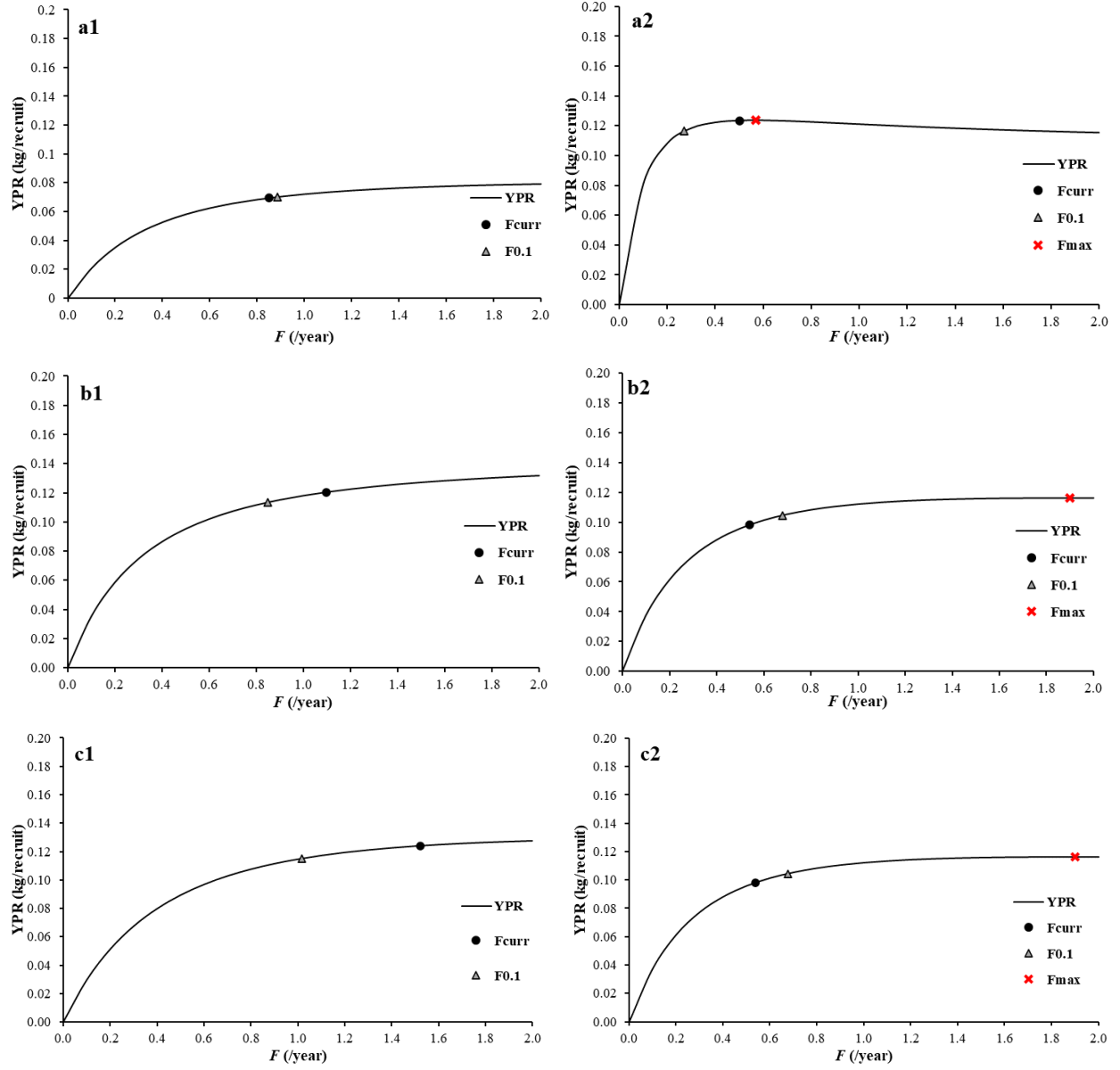


Figure 33. YPR line plots at constant t_c for *Bh* at TH/GT (a1: male, a2: female), TH/AM (b1: male, b2: female), and ML/AM (c1: male, c2: female).

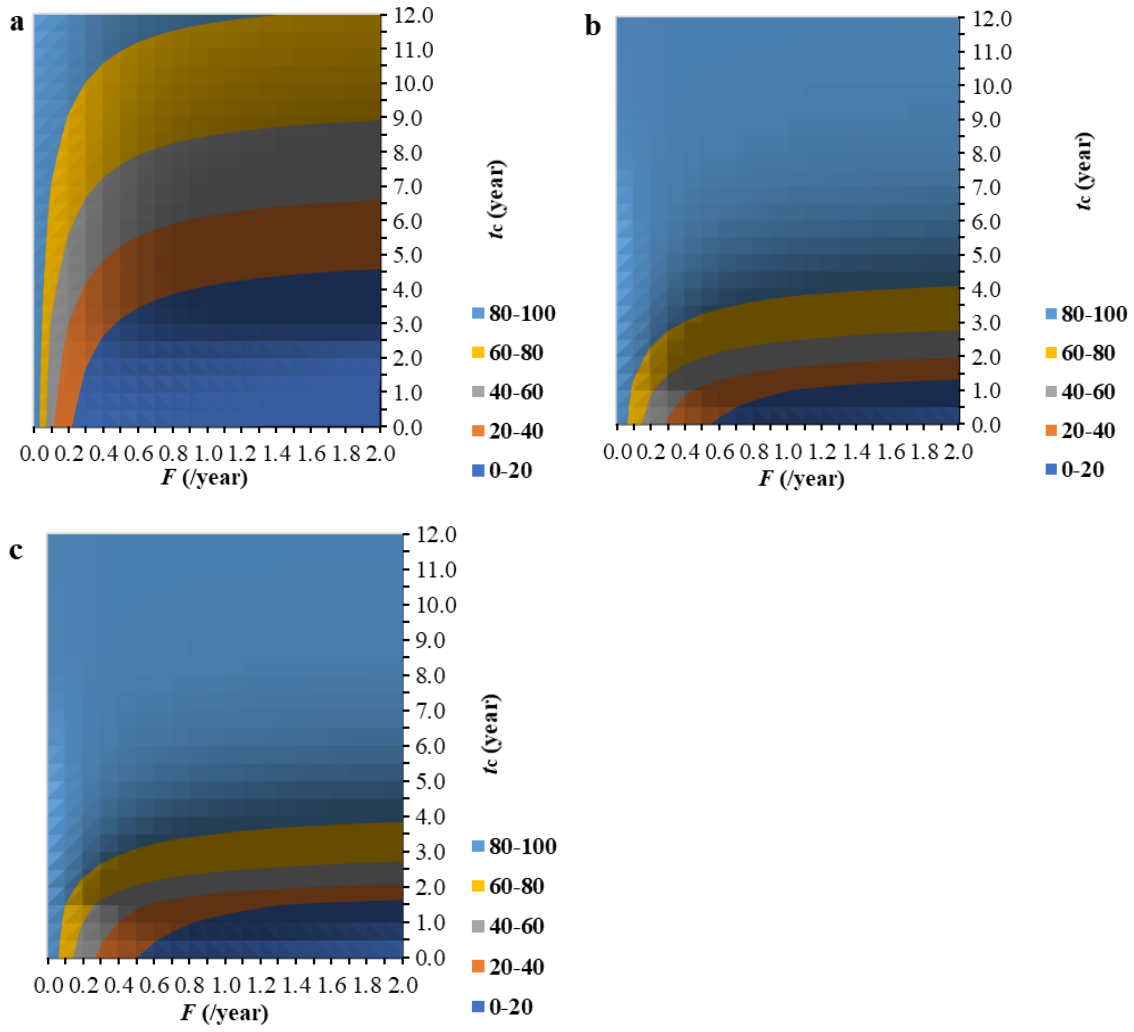


Figure 34. %SPR surface plots for Bh at TH/GT (a), TH/AM (b), and ML/AM (c).

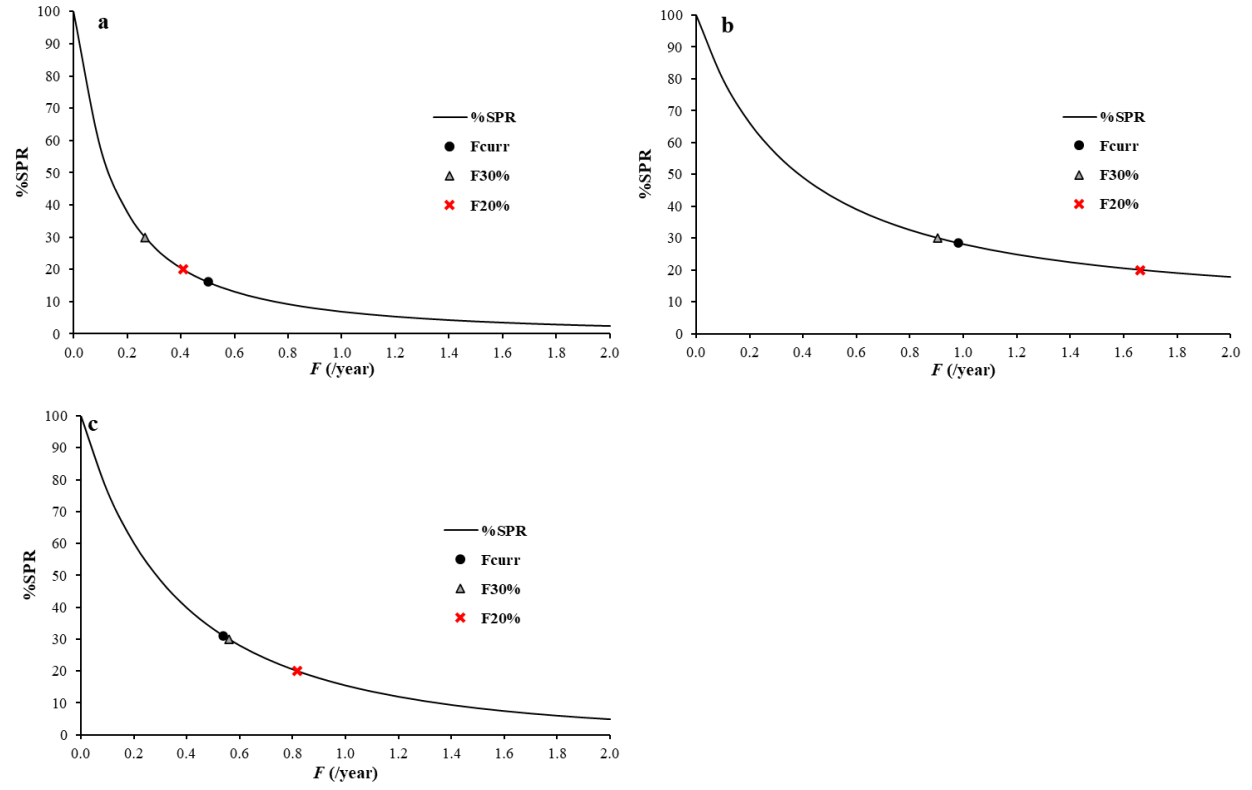


Figure 35. %SPR line plots at constant t_c for *Bh* at TH/GT at TH/GT (a), TH/AM (b), and ML/AM (c).

4.4.2.4. Whitespotted whipray (*Maculabatis gerrardi*)

This large stingray was caught by trawl nets at ML/SC, and ML/AM. The results of YPR are shown in Figures 36 and 37 for YPR's surface plot and line plot at constant t_c . The results of SPR are shown in Figures 38 and 39 for SPR's surface plot and line plot at constant t_c . The F_{curr} and BRPs are shown in Table 20.

Table 20. F_{curr} and BRPs for whitespotted whipray (*Maculabatis gerrardi*)

Reference points	ML/SC All	Mg ML/AM	
		M	F
F_{curr}	0.22	0.36	0.15
$F_{0.1}$	0.11	0.10	0.11
F_{max}	0.12	0.11	0.12
$F_{30\%}$	0.06	**	0.04
$F_{20\%}$	0.09	**	0.05
$F_{\text{curr}}/ F_{0.1}$ (%)	204.55	338.76	137.13
$F_{\text{curr}}/ F_{\text{max}}$ (%)	187.76	315.67	126.90
$F_{\text{curr}}/ F_{30\%}$ (%)	341.11		371.56
$F_{\text{curr}}/ F_{20\%}$ (%)	249.37		270.25

** Only the female can produce $F_{30\%}$ and

$F_{20\%}$ as the ability to produce the offsprings

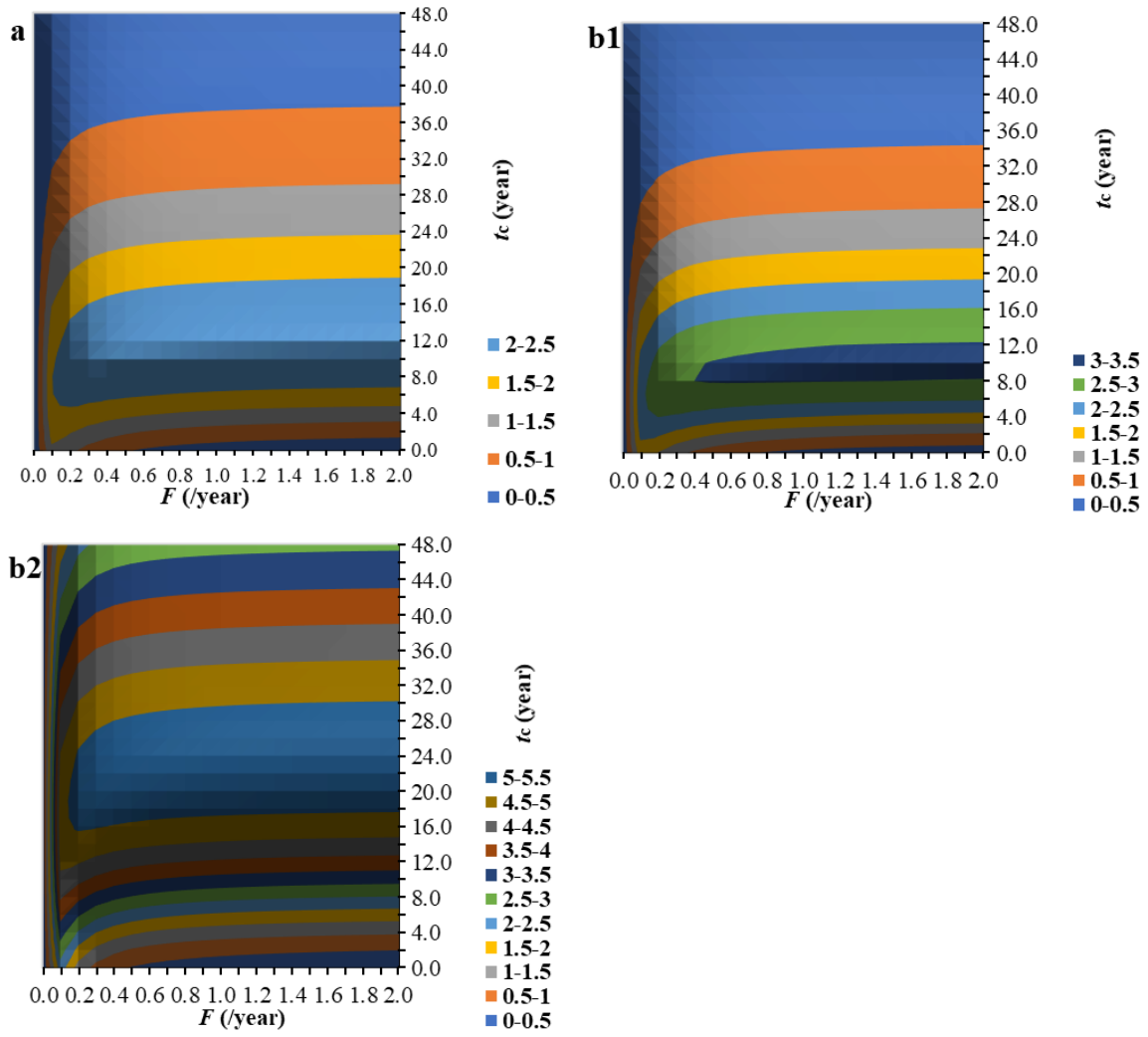


Figure 36. YPR surface plots for Mg at ML/SC (a) and ML/AM (b1: male, b2: female).

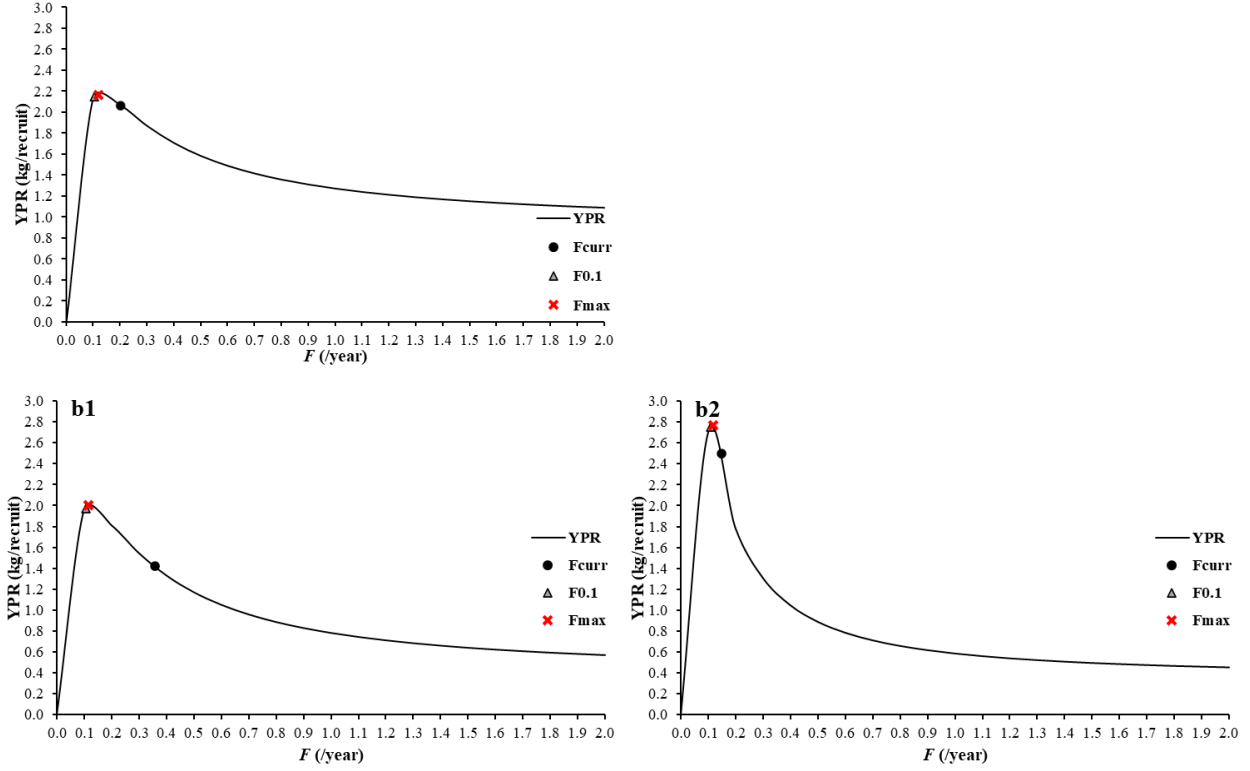


Figure 37. YPR line plots at constant t_c for Mg at ML/SC (a) and ML/AM (b1: male, b2: female).

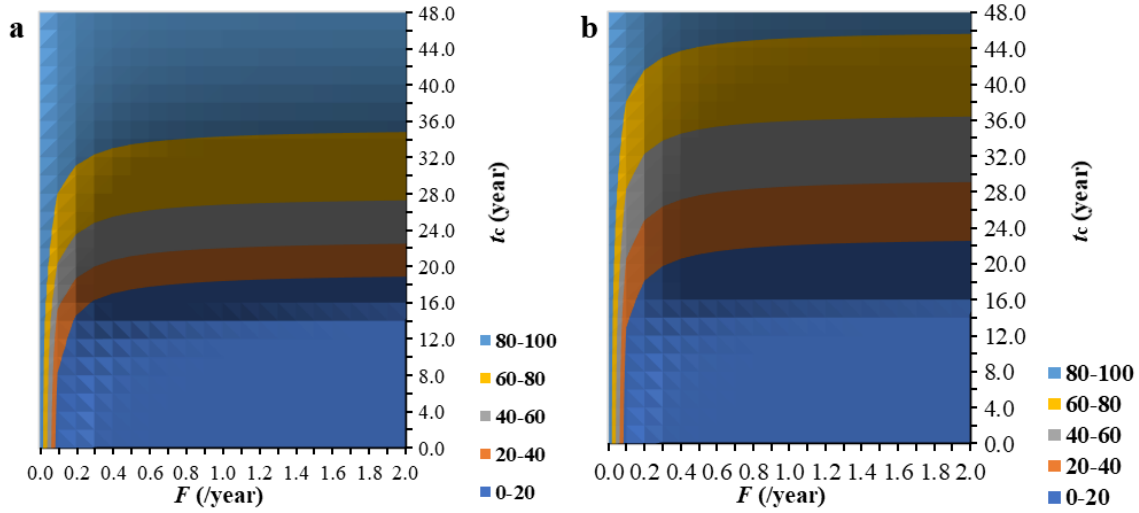


Figure 38. %SPR surface plots for Mg at ML/SC (a) and ML/AM (b).

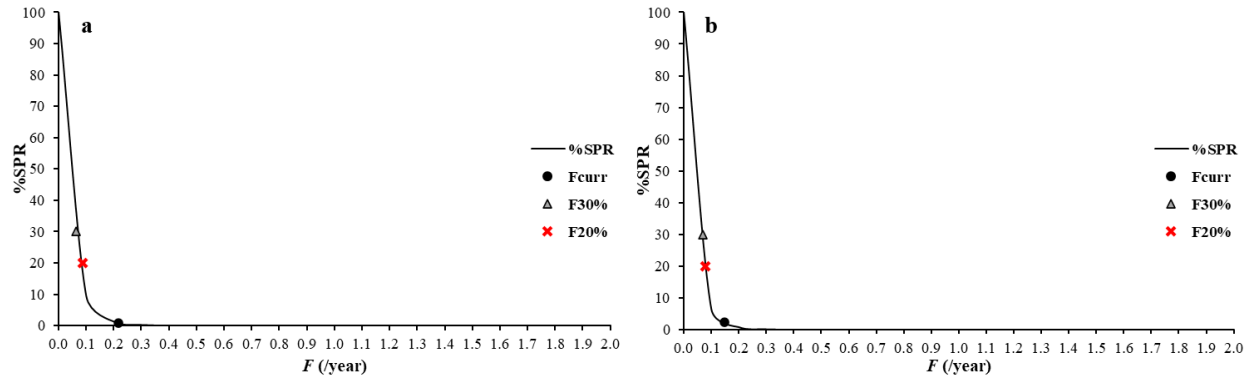


Figure 39. %SPR line plots at constant t_c for Mg at ML/SC (a) and ML/AM (b).

The assessment results are summarized by area as shown in Table 21.

Table 21. Stock status of sharks and rays in Southeast Asia divided into sub-regions. **Green** shows that F_{curr} was smaller than the BRPs, and **red** shows that F_{curr} was equal to or larger than the BRPs

Sub-region	Species	Country	Sex	$F_{curr}/F_{0.1}$	F_{curr}/F_{max}	$F_{curr}/F_{30\%}$	$F_{curr}/F_{20\%}$
Andaman Sea	<i>Chiloscyllium punctatum</i>	Malaysia	All	17.87	7.67	18.73	12.26
	<i>Chiloscyllium hasseltii</i>	Malaysia	All	151.86	72.03	161.24	101.64
	<i>Atelomycterus marmoratus</i>	Malaysia	M	134.43			
			F	28.74		42.14	27.96
	<i>Scoliodon laticaudus</i>	Myanmar	All	37.13	16.61	31.50	19.50
	<i>Telatrygon zugei</i>	Malaysia	All	63.49	0.00	17.08	0.10
	<i>Neotrygon kuhlii</i>	Thailand	M	84.64	51.14		
			F	186.73	114.55	170.65	122.28
		Malaysia	M	98.00			
			F	25.87		42.58	29.01
	<i>Brevitrygon heterura</i>	Thailand	M	149.59			
			F	79.54	28.36	96.27	65.77
		Malaysia	M	129.18			
			F	124.39		142.62	94.72
	<i>Maculabatis gerrardi</i>	Malaysia	M	338.77	315.67		
			F	137.13	126.90	371.56	270.25
Gulf of Thailand	<i>Chiloscyllium punctatum</i>	Cambodia	All	24.99	17.35	44.89	33.02
		Thailand	All	103.48	73.24	128.51	91.37
	<i>Atelomycterus marmoratus</i>	Thailand	M	59.93			
			F	132.79	58.13	207.16	149.09
	<i>Telatrygon zugei</i>	Thailand	M	289.48	179.30		
			F	57.61	32.74	60.80	42.59
	<i>Brevitrygon heterura</i>	Thailand	M	95.86			
			F	184.31	88.19	187.70	122.51
South China Sea	<i>Chiloscyllium punctatum</i>	Malaysia	All	4.68	1.84	5.75	3.97
	<i>Chiloscyllium plagiosum</i>	Malaysia	M	78.58	18.48		
			F	63.98	33.25	95.70	69.60
	<i>Telatrygon zugei</i>	Malaysia	M	63.22			
			F	33.20	14.11	31.35	19.80
	<i>Neotrygon kuhlii</i>	Malaysia	M	56.72	26.68		
			F	67.43	35.89	134.57	98.13
	<i>Maculabatis gerrardi</i>	Malaysia	All	204.55	187.76	341.11	249.37

In the Andaman Sea, the stock status ranged wider than in the Gulf of Thailand; the smallest and largest $F_{curr}/BRPs$ in the Andaman Sea was 3% for F_{curr}/F_{max} in *Cp* and 429% for $F_{curr}/F_{30\%}$ for *Mg*, the range was smaller in the Gulf of Thailand which the smallest was $F_{curr}/F_{0.1}$ from *Am*

(24%) and largest was $F_{curr}/F_{0.1}$ from Tz (108%). However, the percentage of the healthy stock was the same between these two areas (8 out of 16 for AM and 4 out of 8 for GT).

In the South China Sea, the $F_{curr}/BRPs$ ratio was smaller than in those areas (range between 4-314%). With the higher amount of healthy stock (6 out of 8 stocks), South China Sea can potentially be indicated as the healthy area. However, the result from the South China Sea was derived from only Malaysia, therefore, this cannot be the true representative for the sub-region.

4.5. Sensitivity test

The results of the sensitivity test for F_{curr} by the difference of L_{∞} , K , and t_{max} were provided in Figure 40.

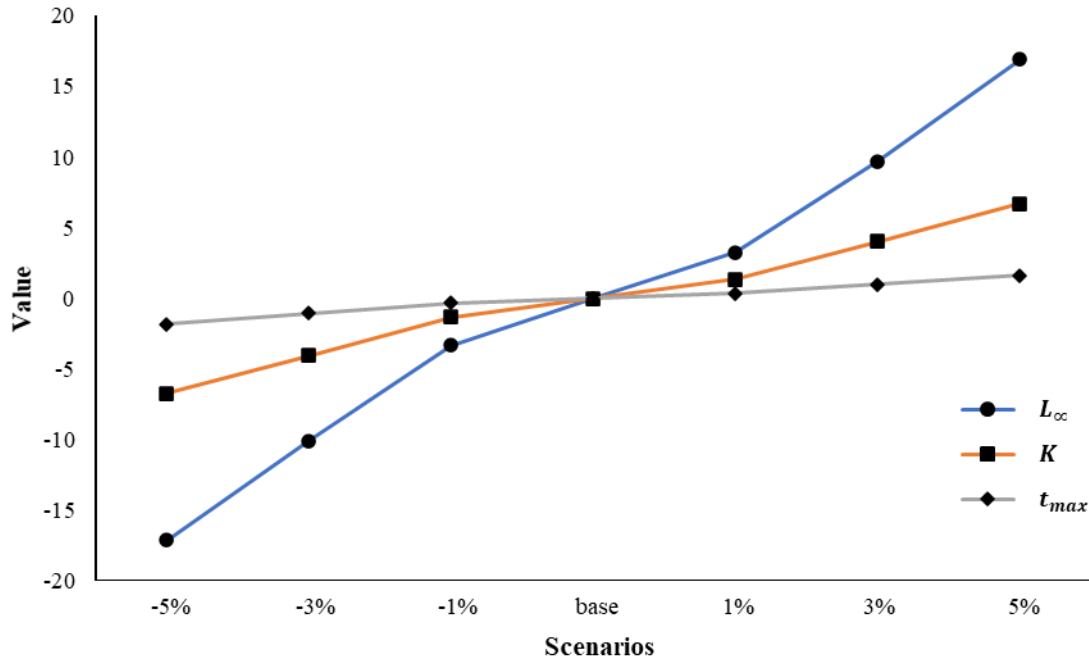


Figure 40. Sensitivity test for F_{curr} varied by three parameters, L_{∞} and K , and t_{max} .

The sensitivity analysis shows that F_{curr} is directly affected by these three parameters. The parameter L_{∞} affects at the highest rate. If L_{∞} was overestimated by 5%, F_{curr} was overestimated by 18%. On the other hand, t_{max} provides the smallest variation (the error was ranged between

1-8% for the 5% variation from the base case for each parameter). The results as shown in Table 22

Table 22. Percentage of variation in the sensitivity test of F_{curr} for each scenario of three observed parameters

Case	L_{∞}			K			t_{max}		
	max	med	min	max	med	min	max	med	min
-5%	-8.94	-17.10	-24.89	-6.37	-6.72	-12.77	-1.45	-1.80	-8.69
-3%	-5.35	-10.08	-14.53	-3.82	-4.03	-7.87	-0.85	-1.06	-4.81
-1%	-0.15	-3.31	-4.75	-1.27	-1.34	-2.62	-0.28	-0.34	-1.57
Base	0	0	0	0	0	0	0	0	0
+1%	+4.68	+3.27	+1.77	+2.62	+1.34	+1.27	+2.49	+0.34	+0.27
+3%	+13.87	+9.72	+5.30	+7.87	+4.03	+3.82	+5.59	+1.00	+0.80
+5%	+44.21	+16.93	+8.81	+13.12	+6.72	+6.37	+7.60	+1.64	+1.31

4.6. Shark and ray stock status by sub-regions

In this study, 3 sub-regions were involved namely the Andaman Sea, Gulf of Thailand, and South China Sea (Figure 9). The use of the reference points was provided in this study was implemented by comparing F_{curr} with 2 kinds of BRPs as F_{target} , and F_{limit} . When the F_{target} is referred to as a target BRP, The F_{limit} is referred to as a limit BRP, which is the upper limit without considering the uncertainties such as F_{max} for YPR and $F_{20\%}$ for SPR. The stock status for each area shown in Table 23.

Table 23. Stock status of elasmobranchs where L (low exploitation): $F_{\text{curr}} < F_{\text{target}}$ and F_{limit} , M (medium exploitation): $F_{\text{target}} < F_{\text{curr}} < F_{\text{limit}}$, and H (high exploitation): $F_{\text{curr}} > F_{\text{target}}$ and F_{limit} .

YPR/SPR		SPR		
		L	M	H
YPR	L	- <i>Cp</i> CB/GT	- <i>Nk</i> TH/AM M	- <i>Nk</i> ML/SC F
		- <i>Cp</i> ML/SC		- <i>Nk</i> ML/AM M
		- <i>Cp</i> ML/AM		
		- <i>Cl</i> ML/SC M		
		- <i>Cl</i> ML/SC F		
		- <i>Am</i> TH/GT M		
		- <i>Am</i> ML/AM F		
		- <i>Sl</i> MY/AM		
		- <i>Tz</i> ML/AM M		
		- <i>Tz</i> ML/AM F		
		- <i>Tz</i> TH/GT M		
		- <i>Tz</i> TH/GT F		
		- <i>Tz</i> ML/AM		
		- <i>Nk</i> ML/SC M		
		- <i>Nk</i> ML/AM F		
	M		- <i>Cp</i> TH/GT	- <i>Ch</i> ML/AM
			- <i>Am</i> TH/GT F	
			- <i>Bh</i> TH/AM F	
	H	- <i>Bh</i> TH/GT M		- <i>Am</i> ML/AM M
		- <i>Bh</i> TH/AM M		- <i>Nk</i> TH/AM F
		- <i>Bh</i> ML/AM M		- <i>Bh</i> TH/GT F
				- <i>Bh</i> ML/AM F
				- <i>Mg</i> ML/SC
				- <i>Mg</i> ML/AM M
				- <i>Mg</i> ML/AM F

The results show that of the 33 selected stocks of elasmobranchs in this study, the utilization levels of both YPR and SPR were high for 7 stocks ($F_{\text{curr}} > F_{\text{target}}$ and F_{limit}), medium for 3 stocks ($F_{\text{target}} < F_{\text{curr}} < F_{\text{limit}}$), and low for 15 stocks ($F_{\text{curr}} > F_{\text{target}}$ and F_{limit}), while the other 8 stocks having a different result between YPR and SPR.

5. DISCUSSION

5.1. Data selection, length-weight relationship, and growth parameter estimation

5.1.1. Data selection

The secondary length-weight and length-frequency data obtained from the SEAFDEC “shark, ray and skate data collection project” during 2015-2016 were utilized in this study. The data were collected from various participating countries in Southeast Asia. The data quality from the program varied widely despite using standard procedures in all the countries. The procedures were taught to local enumerators by experts, and the local enumerators collected the data. The indirect instruction of the standard procedure cannot be avoided because of the local difficulties such as the travelling distance, infrastructures, and basic knowledge of the local enumerators (Wanchana et al., 2020), but it may affect the data quality.

Using the criteria mentioned in the materials and methods, reliable data were selected from the raw data, which included 8 species of sharks, and 4 species of rays. The other non-selected species had some issues such as low R^2 . Even after fixing the outliers and other necessary errors, data with R^2 smaller than 0.60 were omitted. In addition, from the observation of the length-frequency data, obviously erroneous length-frequency data were omitted, such as the data with many no-data months or obviously biased data from possibly already size selected samples. Examples are shown in Figure 6.

In future data collection projects similar to this, the local enumerator training program should be conducted carefully with close communication between the enumerators and the experts. For international projects, the project should be divided and conducted country by country. The experts should have opportunities to join data collection activities in the field.

5.1.2. Length-weight relationship

The length-weight relationship study revealed the isometric growth pattern of elasmobranch species. A regression factor b equal to 3 results in an ideal isometric growth pattern. In this study, a clear isometric growth pattern was observed from *Atelomyxerus marmoratus* (Am) and *Brevitrygon heterura* (Bh) from TH/SC, and *Maculabatus gerrardi* (Mg) and *Telatrygon zugei* (Tz) from the ML/SC with a range of b that was included 3, as shown in Table 7. In all species, b fell within the isometric range, 2.5-3.5 (Froese, 2006), except for *Scoliodon laticaudus* (Sl), which b was estimated as 2.18 with 95% confidential intervals $2.08 \leq b \leq$

2.28. Former studies on the length-weight relationship showed that the b value of Sl fell into Froese's isometric range. For example, Devadoss (1989) estimated the b values for males and females were 2.89 and 2.96, respectively. A recent study showed similar values of b for Sl : 2.89, 2.93, and 2.92 for males, females, and pooled sex, respectively (Gladston et al., 2018). These b values are in the isometric range according to Froese's criteria.

The difference in the b value in this study could have been due to measurement errors during data collection. The equation of the length-weight relationship was used to estimate the average maximum weight (W_{∞}), which could cause changes in the yield at each t_c and F . However, this change will affect only the amount of the yield and not affect the estimation of BRPs in YPR and SPR. Therefore, the out of isometric range of b was negligible.

5.1.3. Growth parameter estimation

The growth parameters used in this study were selected from four models: K Scan; RSA; ELEFAN combined with simulate annealing, ELEFAN_SA, and ELEFAN combined with genetic algorithm, ELEFAN_GA, based on the highest quantitative score known as R_n (Gayanilo et al., 2005; Mildenerberger et al., 2017; Scrucca, 2013; Taylor and Mildenerberger, 2017; Xiang et al., 2013). R_n was calculated based on the ratio between the number of peaks of length-frequency data and the number of peaks that were fitted by the growth curve. The higher R_n is, the more reliable the results are (Mildenerberger et al., 2017). The results were cross-checked by the comparing growth performance index, Φ' , with the literature (see Appendix B). It can be used to compare the growth parameters within the species or between species with similar shapes (Munro and Pauly, 1983). Φ' was used together with R_n . All results and R_n are shown in Appendix B.

The growth parameters in this study were selected from the highest R_n of the 4 functions. However, the estimated parameters with maximum R_n were also affected by the quality of the collected length-frequency data. For example, the estimated parameters with maximum R_n of male *Neotrygon kuhlii* (Nk) from ML/SC shown unreliable growth parameters because K was obviously too high compared with the previous literature (Pierce and Bennett, 2009; Jacobsen and Bennett, 2010). In this case, the estimated parameters with the second score of R_n were selected by comparing the Φ' and fitting the growth curve (see Appendices B and C). The smaller L_{∞} with larger K of the Nk in this area compared to the literature was likely to be the results of the difference in size or age composition in each fishing ground.

The sensitivity test of F_{curr} by changes of $\pm 5\%$ in the variables L_{∞} , K , and t_{max} (Table 22) showed that the growth parameter L_{∞} gives the highest variation in F_{curr} ($\pm 18\%$) while the change of K for 5% gave a lower variation for F_{curr} ($\pm 7\%$). The variation of F_{curr} can affect the results of YPR and SPR, especially, for species with a F_{curr} that is very close to the BRPs. In this study, the growth-parameter were estimated using a widely used method for tropical length-based stock assessment such as the R_n score observation combined with the fitting growth curve with the comparison of Φ' with the literature as cross-check. The results were expected to be the most reliable and widely acceptable in the limitation of data quality for the selected stock in this study.

5.2. Mortality estimation and gear selectivity

This study used the length-converted catch curve to estimate mortality. This model estimates the negative slope of the size-frequency of the sample or the catch curve, as the total mortality (Pauly 1983; 1984).

Natural mortality, M , is an important parameter for a wide range of stock assessment models. Various equations have been developed based on life-history parameters (Pauly, 1980; Then et al., 2015). Among various equations, the Tanaka model (Equation 9, Tanaka, 1960) was selected for this study because of its wide applications, especially in Japanese official stock assessments. This method uses maximum age, t_{max} , which was expected to reduce the effect of the growth parameters involved in the M estimation.

The range of elasmobranch longevity is wide. Fast-growing species such as the round stingray live 8-10 years (Mejía-Falla et al., 2014). While the slow-growing species can live 40-50 years in hammerhead (*Sphyrna* spp.) and whale sharks (*Rhincodon typus*), or over 100 years in the Greenland shark (*Somniosus microcephalus*) (Chen et al., 2007; Dudgeon et al., 2016; Kotas et al., 2011; Liu et al., 2015; Nielsen et al., 2016; Ong et al., 2020). However, studies about the t_{max} of elasmobranchs in SE are limited. To estimate the appropriate t_{max} in this study, various traditional models were applied (Froese and Binohlan, 2000; Hoenig, 1983; Pauly, 1983; Taylor, 1958). All the estimated results were finalized by calculating the median of t_{max} . The sensitivity showed that t_{max} provides the lowest effect to the YPR and SPR estimation through M estimation ($\pm 1.80\%$).

5.3. Stock status from YPR and SPR

Three species, 1 shark and 2 rays, were reported as unhealthy, namely *Chiloscyllium hasseltii* (*Ch*), from ML/AM, and female *Nk* TH/AM and *Mg* from ML/SC and ML/AM. These stocks have an unhealthy stock status because of the small t_c and large F . For *Ch* and *Nk*, the small t_c and large F caused the sharp negative slope of the catch curve and produced a larger Z compared to the others (Figure 10 and 11, respectively).

For *Mg*, the cause of unhealthy stock status has been combined with a slow growth rate, K , which makes the stock more vulnerable against the small t_c and large F . The major issue that affects the YPR and SPR of *Mg* was the size composition of the catch where the majority of size at first captured, L_c . For ML/SC, and ML/AM stock, L_c ranged between 51-68% of L_m , and 23-48% of L_∞ which were too small at the current fishing mortality. The small size of the catch causing the small amount of YPR with the F_{max} was closer to 0 (approximately 10-50% of the F_{max} for *Nk* caught from the same area, please see Table 18 for *Nk* and 20 and Figure 36 and 37 for *Mg*). For the SPR, the L_c was very important as the comparative parameter to the L_m in the form of t_c and t_m . The small value of t_c with the large t_m resulted in the small value of $F_{30\%}$ and $F_{20\%}$. At the current F_{curr} , the increase of t_c from 0.80 to 16 years can achieve the $F_{20\%}$ and the increase of t_c to 18 years can achieve $F_{30\%}$. Another option was to reduce F_{curr} . To reduce F_{curr} by half, the $F_{20\%}$ can be achieved at this level (please see Figure 44a). However, the rapid reduction of t_c and F were difficult in real situations. Area management can be combined for this species.

The result of *Ch* was slightly different from the other large, slow-growing species (Table 12 and Figure 13c, 14c, 15c, and 16c). F_{curr} fell between $F_{0.1}$ and F_{max} for YPR (52% larger than $F_{0.1}$ and 28% smaller than F_{max}) and was slightly larger than $F_{20\%}$ for 2%. The stock status of *C. hasseltii* was recognized as, so-called, medium-high exploitation. In the term of YPR, this stock was acceptable as the status did not exceed the limit BRP of YPR yet. In contrast, the SPR suggested that the fishing mortality for this species should be reduced by at least 2% to be lower than the limit BRP of SPR. Therefore, under the appropriate management, the population of *C. hasseltii* can recover.

5.4. Suggested management measures

The multi-species fishery situation in the region has made species-specific management approaches difficult (Harlyan et al., 2019). Elasmobranchs are recognized as minor species from the regional point of view, so data collection of this group difficult (SEAFDEC, 2006). YPR and SPR are useful for addressing the status of exploitation. YPR can monitor growth overfishing when the size of fish is reduced by fishing pressure, while SPR can detect recruitment overfishing. These models can be useful for minor species with limited data, but the stock status needs to be clarified.

In this study, the selected species were caught by bottom trawls, which are low-selectivity fishing gear. The low selectivity combined with the multispecies-situations in the region can violate both YPR and SPR of the bycatch at the unappropriated t_c and F . The possible management measures are to adjust either t_c or F or both at the same time.

For t_c management, escaping devices attached to the trawl net called ‘Trawl Efficient Device’ or TED can improve gear selectivity. The increased t_c can consequently increase the YPR and %SPR, as smaller fish have more opportunity to escape from fishing gear. For example, the stock of *Maculabatis gerrardi* in the SC currently has a F_{curr} over the target and limit BRPs (Table 19). If TED was applied and t_c assumed to be increased from 0.8 years to 10 years, the F_{max} of YPR could increase by 73%. The increase of F_{max} will make it 85% higher than F_{curr} indicate that this stock of *M. gerrardi* can be avoided from the highly exploited yield. For the SPR, the limit reference point, $F_{20\%}$, can be 30% larger with only 48% smaller than F_{curr} .

A case study in the Mediterranean Sea suggested that a TED with an appropriate grid size can be effective for the shark escapement in the bottom trawl lobster fishery (Brčić et al., 2015). However, the size of the TED can affect the result of selectivity by reducing the non-target species while not significantly changing the catch amount of target species (Watson et al., 1986). Moreover, the large biodiversity within the region causes the multi-species fishery situation (Brčić et al., 2015; Harlyan et al., 2019; J.W.Watson et al., 1986; Stein et al., 2018). Applying TED to the region is possible with further study required such as the appropriate size and design, catch composition, including fishing ground identification.

In terms of area conservation, the establishment of Marine Protected Areas (MPAs) can conserve the spawning biomass and increase the future recruitment in elasmobranchs (Shibata et al., 2017). MPAs may not have a direct effect on the YPR and SPR, however, they can be used as juvenile protection zones against fishing pressure. An MPA on the nursery ground can protect

juveniles. It can protect the biomass of recruitment from anthropogenic perturbation such as small-scale fisheries targeting other fish before they are recruited to the fishing ground.

YPR will not affect by the establishment of MPAs because YPR does not account for before-recruitment survival. Similarly, the establishment of MPA will not contribute a direct effect to the SPR. However, MPAs can increase recruitment per spawning biomass (RPS). Since the survival in the before-recruit period increases, fewer spawners are required to sustain the stock. Theoretically, when $RPS \times SPR = 1$, the stock will sustainable. Thus, MPAs can change the BRPs of SPR. For example, assume 20%SPR can sustain the stock without an MPA. If MPA increases the survival rate until recruitment twice, 10%SPR can sustain the stock. Since $F_{10\%SPR}$ is larger than $F_{20\%SPR}$, overfishing may be avoided if F_{curr} is between $F_{10\%SPR}$ and $F_{20\%SPR}$.

As the higher the recruitment migrates to the fishing ground with the improvement of t_c or F , the larger the SPR can be with the larger capacity to accept the larger F_{curr} . To conduct the MPA approach, the appropriate nursery ground should be identified properly. For some elasmobranchs such as species in the division Batomorphi (ray, guitarfish, sawfish, skate, etc.) the nursing ground is a key factor for the population increasing (Carlisle and, Starr, 2009; Martins et al., 2018). By area identification, specific MPA and other necessary approaches should be conducted (Heupel et al., 2019).

Dwyer et al. (2020) suggested that the percentage of success of MPA conducted also depends on the fishing pressure of each area. The Pacific Ocean which appeared to get higher fishing pressure requires 1.4-1.6 times larger MPAs for elasmobranch species than those required in the Atlantic Ocean or the Mediterranean Sea. Therefore, MPAs should be carefully applied region by region.

The fishing zonation may have a similar effect to MPA. It has been widely applied in several SEA countries. For example, in Malaysia, the fishing ground has been divided into several zones by distance from the shoreline. The fishing vessel is also divided by the gross tonnage and the permission of the fishing operation is decided by the zone as shown in Figure 41 (Department of Fisheries Malaysia, 2021; 2016; Muawanah et al., 2018; Ramli, 2015).

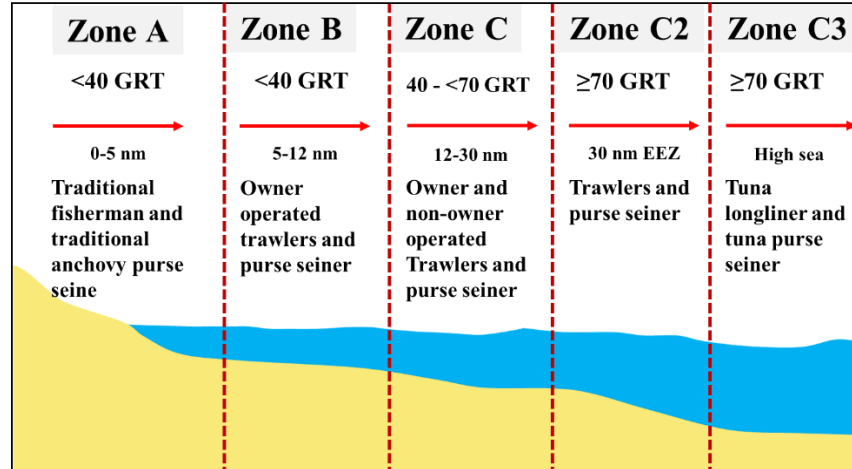


Figure 41. Malaysian's fishing zonation from the shoreline (Zone A) to high sea (Zone C3) (applied from DOF, 2021)

In this study, the effectiveness of zonation can be observed from the results of 2 stocks of *Neotrygon kuhlii* from the connected area between TH and ML in the AM. Results show that under a similar fishing capacity, the observed t_c of Thai stock was smaller than Malaysian stock for both males and females (Table 10 and Figure 13). For YPR and SPR, the F_{curr} of the Thai stock exceeded both target and limit BRPs. Meanwhile, the F_{curr} of the Malaysian stock was still under the target reference point, $F_{0.1}$, while the limit reference point, F_{max} , cannot be observed as the peak of YPR was not presented (Table 17). This result was affected by the national regulation which prohibits the high gross tonnage fishing vessel from operating near the shoreline where home for juvenile elasmobranchs and teleost fishes (Ramli, 2015). The result was the reduction of fishing pressure on these stocks.

Speed et al. (2016) suggested that juvenile elasmobranchs are more likely to inhabit the shoreline. Therefore, zoning can be used as a sanctuary-like area for juvenile stock. The zoning can also control the t_c of the fish because the accessibility of fishing vessels is limited. To confirm this approach, a case study from the Mediterranean Sea was given the effectiveness of the zonation in increasing the t_c of elasmobranch bycatch (Giménez et al., 2020). In Malaysia, such a kind of zoning regulation has been implemented since the 1980s. The coastal area (Zone A, 0-5 nm) was announced as an MPA (Department of Fisheries Malaysia, 2014; Ramli, 2015). The merit of the fishing zonation was the reduced effect of fishing pressure on the entire stock, which contributed

to the direct effect to YPR and SPR by increasing t_c as the larger elasmobranchs will be distributed in the deeper water.

6. GENERAL CONCLUSIONS

The scientific-based fisheries management measures for elasmobranchs in Southeast Asia have not been conducted widely. In this study, 32 stocks of elasmobranchs were selected, and stock assessments were conducted. As a result, 5 stocks (16%) were found to be highly exploited stock with higher F_{curr} higher than all of the BRPs, while 12 stocks (37%) were acceptably exploited with F_{curr} lower than the limit BRPs, and 15 stocks (47%) were identified as the low exploited stock with F_{curr} lower than all BRPs.

According to the results of this study, species with a slow to medium growth rate tend to be caught with a relatively high exploitation rate compared to other species with a faster growth rate. Thus, appropriate management measures should be identified and applied to species such as *Maculabatis gerrardi*. The implementation of YPR and SPR can be useful for data-limited species because the required input data for these models are small. However, the improvement of data collection should be considered. A further stock assessment should be conducted based on the YPR and SPR results for more effective management of such species.

From the results of the analysis, three fisheries management measures were suggested. The first option is the improvement of fishing gear. For example, Trawl efficiency Devices, TED, can be applied in the region after further investigations. The second choice is the implementation of MPAs for increasing the survival of juveniles. The third option is the adjustment of fishing zonation. Zonation can prevent high fishing pressure from the shoreline which elasmobranchs use as a nursing area for juveniles and allowing catch of older and larger fish can increase the t_c and ensure the recruitment of sharks.

In general, elasmobranchs have slower growth rates and longer lifespans than teleost. The key to sustainable management for elasmobranchs can be the input control as F approach and t_c approach. By reducing the fishing effort, the F_{curr} will decline to a level that the stock can accept, even if the t_c is low. On the other hand, the optimum t_c will theoretically allow elasmobranchs to reproduce before being caught. In such a case, the stock can be sustained even when F is large.

In real situations, if it is difficult to lead the fishery sustainable with changing only F or t_c independently, the combination of these two approaches may make sustainable fisheries with acceptable modification of the current fisheries. The YPR and SPR can monitor the level of the F_{curr} by compared with the BRPs which were produced from the model at each different t_c and vice

versa. The combination of these two approaches based on YPR and SPR can make the scientific-based stock management for data-limited species such as elasmobranchs and other species.

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APPENDICES

Appendix A: Length-weight relationship of the selected elasmobranchs

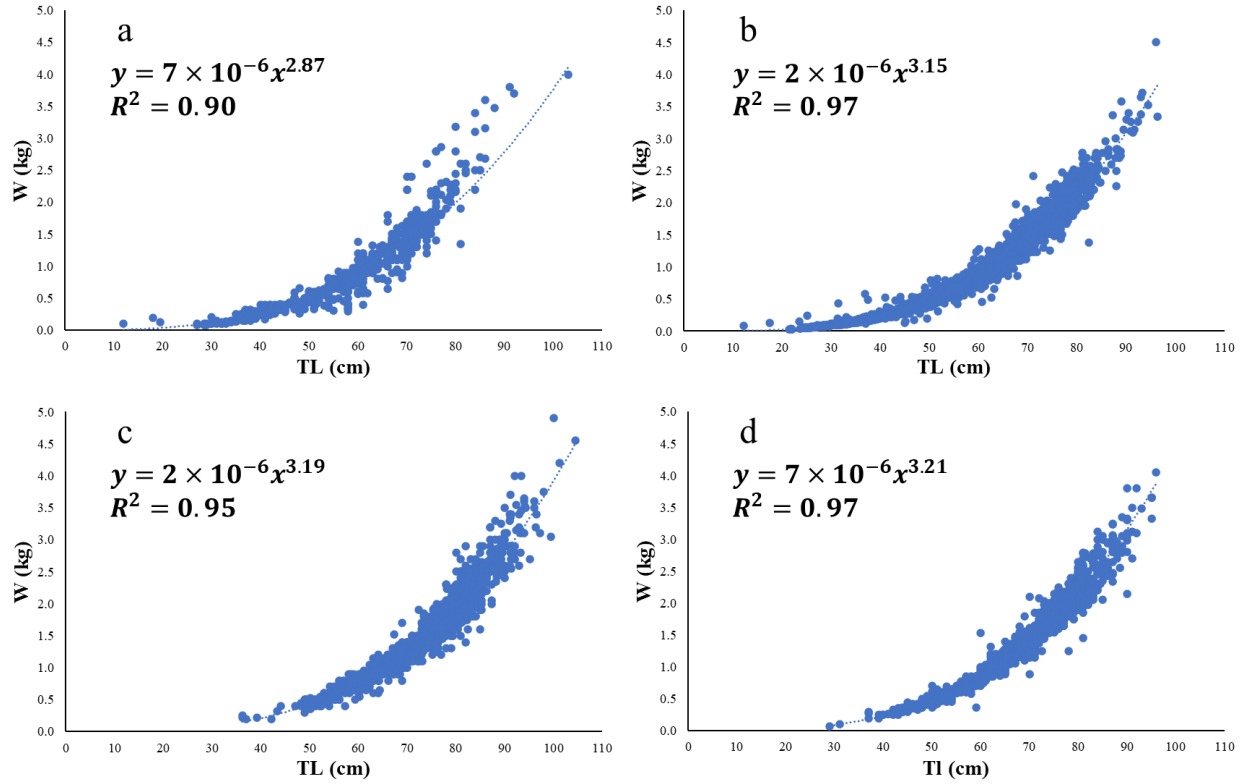


Figure A1. Length-weight relationship of *Cp* from CM/GT (a1), TH/GT (a2), ML/SC (a3), and ML/AM (a4).

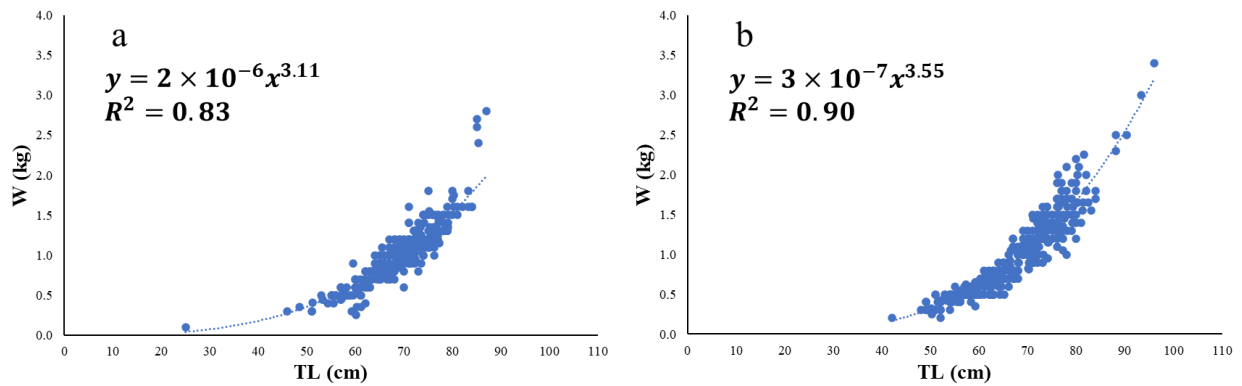


Figure A2. Length-weight relationship of *Cl* from ML/SC for male (a) and female (b).

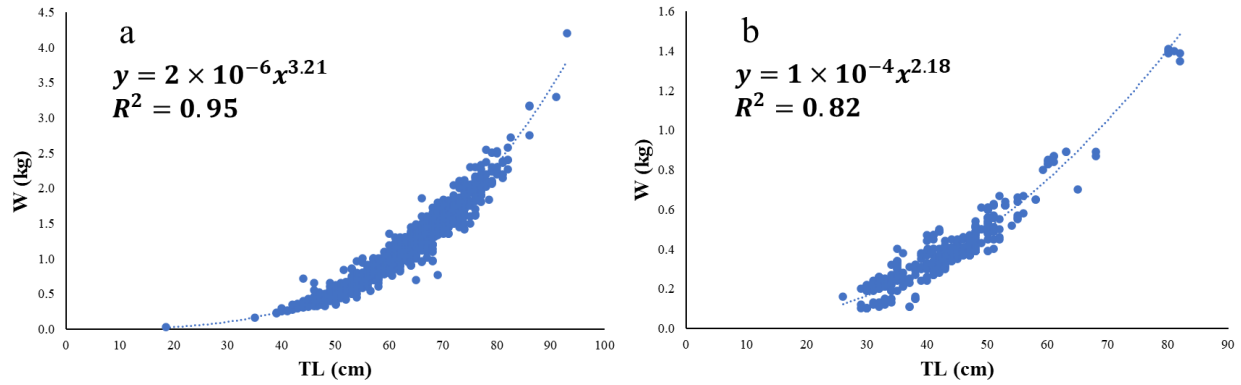


Figure A3. Length-weight relationship of *Ch* from ML/AM (a) and *Sl* from MY/AM (b).

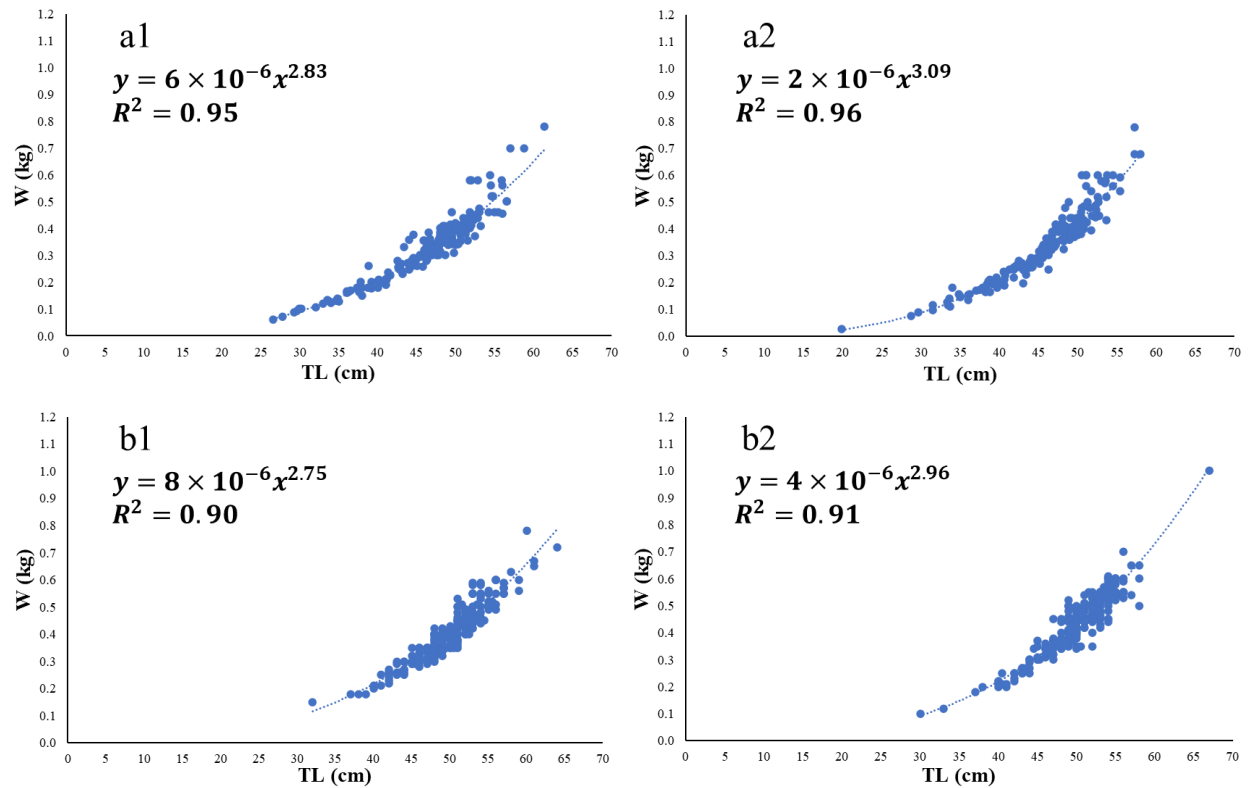


Figure A4. Length-weight relationship of *Am* for TH/GT (a1: male, a2: female), and ML/AM (b1: male, b2: female).

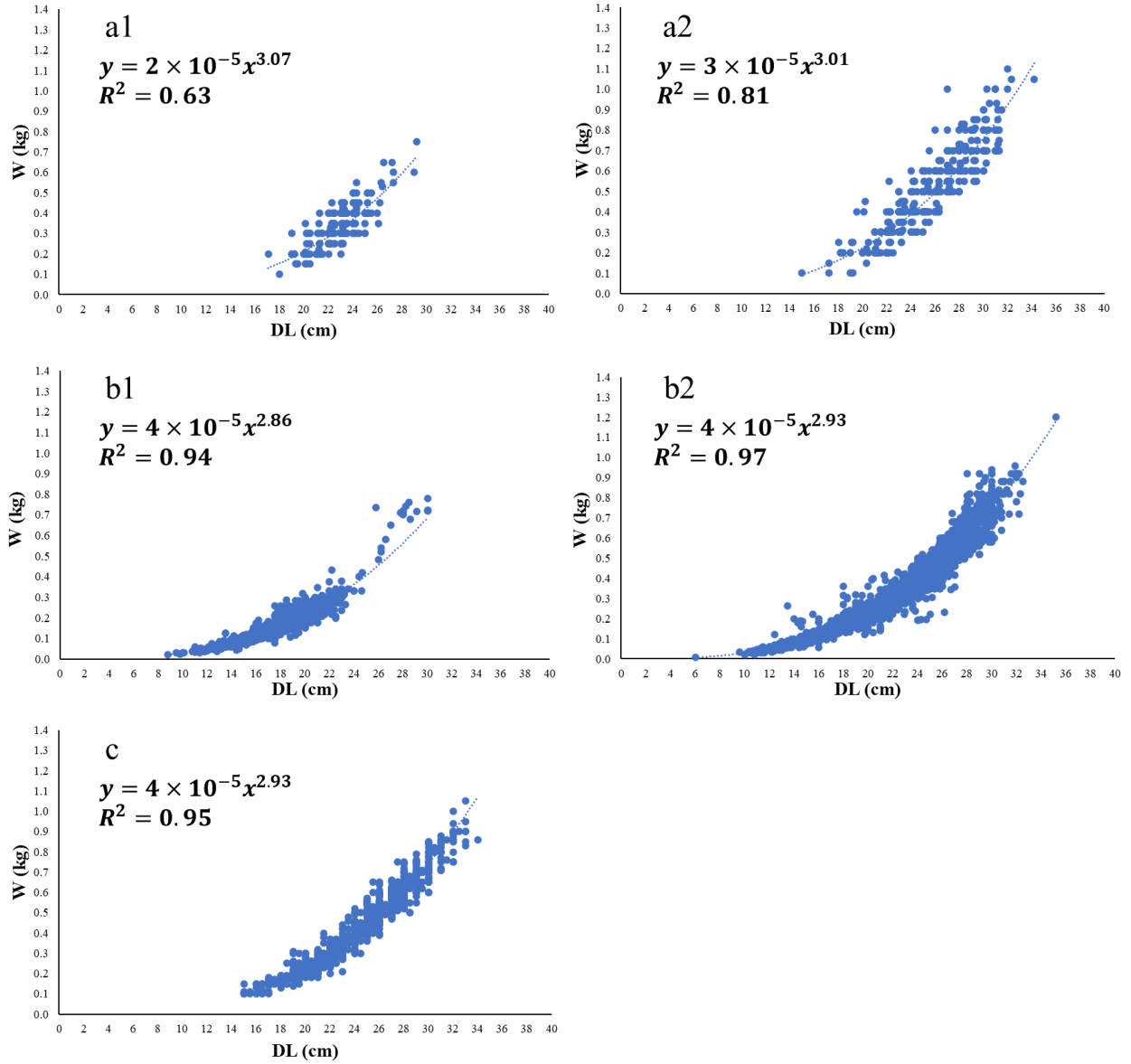


Figure A5. Length-weight relationship of *Tz* for ML/SC (a1: male, a2: female), TH/GT (b1: male, b2: female), and ML/AM (c).

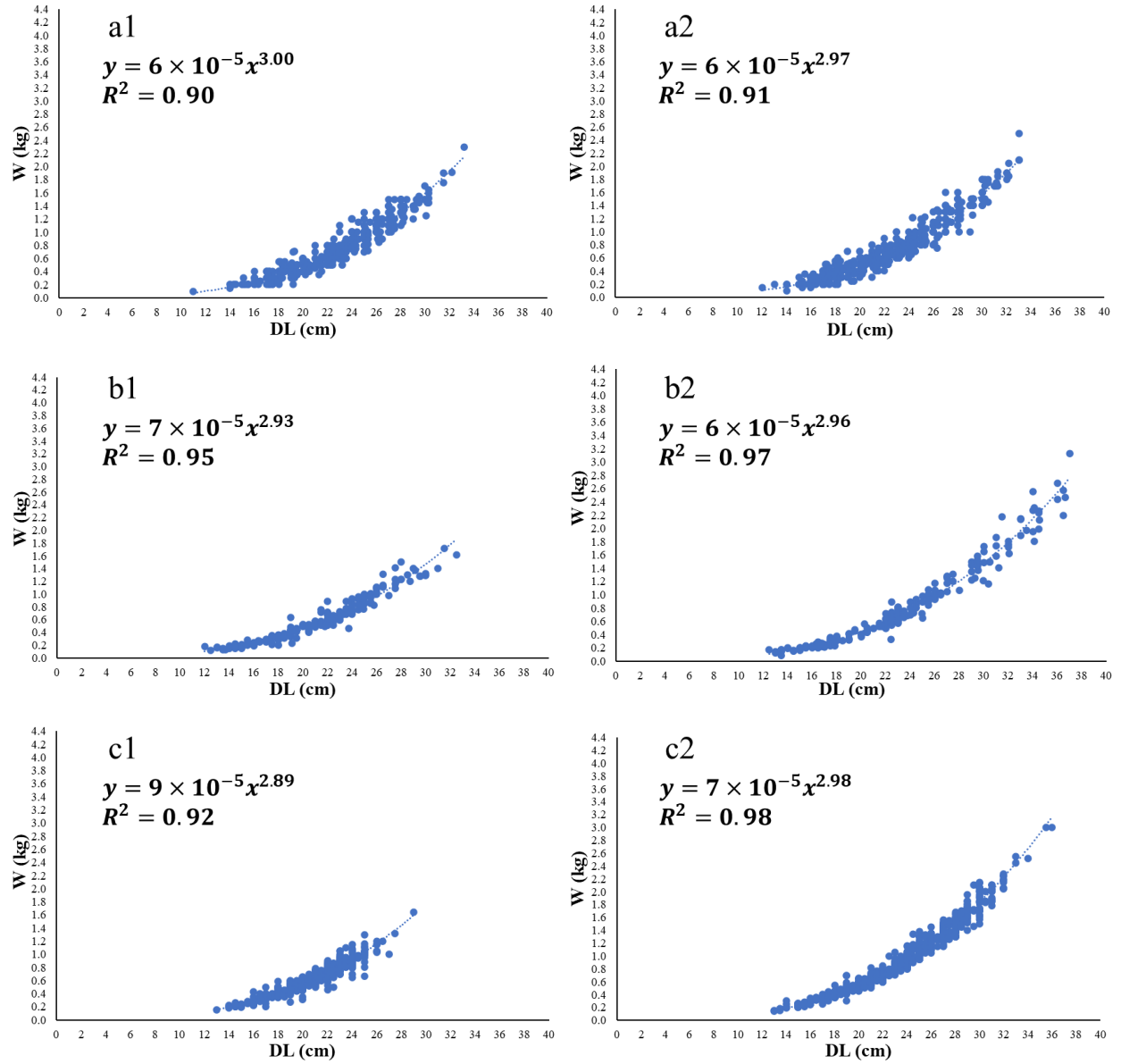


Figure A6. Length-weight relationship of *Nk* for ML/SC (a1: male, a2: female), TH/GT (b1: male, b2: female), and ML/AM (c1: male, c2: female).

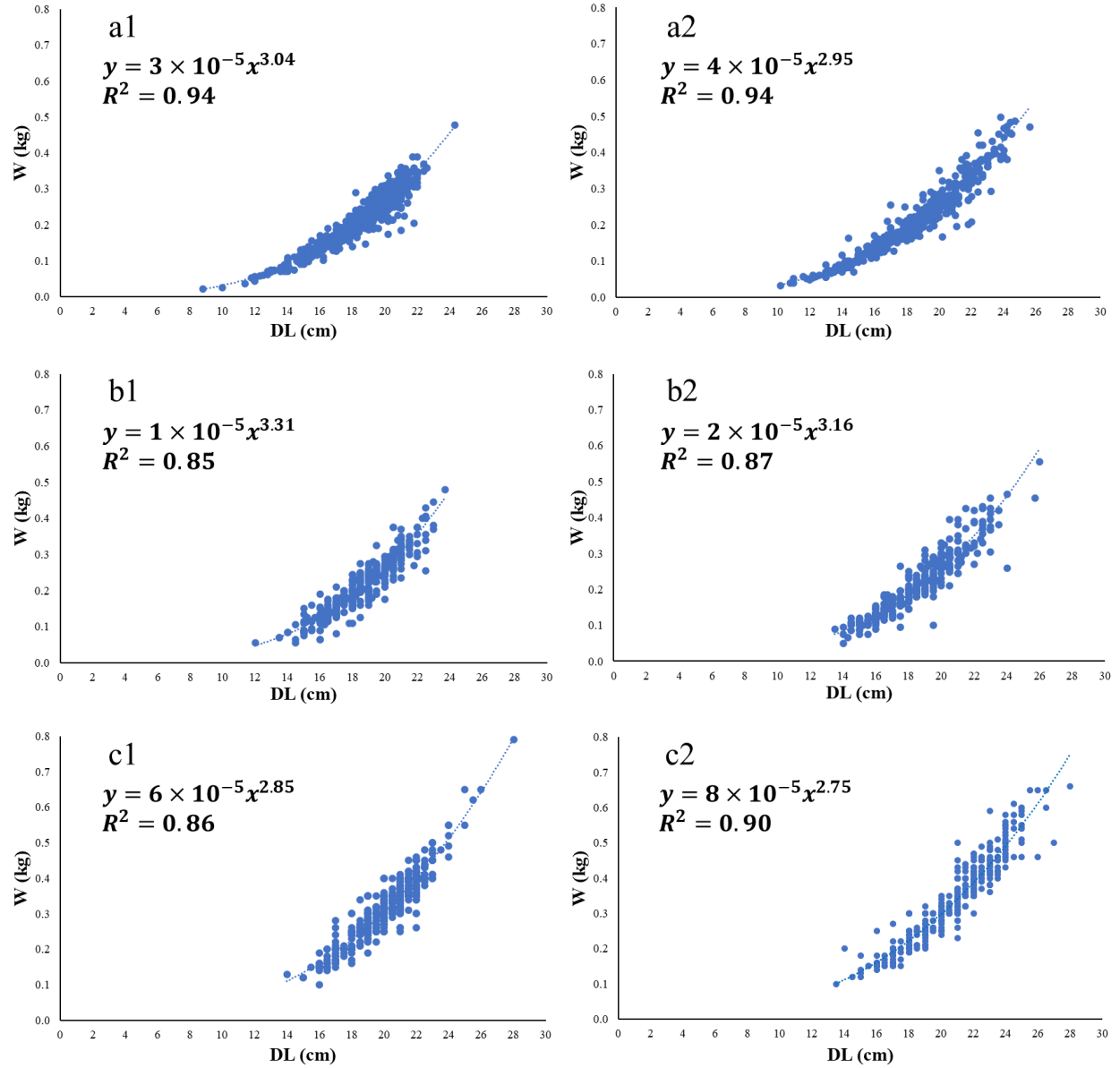


Figure A7. Length-weight relationship of *Bh* for TH/GT (a1: male, a2: female), TH/AM (b1: male, b2: female), and ML/AM (c1: male, c2: female).

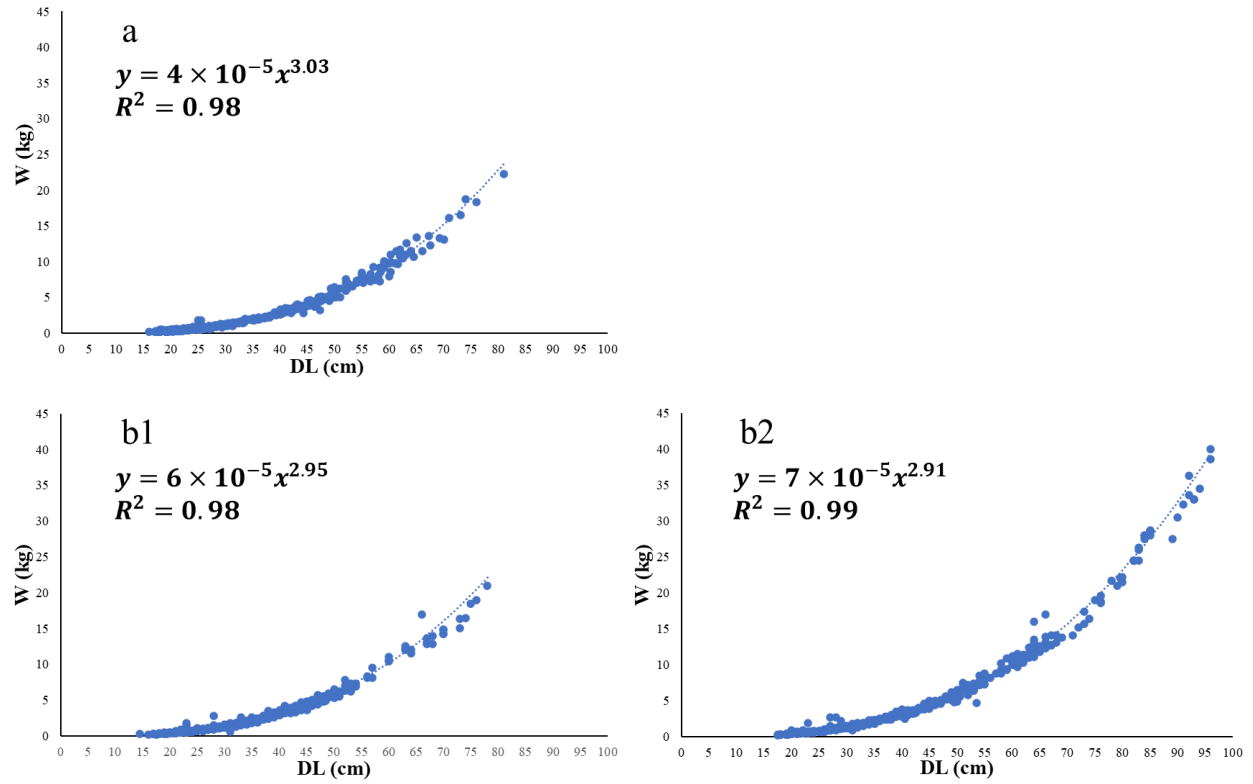


Figure A8. Length-weight relationship of *Mg* for ML/SC (a), and ML/AM (b1: male, b2: female).

Appendix B: Growth parameters of the selected elasmobranchs

Table B1. Summary of growth parameters for each species from K-Scan, Response Surface Analysis (RSA), ELEFAN_SA, and ELEFAN_GA.

Species	Methods	L_{∞}	K	Φ'	R_n	Remarks
<i>CpCMGT</i>	K-Scan	78.82	0.44	3.44	0.19	
	RSA	75.30	0.21	3.08	0.30	Used
	ELEFAN_SA	75.85	0.55	3.50	0.26	
	ELEFAN_GA	81.62	0.37	3.39	0.23	
<i>CpTHGT</i>	K-Scan	87.25	0.23	3.24	0.16	
	RSA	93.70	0.41	3.55	0.19	Used
	ELEFAN_SA	80.77	0.33	3.33	0.19	
	ELEFAN_GA	88.09	0.51	3.60	0.17	
<i>CpMLSC</i>	K-Scan	86.66	1.12	3.92	0.17	
	RSA	85.10	1.21	3.94	0.21	Unrealistic
	ELEFAN_SA	87.12	0.25	3.28	0.18	Used
	ELEFAN_GA	86.48	0.40	3.48	0.17	
<i>CpMLAM</i>	K-Scan	85.25	0.40	3.46	0.16	
	RSA	84.10	0.41	3.46	0.17	
	ELEFAN_SA	86.52	0.21	3.21	0.19	Used
	ELEFAN_GA	84.76	0.67	3.68	0.17	
<i>C/MLSCM</i>	K-Scan	77.68	1.12	3.83	0.28	
	RSA	77.90	1.11	3.83	0.28	
	ELEFAN_SA	81.13	0.21	3.15	0.36	Used
	ELEFAN_GA	77.82	0.29	3.24	0.33	
<i>C/MLSCF</i>	K-Scan	80.25	0.40	3.41	0.27	
	RSA	81.60	0.51	3.53	0.31	
	ELEFAN_SA	84.30	0.18	3.11	0.37	Used
	ELEFAN_GA	80.46	0.22	3.16	0.35	
<i>ChMLAM</i>	K-Scan	89.36	0.31	0.39	0.22	
	RSA	91.60	0.31	3.41	0.22	
	ELEFAN_SA	96.79	0.24	3.35	0.22	
	ELEFAN_GA	90.34	0.33	3.42	0.23	Used
<i>AmTHGTM</i>	K-Scan	51.19	0.81	3.33	0.33	
	RSA	54.90	0.51	3.19	0.44	
	ELEFAN_SA	54.99	0.53	3.20	0.45	Used
	ELEFAN_GA	52.96	0.70	3.30	0.41	
<i>AmTHGTF</i>	K-Scan	51.04	2.36	3.79	0.35	
	RSA	59.30	0.51	3.25	0.49	
	ELEFAN_SA	59.05	0.52	3.26	0.50	Used
	ELEFAN_GA	53.73	0.74	3.33	0.43	
<i>AmMLAMM</i>	K-Scan	56.82	3.13	4.00	0.21	Unreliable

	RSA	62.80	1.41	4.05	0.23	Unreliable
	ELEFAN_SA	64.34	0.96	3.60	0.19	Unreliable
	ELEFAN_GA	63.50	0.72	3.46	0.18	Used
<i>AmMLAMF</i>	K-Scan	58.19	1.63	3.74	0.29	
	RSA	56.10	0.71	3.35	0.40	Used
	ELEFAN_SA	57.53	0.53	3.24	0.38	
	ELEFAN_GA	56.89	0.64	3.32	0.37	
<i>SIMYAM</i>	K-Scan	62.23	1.29	3.70	0.23	
	RSA	54.30	0.71	3.32	0.35	
	ELEFAN_SA	52.54	0.86	3.38	0.37	Used
	ELEFAN_GA	54.55	0.69	3.31	0.35	
<i>TzMLSCM</i>	K-Scan	25.04	0.89	2.75	0.59	Used
	RSA	25.00	0.91	2.75	0.59	
	ELEFAN_SA	25.25	0.86	2.74	0.58	
	ELEFAN_GA	25.52	0.75	2.69	0.46	
<i>TzMLSCF</i>	K-Scan	31.18	0.81	2.90	0.28	
	RSA	30.70	0.91	2.94	0.29	
	ELEFAN_SA	31.14	0.51	2.70	0.30	Used
	ELEFAN_GA	31.79	0.62	2.80	0.29	
<i>TzTHGTM</i>	K-Scan	30.11	0.44	2.60	0.26	
	RSA	25.40	0.61	2.59	0.30	
	ELEFAN_SA	32.83	0.35	2.58	0.34	Used
	ELEFAN_GA	28.34	0.56	2.65	0.28	
<i>TzTHGTF</i>	K-Scan	32.59	0.77	2.90	0.18	
	RSA	32.20	0.61	2.80	0.22	
	ELEFAN_SA	28.02	0.85	2.82	0.23	Used
	ELEFAN_GA	31.37	0.61	2.78	0.22	
<i>TzMLAM</i>	K-Scan	34.39	1.12	3.12	0.23	
	RSA	30.00	1.01	2.96	0.35	
	ELEFAN_SA	30.01	1.00	2.95	0.37	Used
	ELEFAN_GA	31.03	0.84	2.91	0.34	
<i>NkMLSCM</i>	K-Scan	30.59	0.67	2.80	0.20	
	RSA	28.80	1.31	3.04	0.24	Unreliable
	ELEFAN_SA	31.87	0.61	2.79	0.23	Used
	ELEFAN_GA	29.90	0.78	2.85	0.22	
<i>NkMLSCF</i>	K-Scan	31.84	1.07	3.04	0.17	
	RSA	30.30	0.51	2.67	0.21	Used
	ELEFAN_SA	30.12	0.53	2.68	0.21	
	ELEFAN_GA	26.36	0.82	2.76	0.18	
<i>NkTHAMM</i>	K-Scan	28.62	0.93	2.88	0.30	
	RSA	29.90	0.51	2.66	0.33	Used
	ELEFAN_SA	29.89	0.51	2.66	0.32	
	ELEFAN_GA	30.03	0.76	2.83	0.29	
<i>NkTHAMF</i>	K-Scan	36.76	0.31	2.63	0.35	
	RSA	36.40	0.51	2.83	0.41	
	ELEFAN_SA	43.47	0.18	2.50	0.40	

	ELEFAN_GA	43.06	0.18	2.51	0.42	Used
<i>NkMLAMM</i>	K-Scan	27.97	0.89	2.74	0.48	Used
	RSA	25.00	0.91	2.75	0.40	
	ELEFAN_SA	24.97	0.92	2.76	0.41	
	ELEFAN_GA	25.43	0.79	2.71	0.46	
<i>NkMLAMF</i>	K-Scan	33.05	0.51	2.74	0.21	
	RSA	30.00	0.81	2.86	0.23	Used
	ELEFAN_SA	29.11	0.92	2.89	0.23	
	ELEFAN_GA	34.19	0.32	2.56	0.20	
<i>BhTHGTM</i>	K-Scan	23.80	0.64	2.53	0.37	Used
	RSA	21.30	1.41	2.81	0.44	L_∞ too small
	ELEFAN_SA	21.42	0.99	2.66	0.39	L_∞ too small
	ELEFAN_GA	22.08	0.61	2.47	0.37	L_∞ too small
<i>BhTHGTF</i>	K-Scan	25.90	0.51	2.53	0.21	
	RSA	29.40	0.21	2.26	0.29	Used
	ELEFAN_SA	20.58	0.64	2.43	0.29	
	ELEFAN_GA	20.71	0.63	2.43	0.29	
<i>BhTHAMM</i>	K-Scan	21.70	2.26	3.03	0.33	
	RSA	26.00	0.91	2.79	0.43	
	ELEFAN_SA	26.79	0.82	2.77	0.43	Used
	ELEFAN_GA	28.38	0.56	2.65	0.37	
<i>BhTHAMF</i>	K-Scan	27.57	0.34	2.41	0.26	
	RSA	24.90	0.61	2.58	0.38	
	ELEFAN_SA	24.67	0.59	2.55	0.39	Used
	ELEFAN_GA	24.56	0.65	2.59	0.34	
<i>BhMLAMM</i>	K-Scan	24.90	0.53	2.52	0.29	Used
	RSA	22.40	1.41	2.85	0.84	L_∞ too small
	ELEFAN_SA	22.57	0.93	2.68	0.68	L_∞ too small
	ELEFAN_GA	23.00	0.78	2.62	0.66	L_∞ too small
<i>BhMLAMF</i>	K-Scan	24.32	1.56	2.96	0.32	L_∞ too small
	RSA	23.30	2.61	3.15	0.33	L_∞ too small
	ELEFAN_SA	30.77	0.55	2.72	0.28	Used
	ELEFAN_GA	23.38	0.56	2.67	0.26	L_∞ too small
<i>MgMLSC</i>	K-Scan	75.92	0.10	2.76	0.44	
	RSA	73.60	0.11	2.77	0.49	Used
	ELEFAN_SA	70.44	0.12	2.76	0.48	
	ELEFAN_GA	74.65	0.13	2.85	0.42	
<i>MgMLAMM</i>	K-Scan	76.57	0.13	2.88	0.24	
	RSA	70.5	0.11	2.74	0.24	
	ELEFAN_SA	70.39	0.16	2.90	0.26	
	ELEFAN_GA	77.97	0.13	2.89	0.29	Used
<i>MgMLAMF</i>	K-Scan	92.07	0.11	2.97	0.26	
	RSA	93.40	0.11	2.98	0.29	
	ELEFAN_SA	93.86	0.06	2.71	0.40	Used
	ELEFAN_GA	93.70	0.06	2.75	0.39	

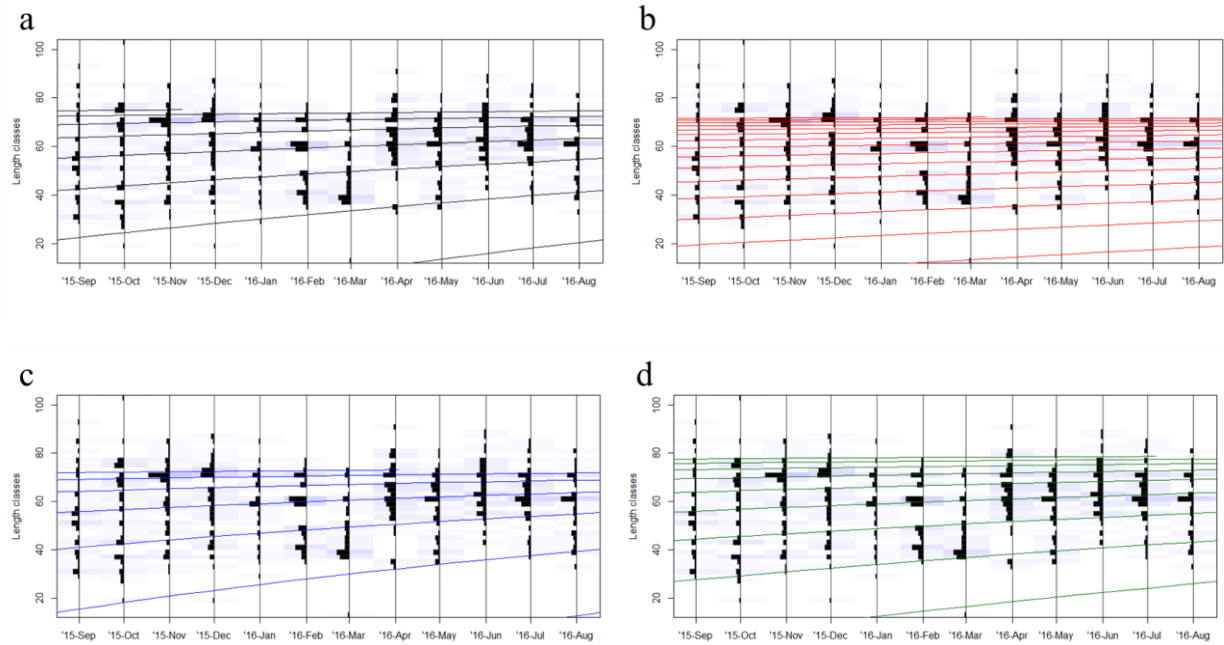


Figure B1. The growth curve of C_p from CM/GT using K Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

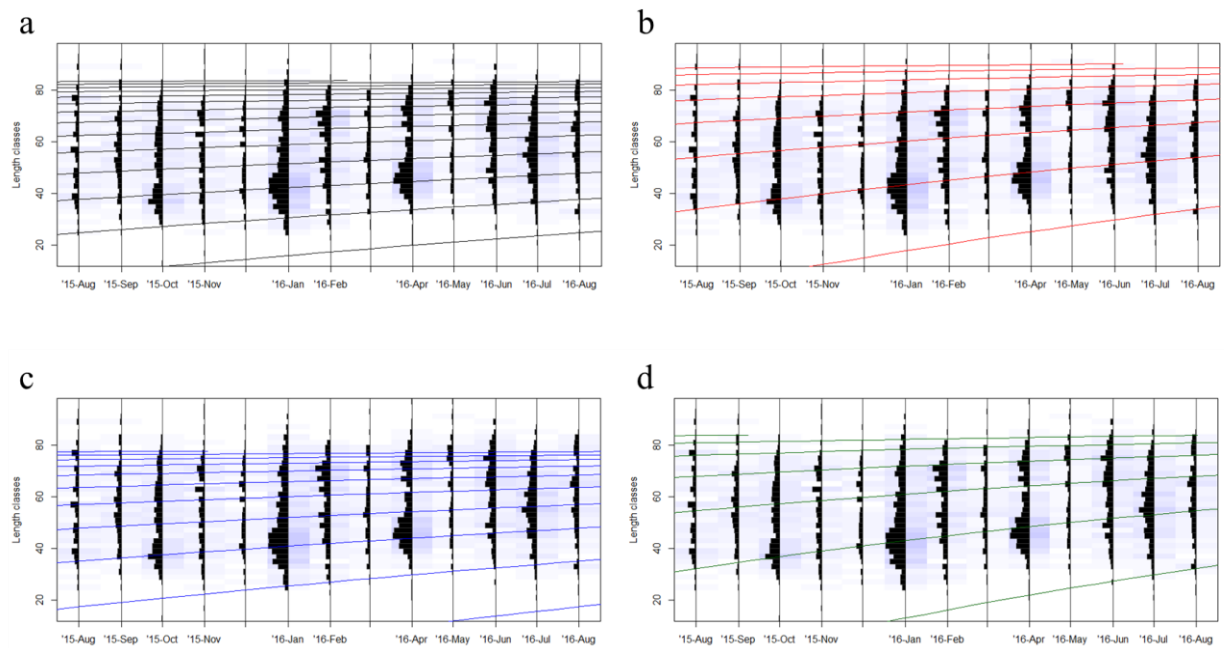


Figure B2. The growth curve of C_p from TH/GT using K Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

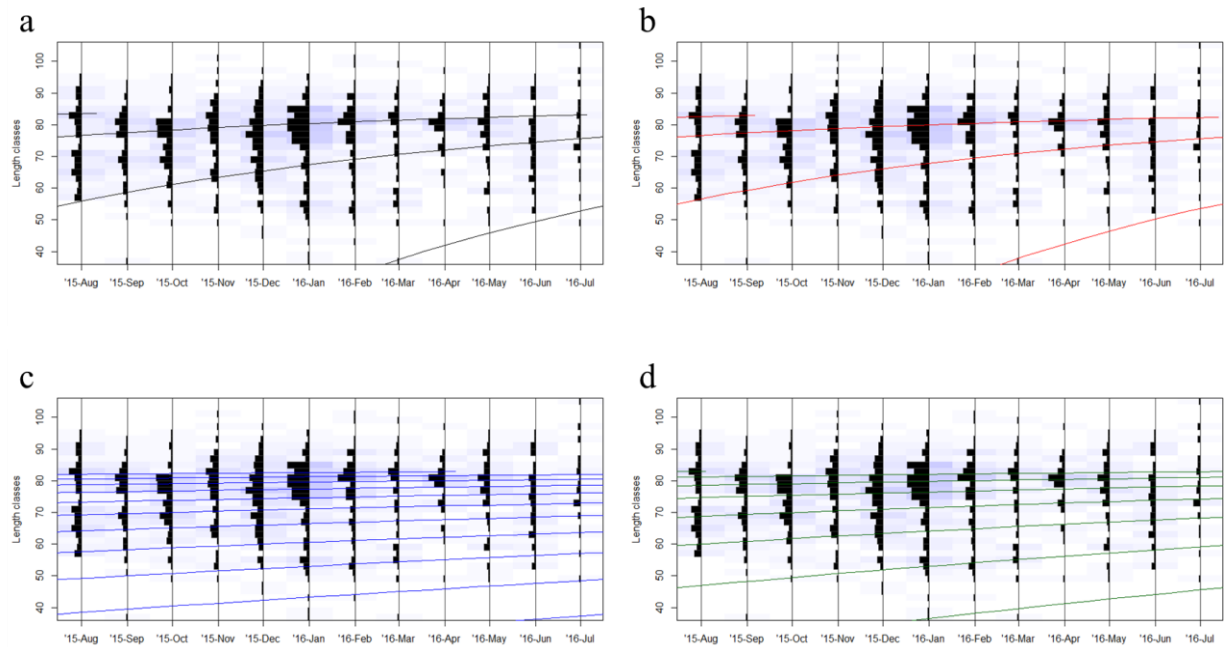


Figure B3. The growth curve of C_p from ML/SC using K Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

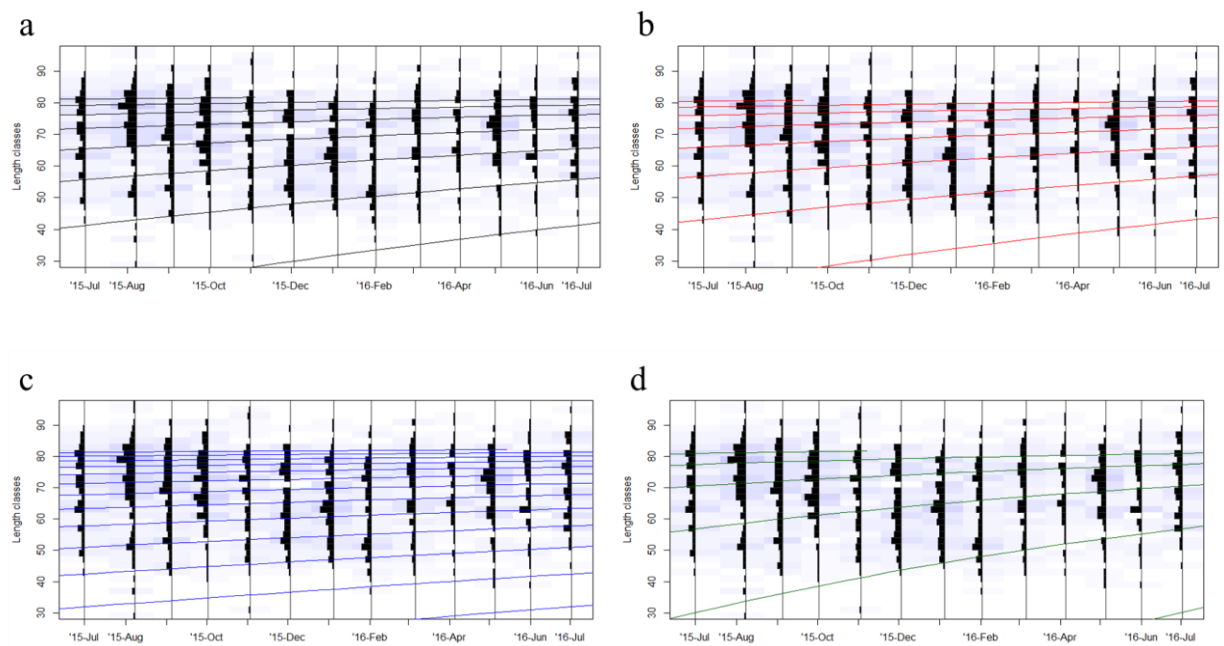


Figure B4. The growth curve of C_p from ML/AM using K Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

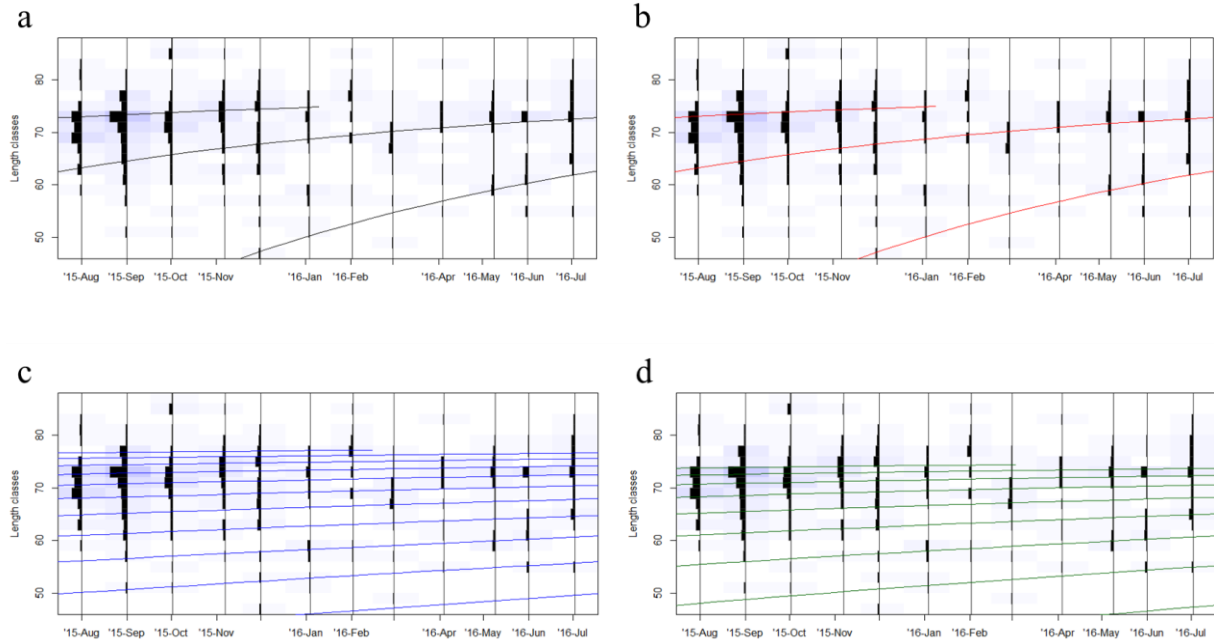


Figure B5. The growth curve of male *Cl* from ML/SC using *K* Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

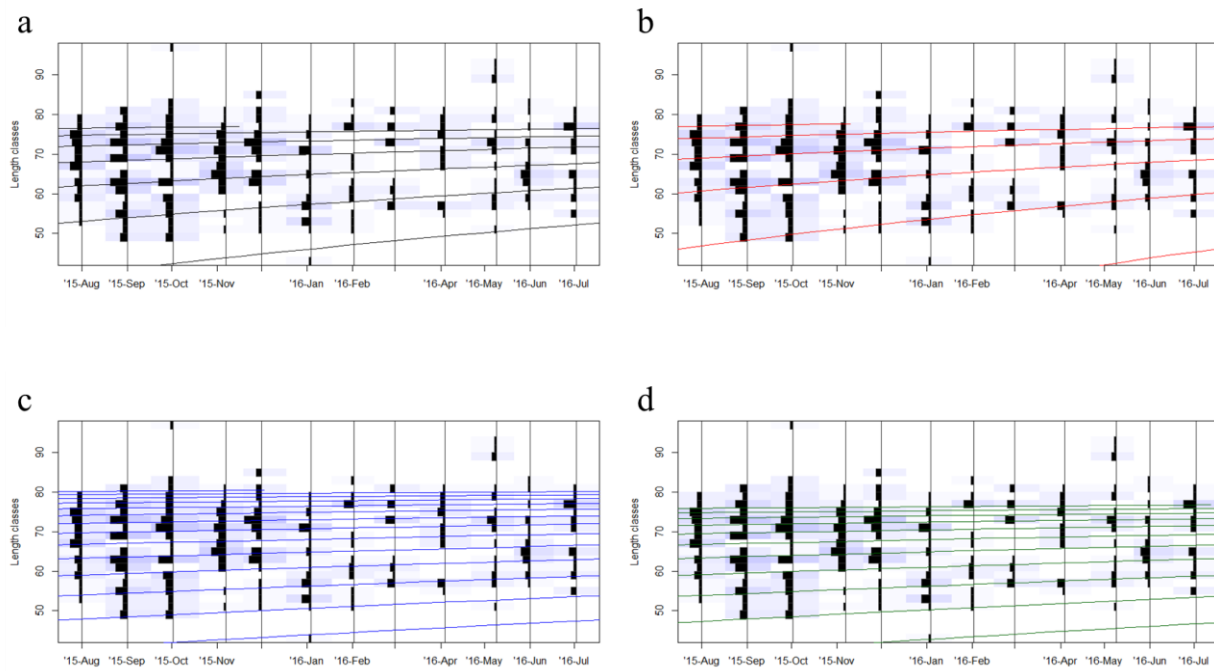


Figure B6. The growth curve of female *Cl* from ML/SC using *K* Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

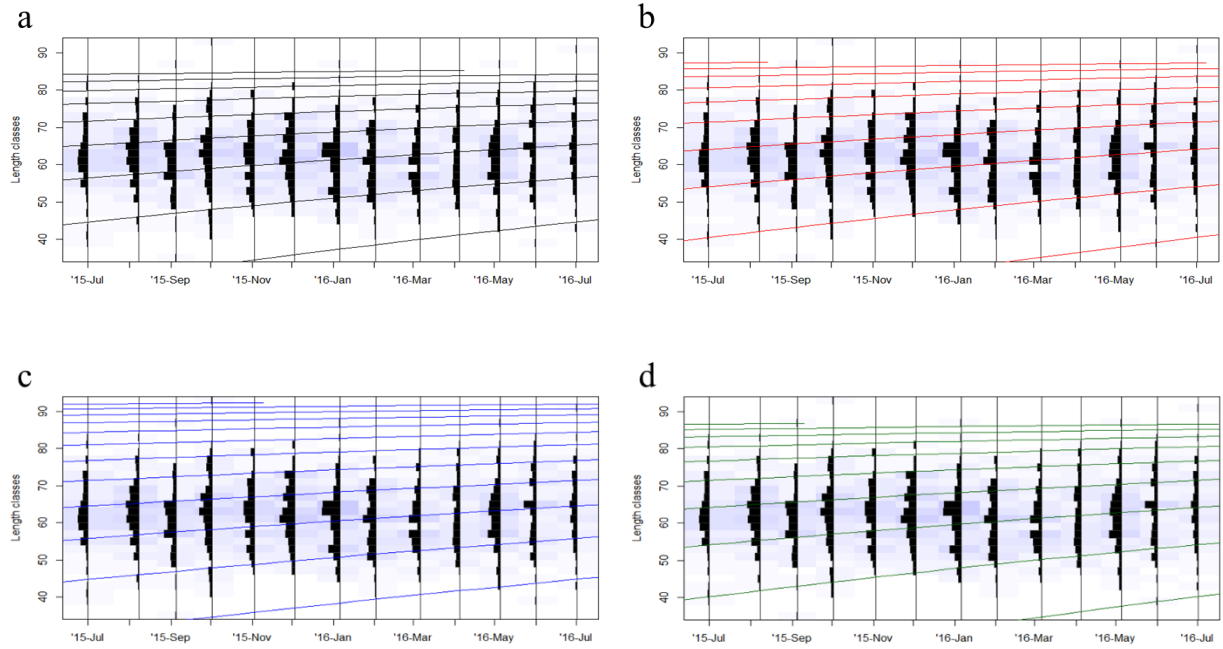


Figure B7. The growth curve of *Ch* from ML/AM using *K* Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

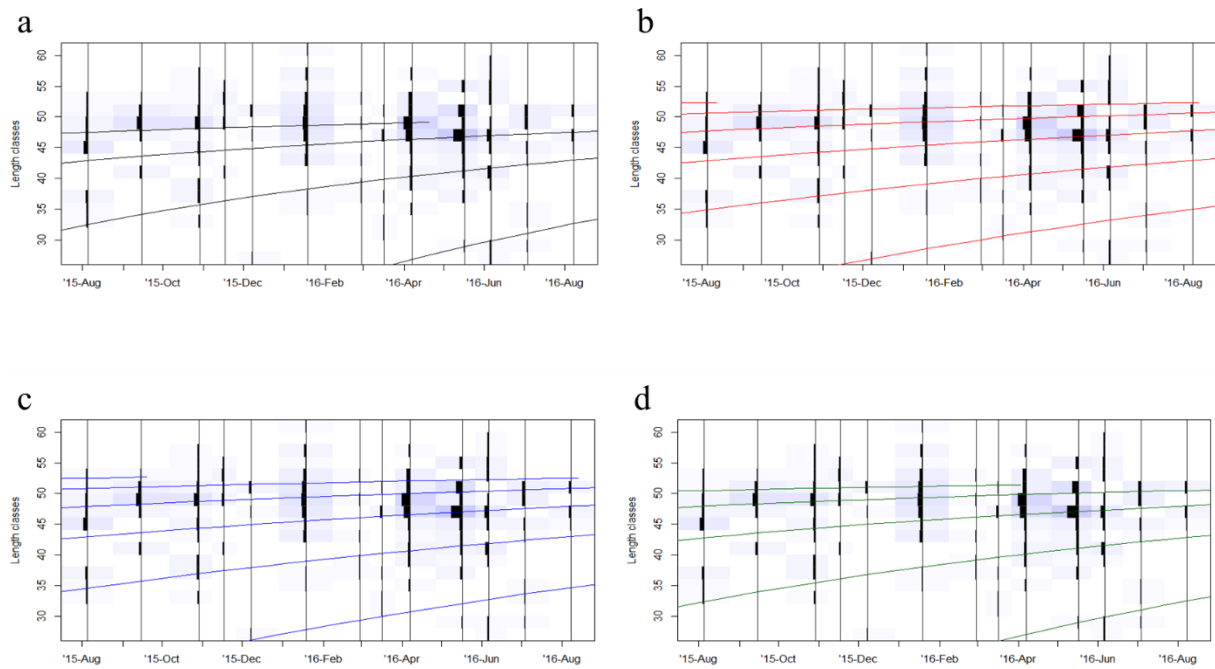


Figure B8. The growth curve of male *Am* from TH/GT using *K* Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

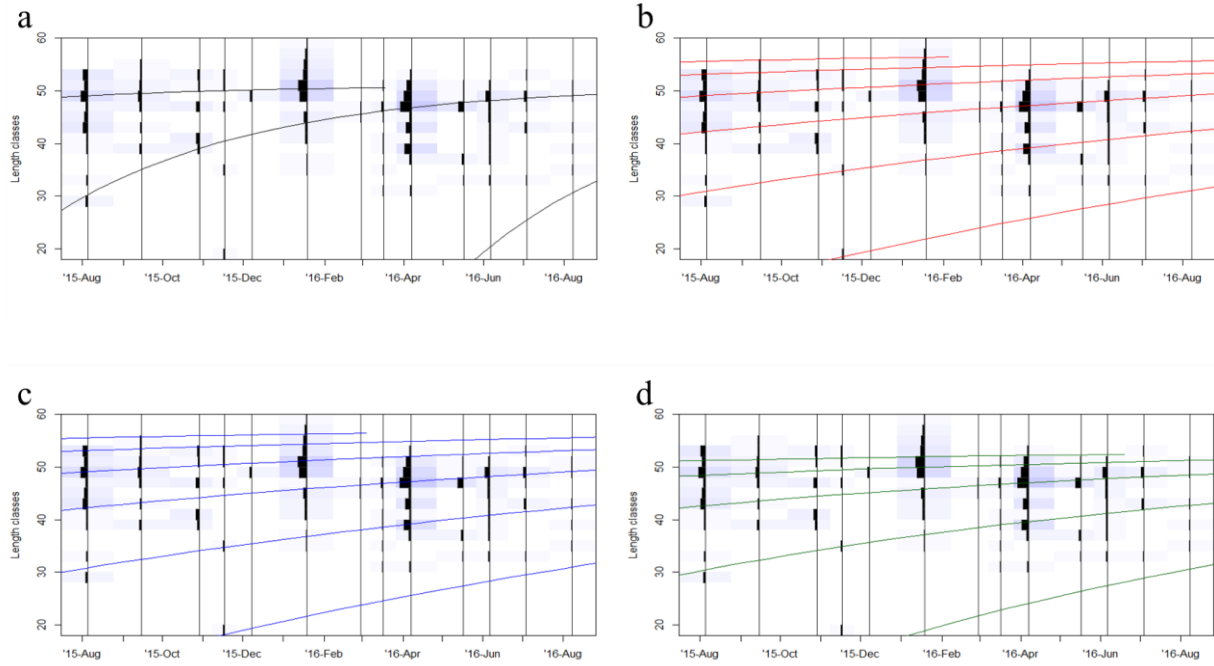


Figure B9. The growth curve of female *Am* from TH/GT using K Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

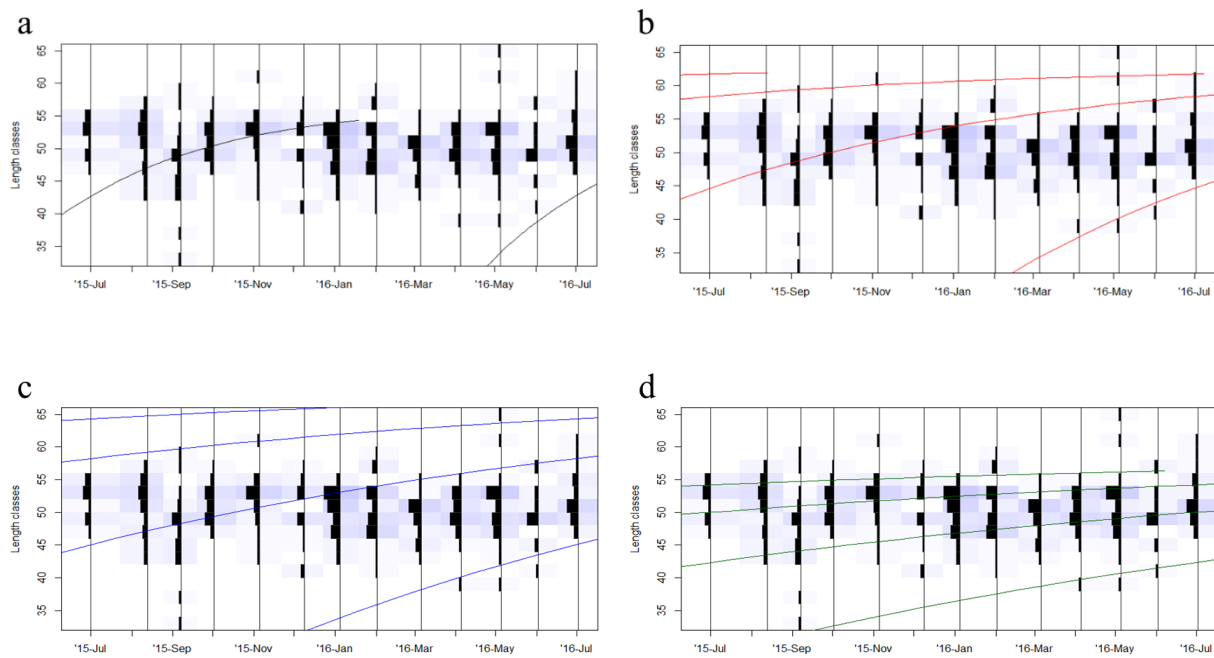


Figure B10. The growth curve of male *Am* from ML/AM using K Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

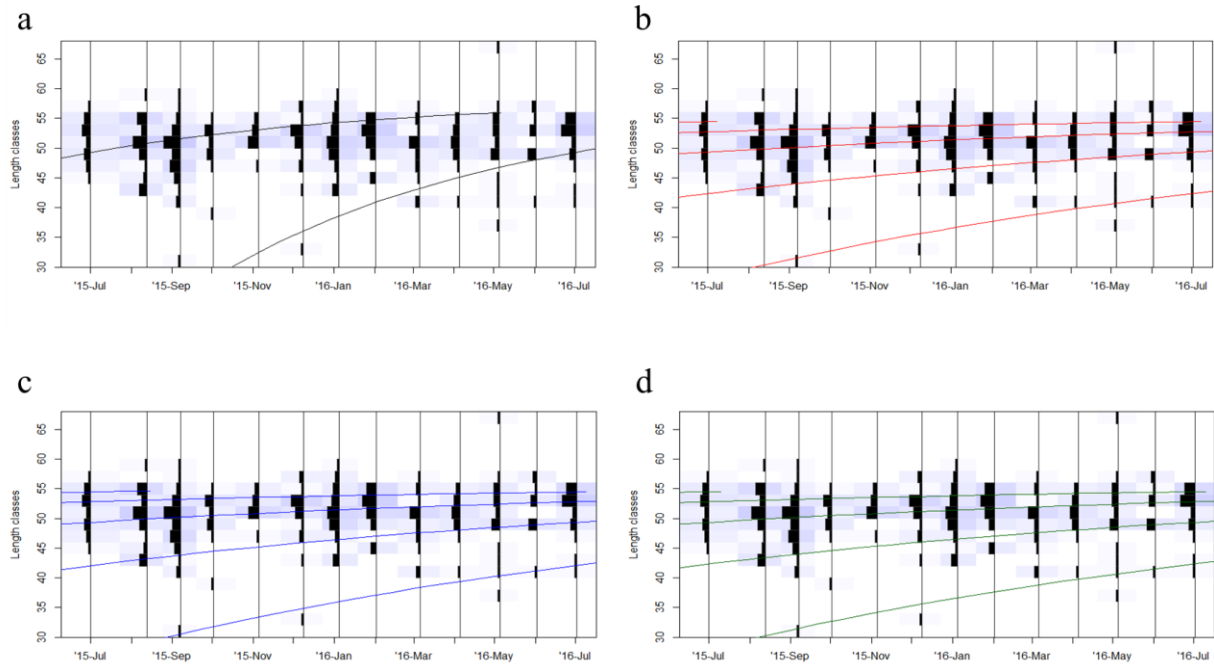


Figure B11. The growth curve of female *Am* using *K* Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

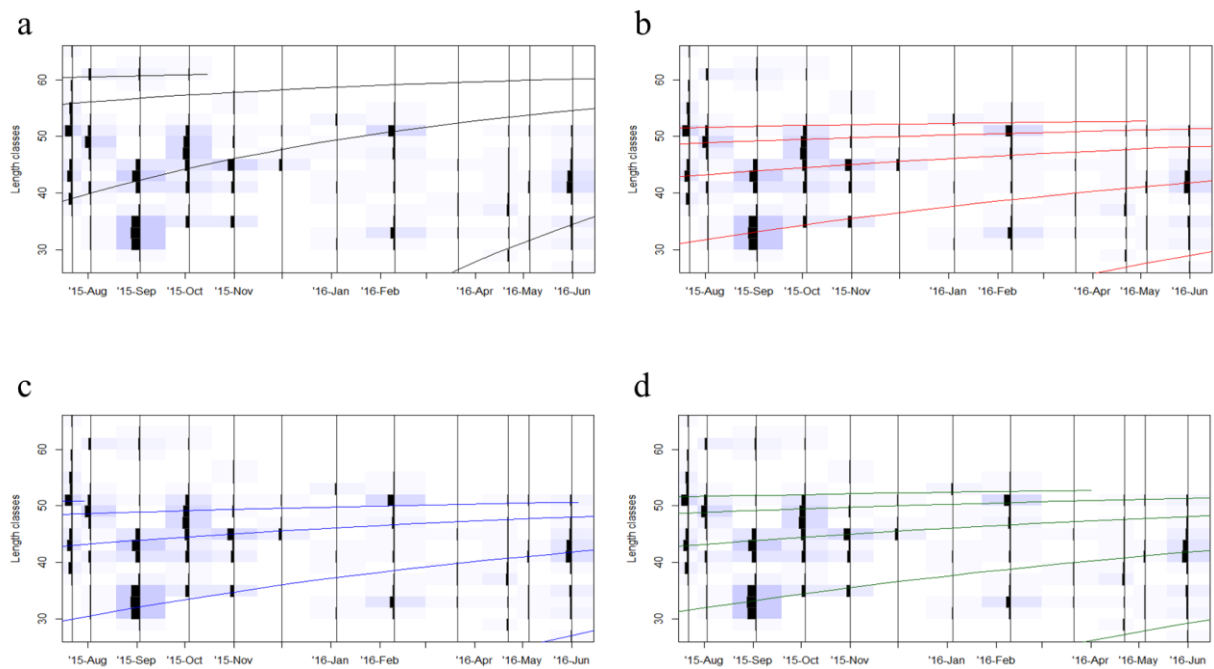


Figure B12. The growth curve of *Sl* from MY/AM using *K* Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

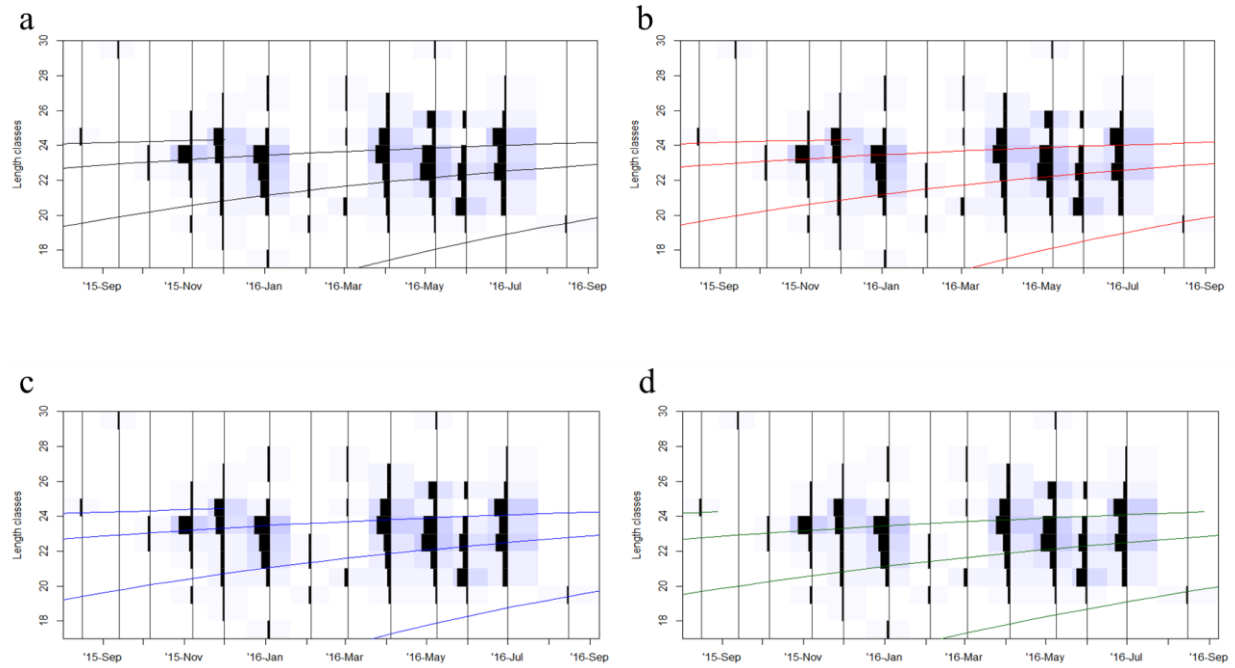


Figure B13. The growth curve of male *Tz* from ML/SC using *K* Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

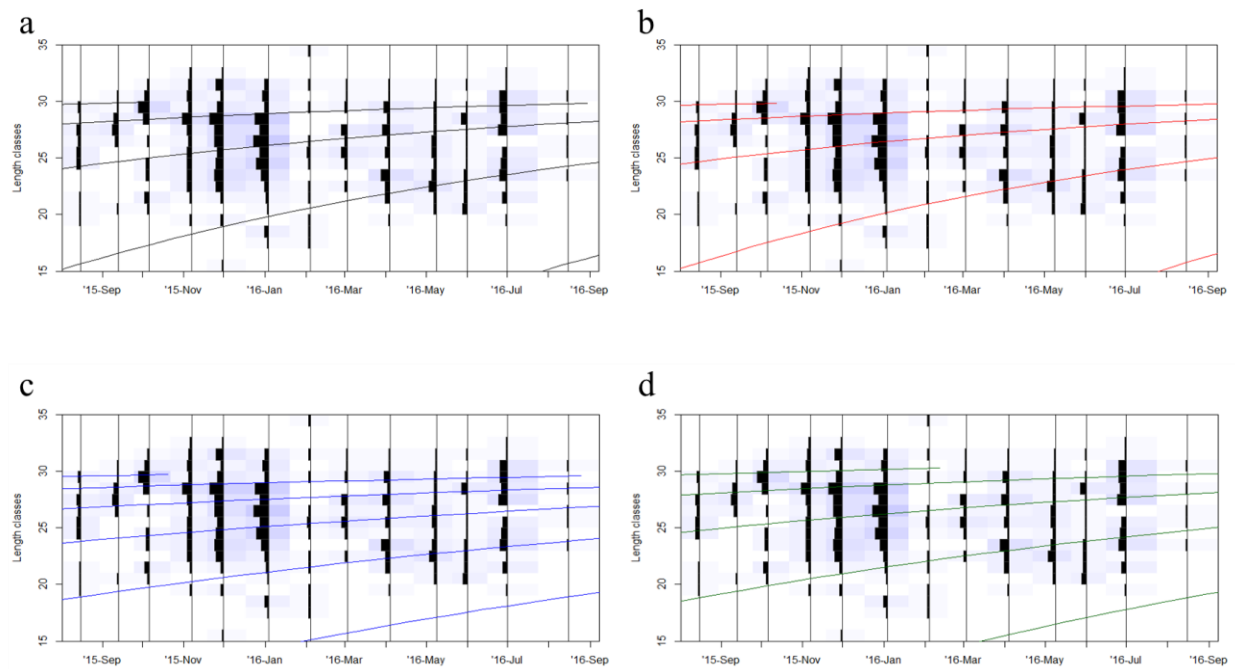


Figure B14. The growth curve of female *Telatrygon zugei* from ML/SC using *K* Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

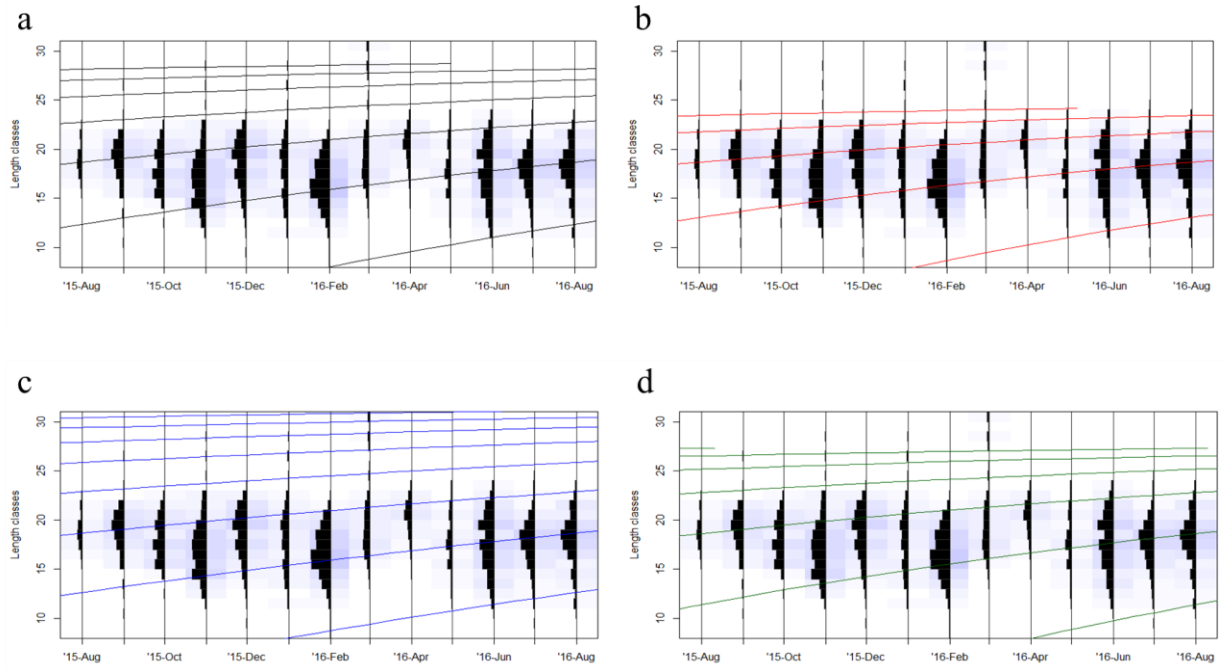


Figure B15. The growth curve of male *Tz* from TH/GT using *K* Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

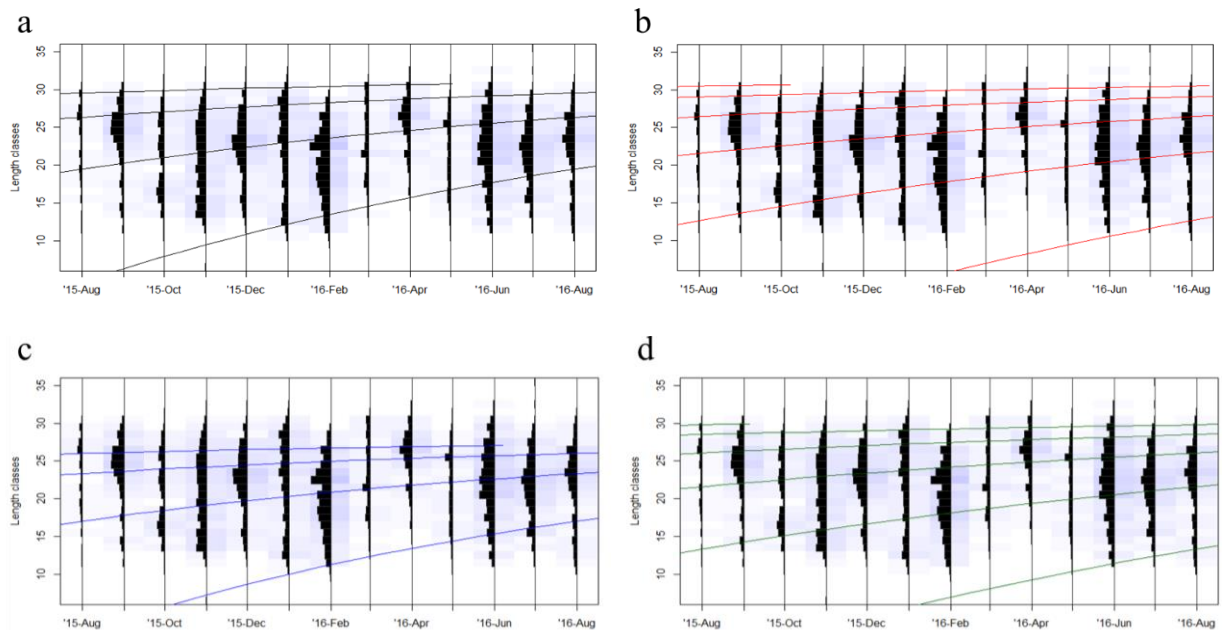


Figure B16. The growth curve of female *Tz* from TH/GT using *K* Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

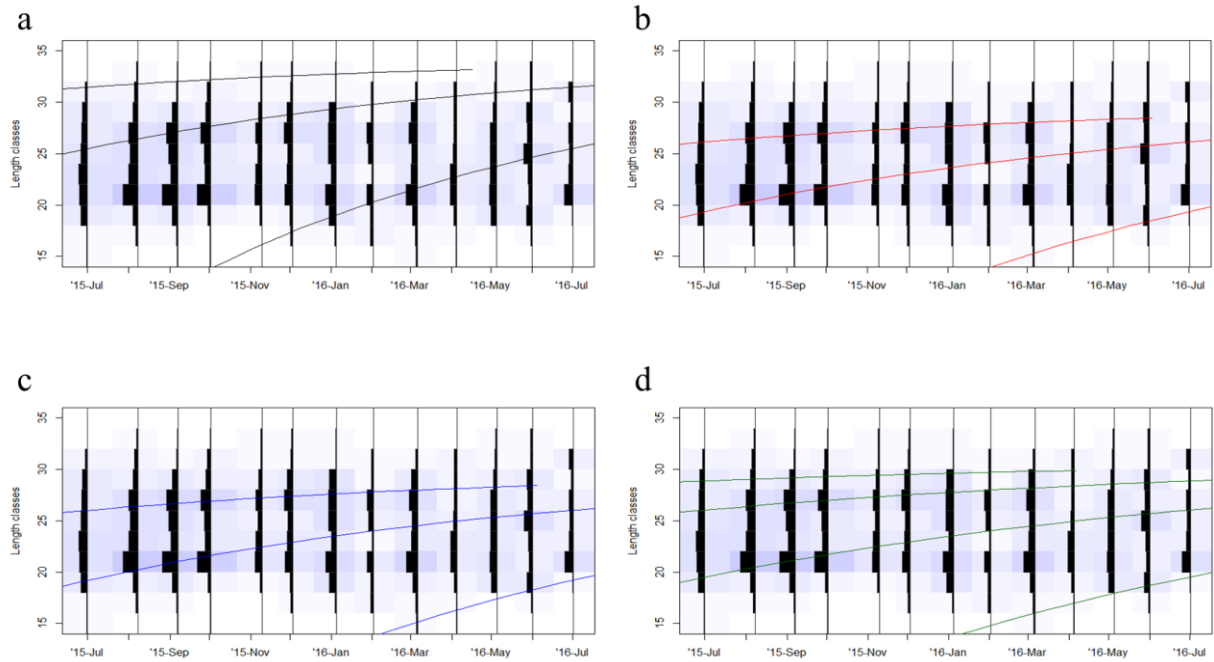


Figure B17. The growth curve of T_z from ML/AM using K Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

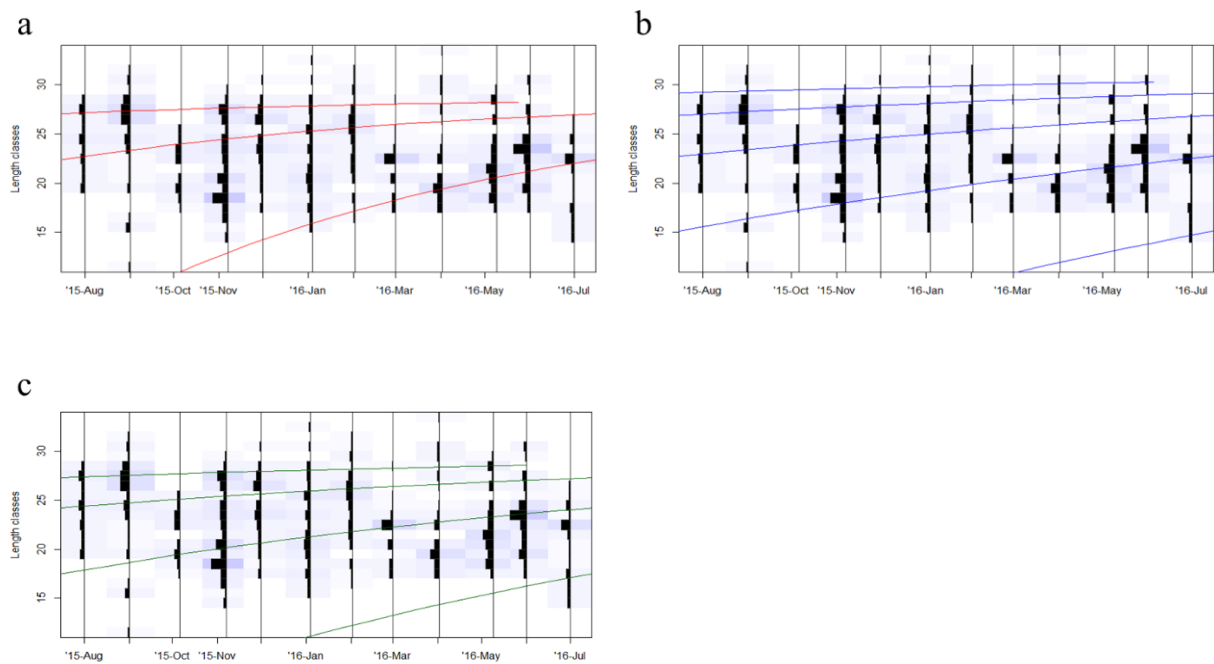


Figure B18. The growth curve of male N_k from ML/SC using RSA (a), ELEFAN_SA (b), and ELEFAN_GA (c).

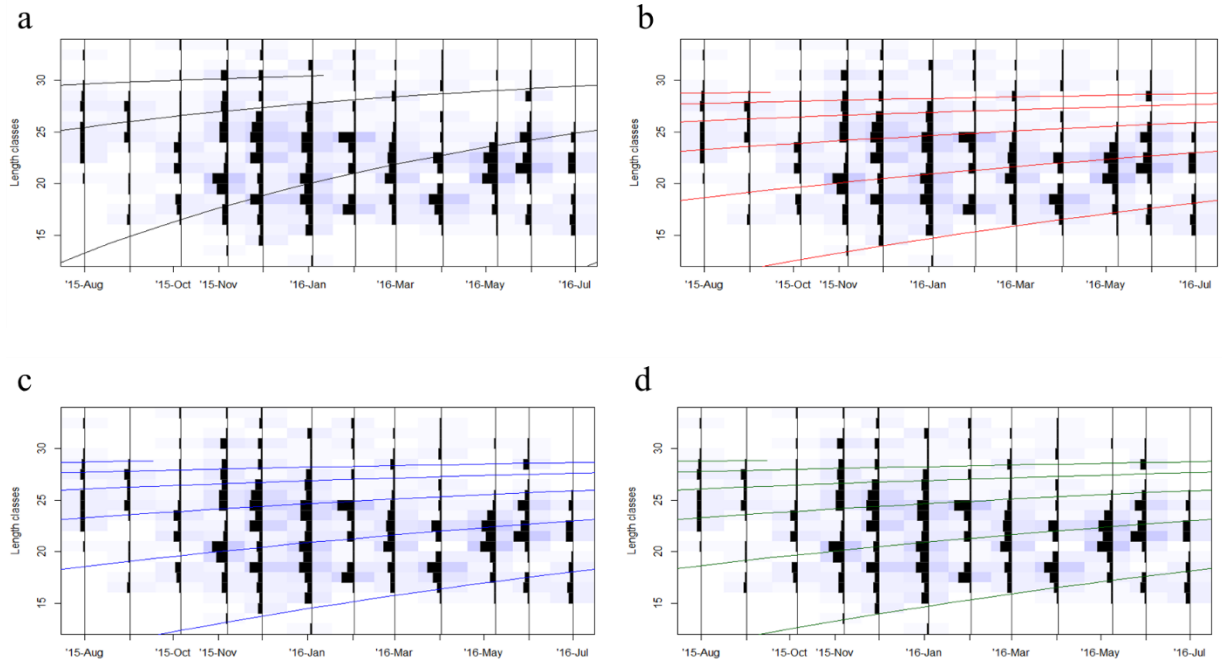


Figure B19. The growth curve of female *Nk* from ML/SC using *K* Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

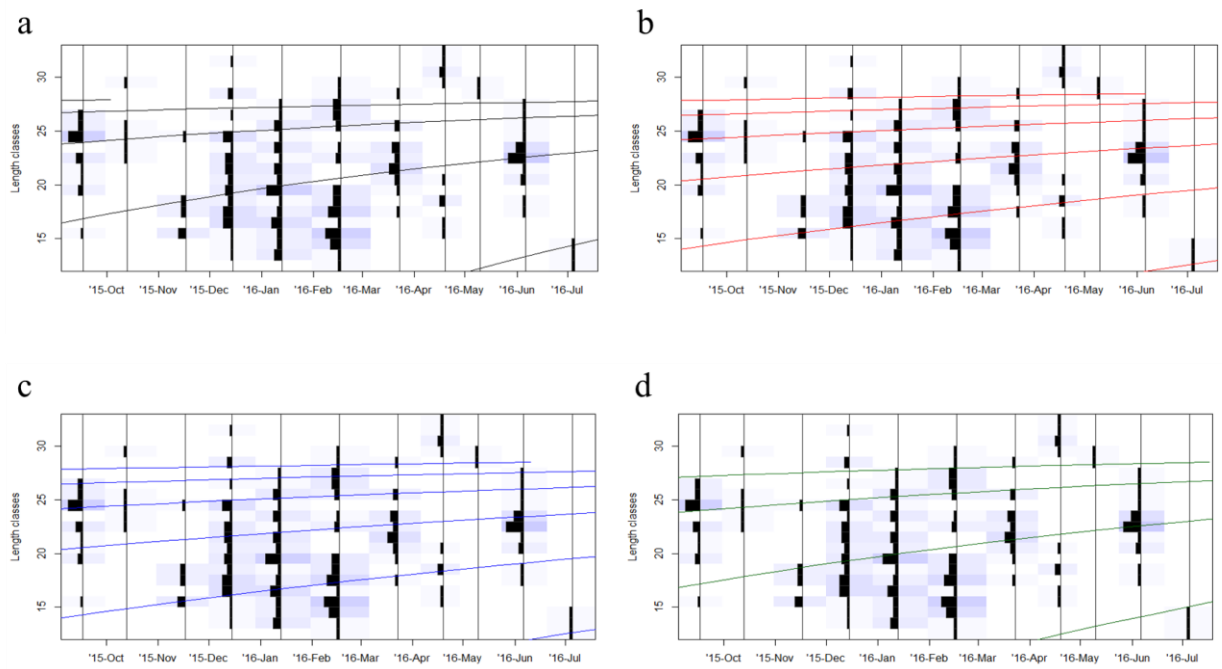


Figure B20. The growth curve of male *Nk* from TH/AM using *K* Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

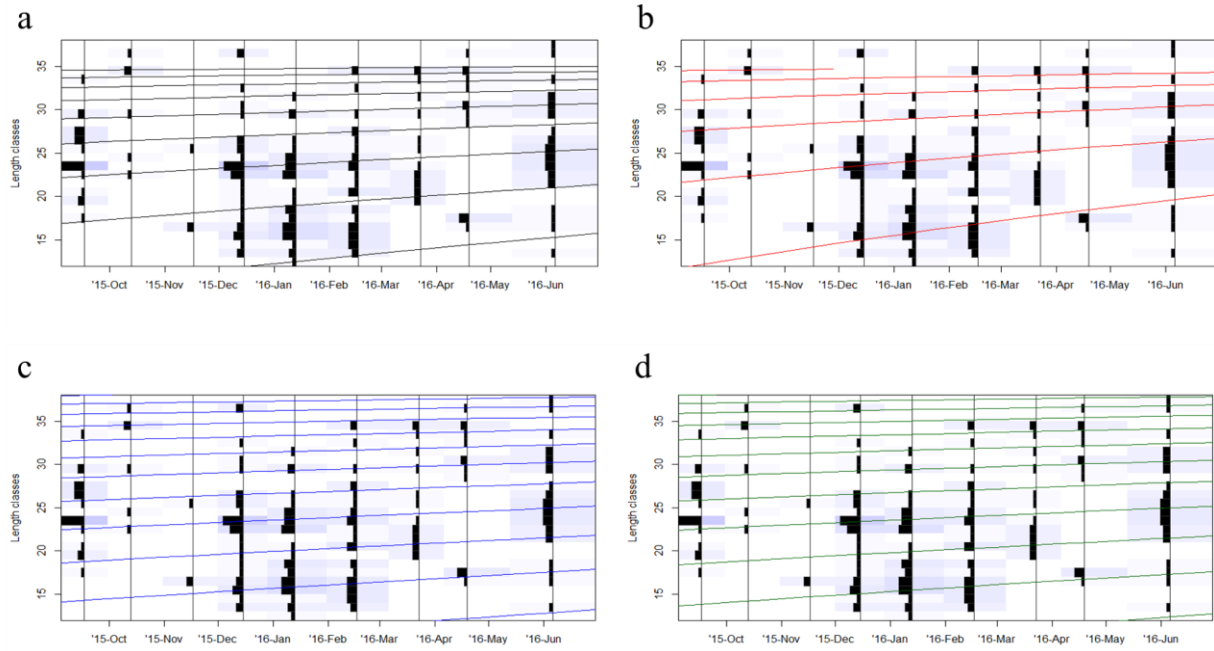


Figure B21. The growth curve of female *Nk* from TH/AM using *K* Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

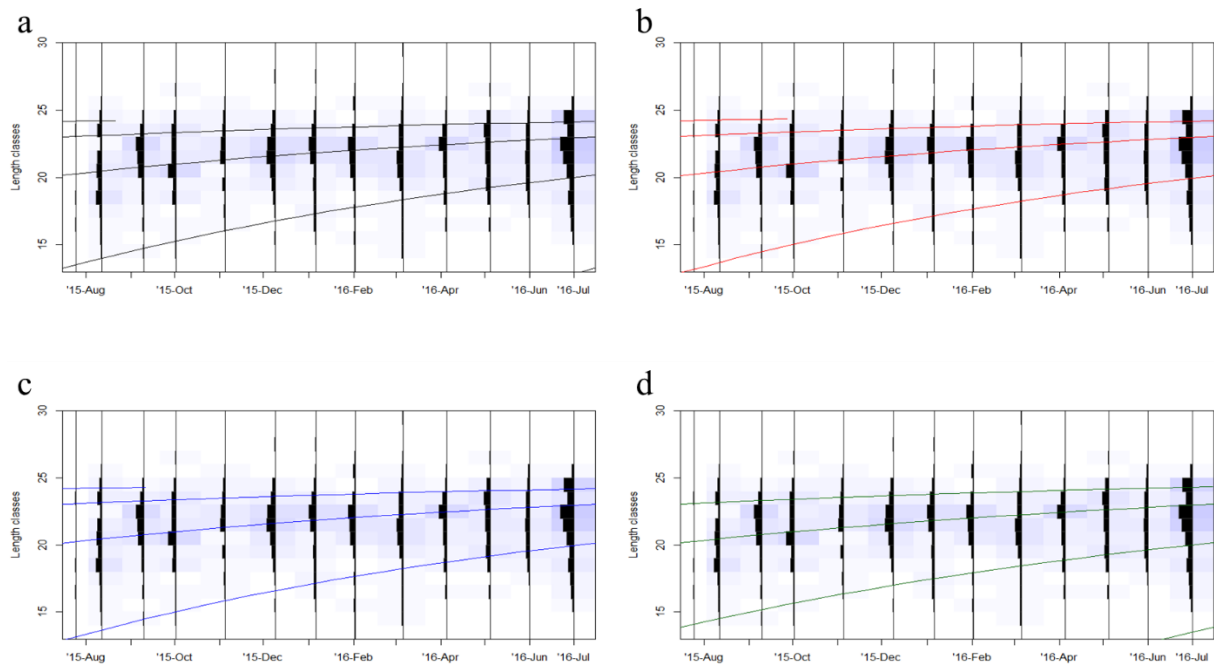


Figure B22. The growth curve of male *Nk* from ML/AM using *K* Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

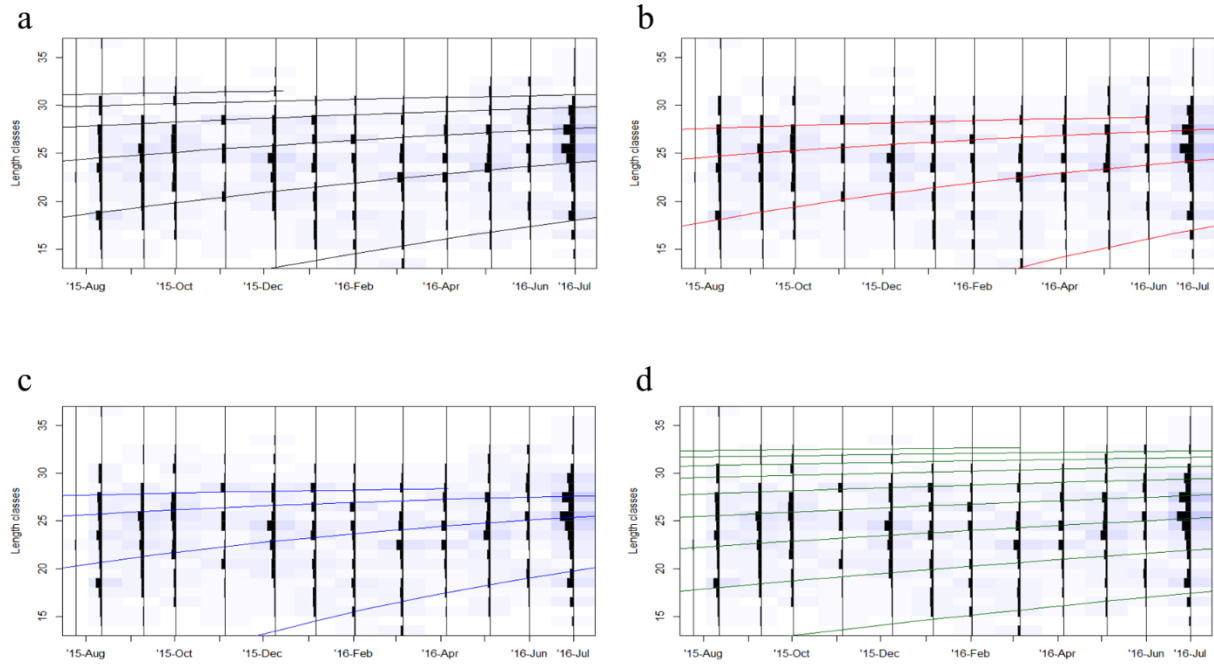


Figure B23. The growth curve of female *Nk* from ML/AM using *K* Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

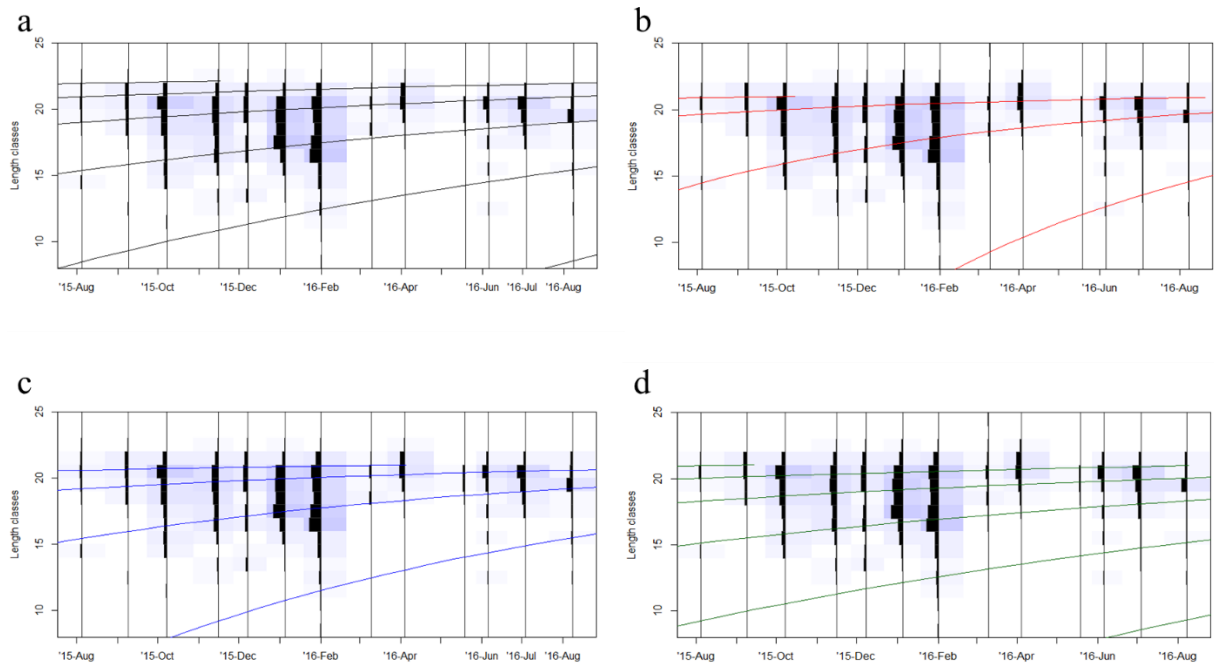


Figure B24. The growth curve of male *Bh* from TH/GT using *K* Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

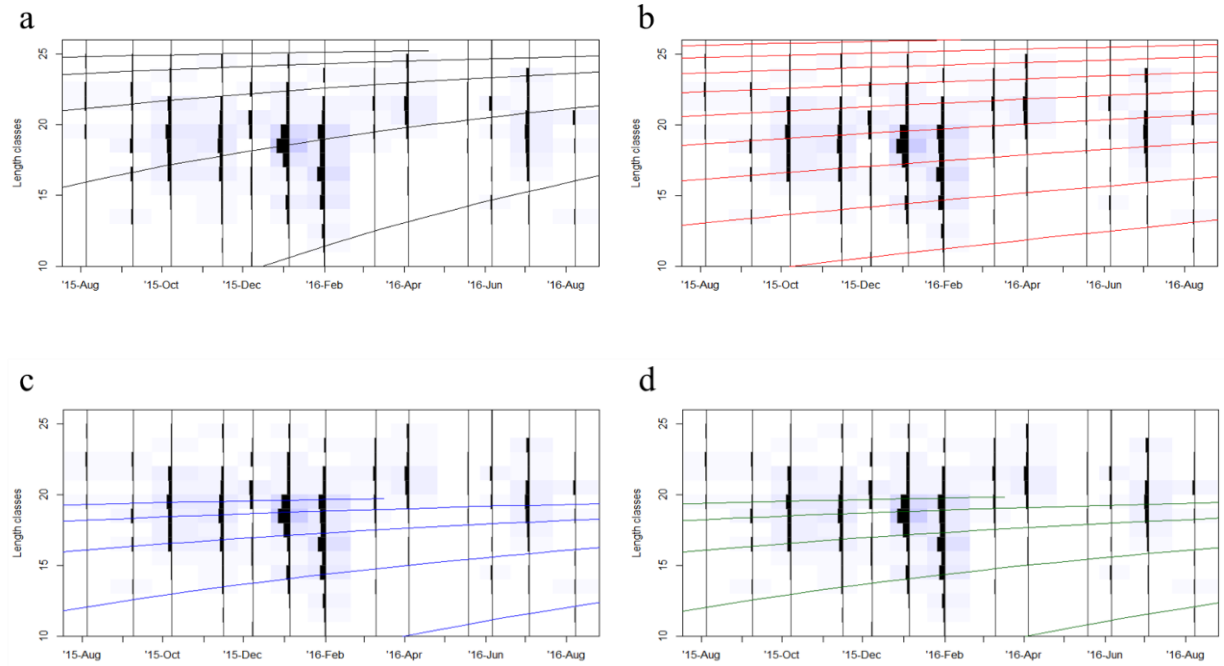


Figure B25. The growth curve of female *Bh* from TH/GT using *K* Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

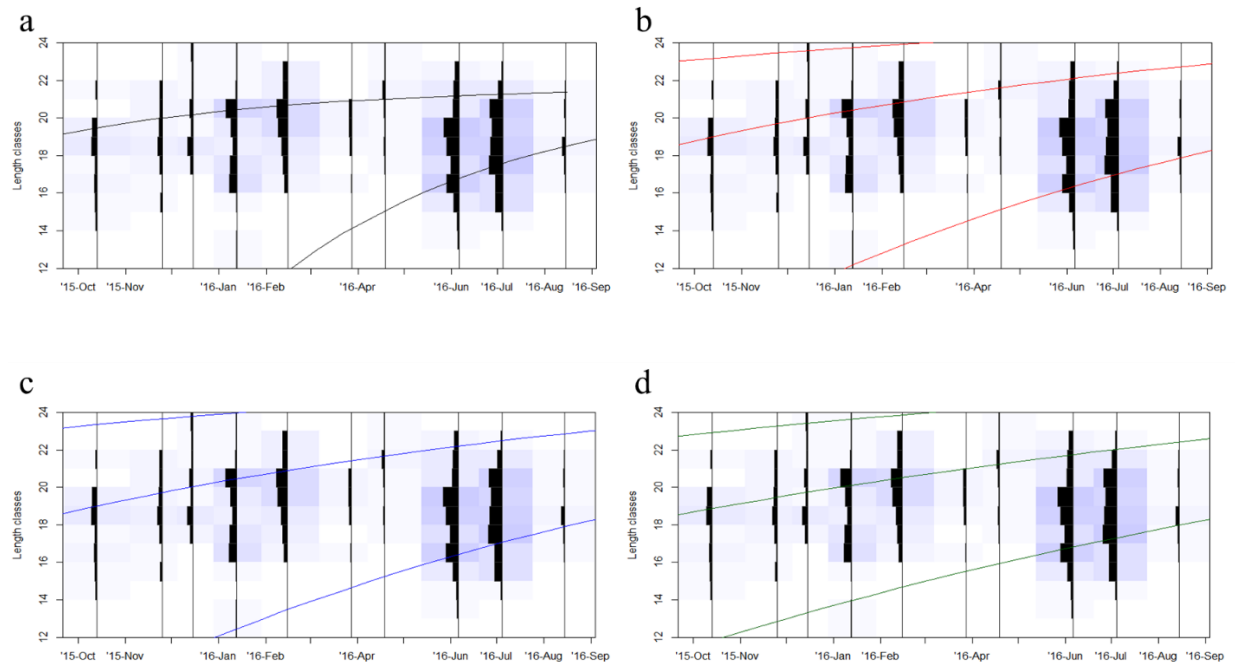


Figure B26. The growth curve of male *Bh* from TH/AM using *K* Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

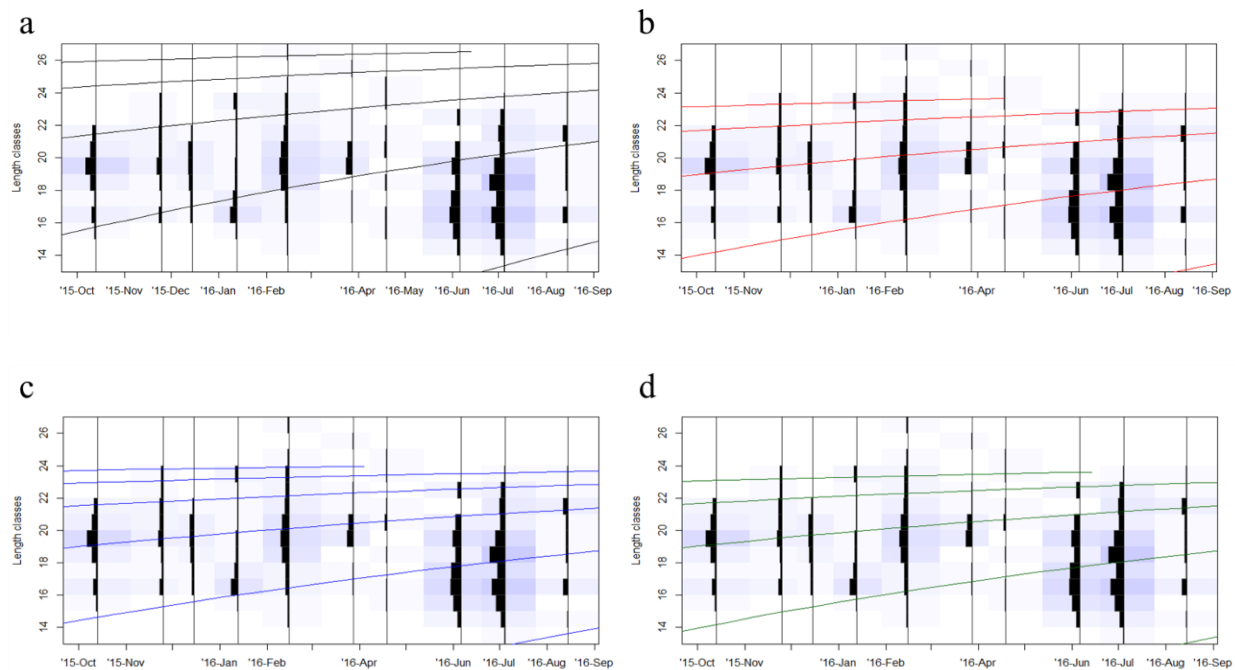


Figure B27. The growth curve of female *Bh* from TH/AM using *K* Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

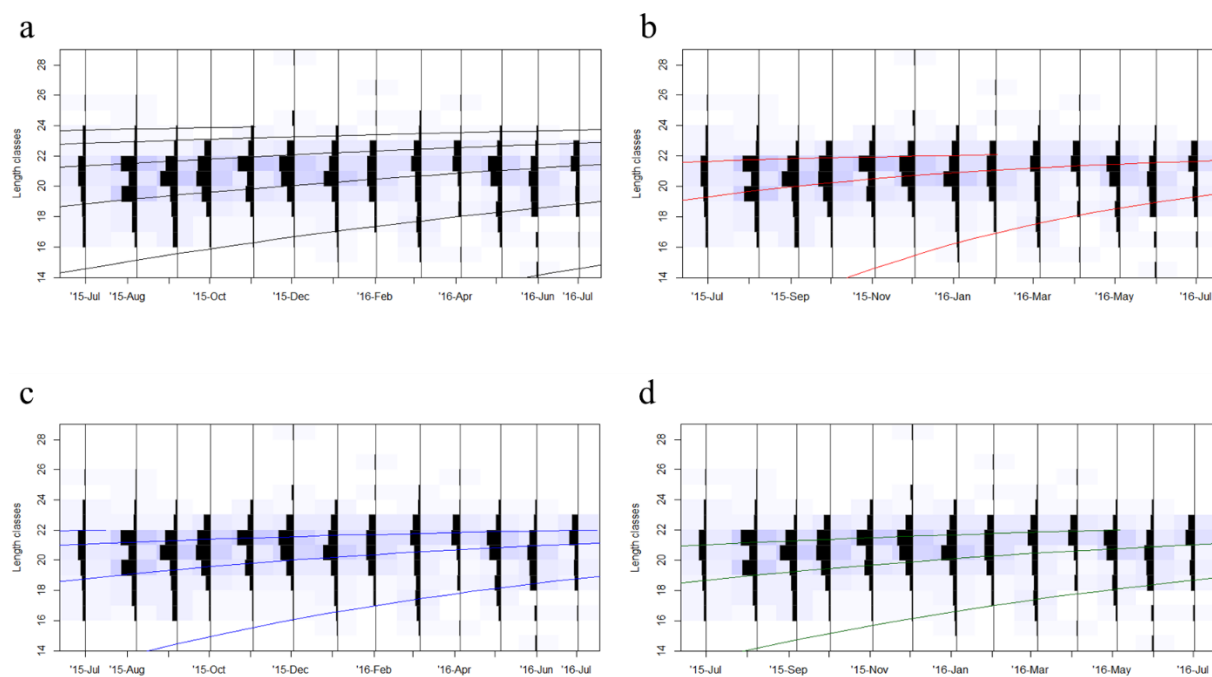


Figure B28. The growth curve of male *Bh* from ML/AM using *K* Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

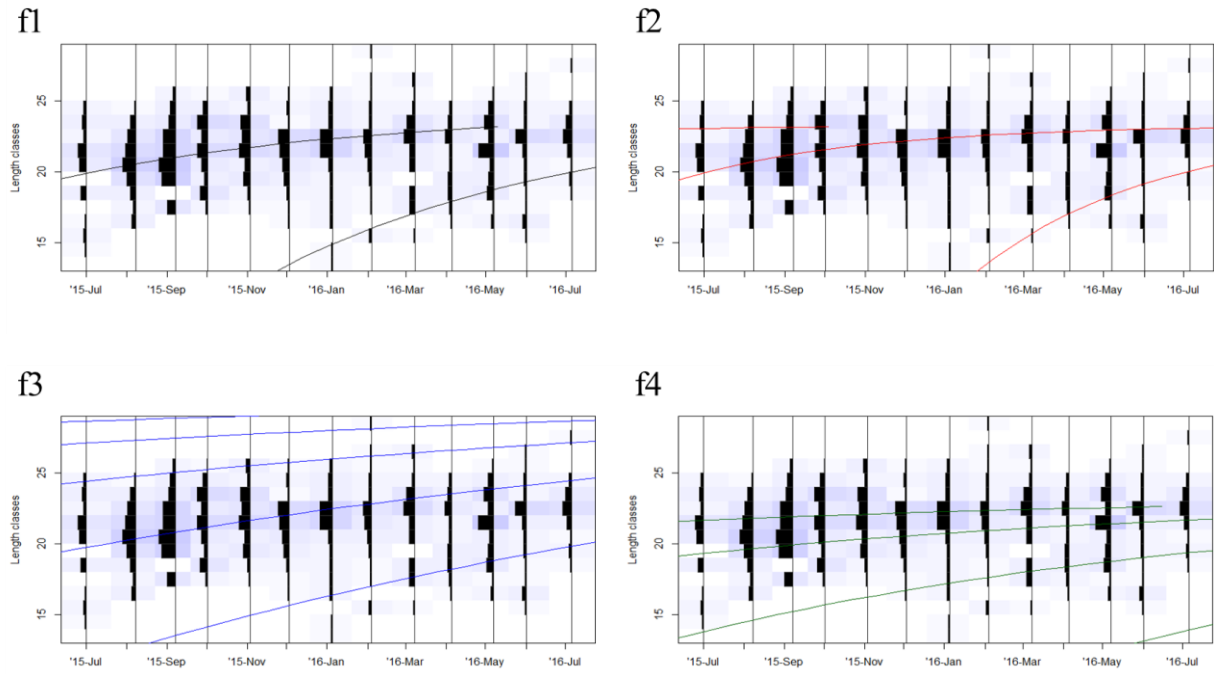


Figure B29. The growth curve of female *Bh* from ML/AM using *K* Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

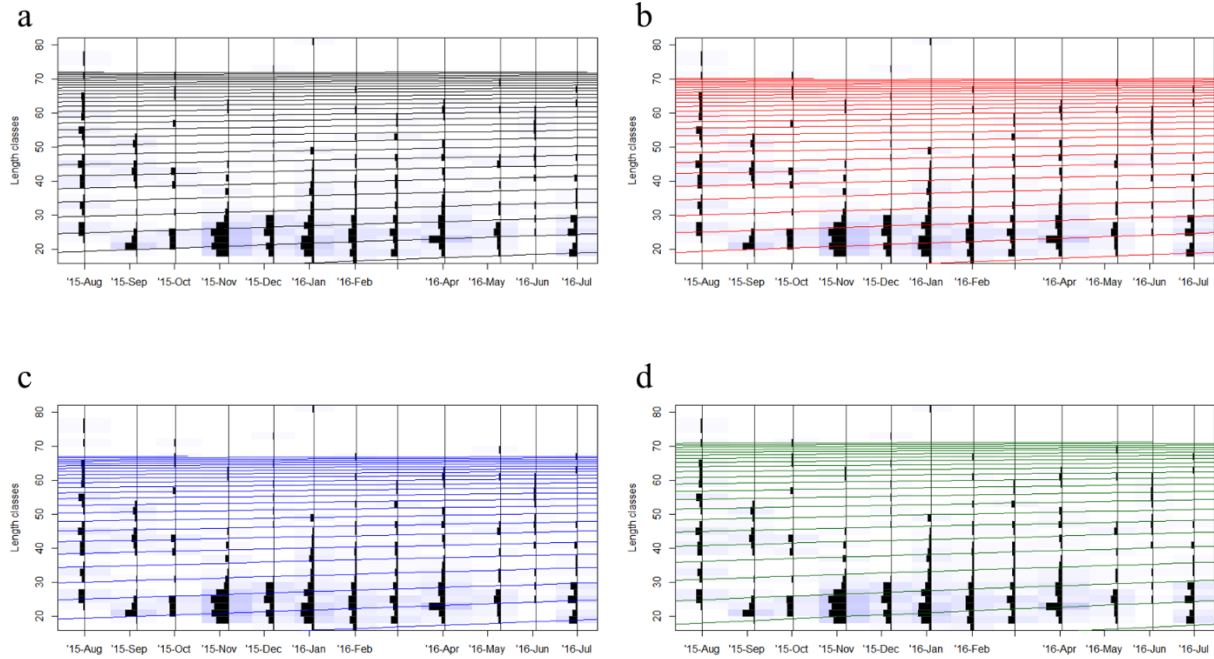


Figure B30. The growth curve of *Mg* from ML/SC using *K* Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

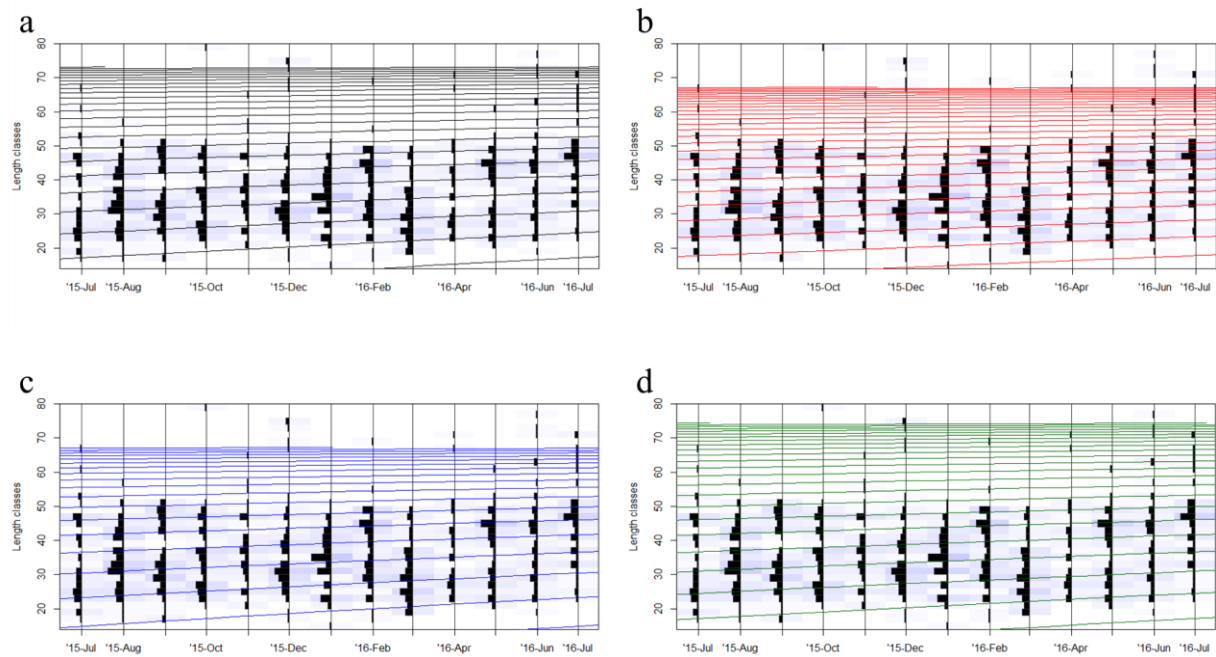


Figure B31. The growth curve of male *Mg* from ML/AM using *K* Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

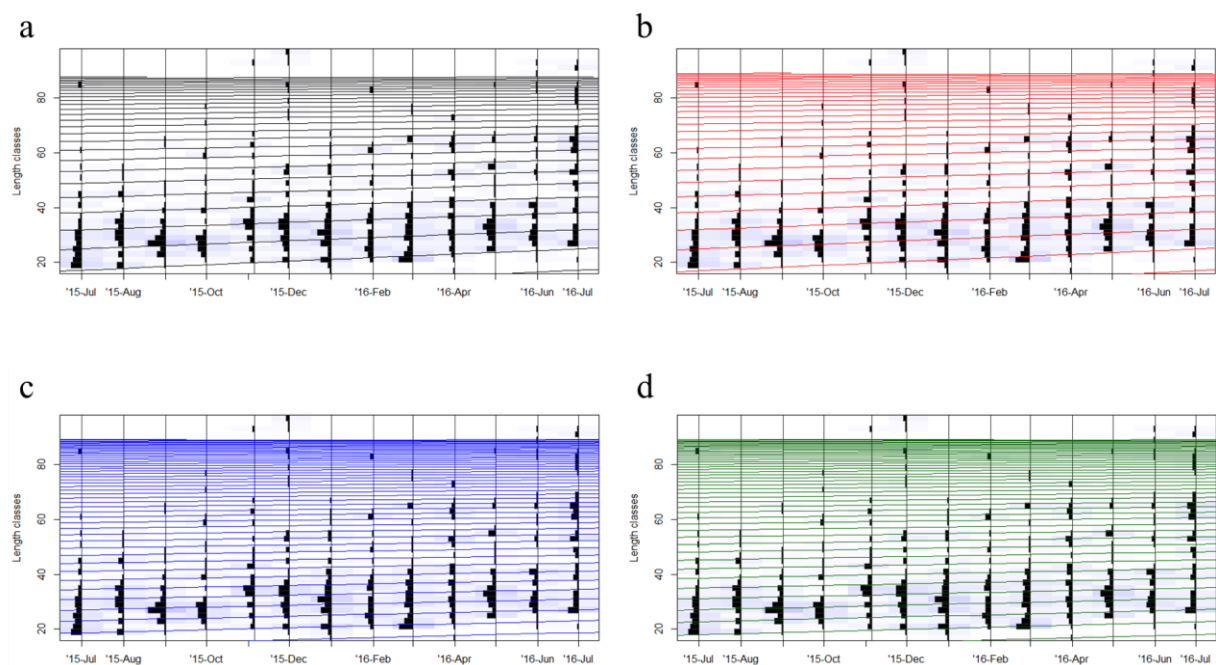


Figure B32. The growth curve of female *Mg* from ML/AM using *K* Scan (a), RSA (b), ELEFAN_SA (c), and ELEFAN_GA (d).

Appendix C: Growth parameters comparison of selected species and literatures

Table C1. Comparison of growth parameters between *Chiloscyllium* spp. and other related elasmobranch species.

Species	Area	Sex	L_{∞}	K	$t_{\max}$	Φ'	References
<i>Chiloscyllium punctatum</i>	CM/GT	P	75.3	0.21	14.88	3.08	This study
	TH/GT	P	93.7	0.41	7.80	3.55	
	ML/SC	P	87.12	0.25	12.70	3.28	
	ML/AM	P	86.52	0.21	15.07	3.21	
<i>C. plagiosum</i>	ML/SC	M	81.13	0.21	15.07	3.15	
		F	84.3	0.18	17.65	3.11	
<i>C. hasseltii</i>	ML/AM	P	90.34	0.33	9.69	3.42	
<i>Orectolobus ornatus</i>	Eastern	P	99.9	0.19	20	3.28	Huveneers et al. (2013)
<i>O. maculatus</i>	Australia	P	163.0	0.09	22	3.38	
<i>O. halei</i>		P	212.8	0.20	27	3.96	
<i>C. plagiosum</i>	Taiwan	M	98.4	0.21	12.5	3.31	Chen et al. (2007)
		F	93.1	0.22		3.28	
<i>Hemiscyllium halmahera</i>	Indonesia	P	81.5	0.51	ND	3.58	Jutan et al. (2018)

Remarks: The M, F, and P stand for Male, Female, and Pooled sex, respectively, and the AM, CM, GT, ML, SC, and TH were Andaman Sea, Cambodia, Gulf of Thailand, Malaysia, South China Sea, and Thailand, respectively.

Table C2. Comparison of growth parameters between *Atelomycterus marmoratus* and other related elasmobranch species.

Species	Area	Sex	L_{∞}	K	$t_{\max}$	Φ'	References
<i>Atelomycterus marmoratus</i>	TH/GT	M	54.99	0.53	5.67	3.20	This study
		F	59.05	0.52	5.83	3.26	
	ML/AM	M	63.5	0.72	4.25	3.46	
		F	56.18	0.71	4.25	3.35	
<i>Scyliorhinus canicula</i>	Mediterranean	M	49.23	0.51	ND	3.11	Amina et al. (2012)
		F	47.70	0.57	ND	3.09	
<i>Orectolobus ornatus</i>	Eastern	P	99.9	0.19	20	3.28	Huveneers et al. (2013)
<i>O. maculatus</i>	Australia	P	163.0	0.09	22	3.38	
<i>O. halei</i>		P	212.8	0.20	27	3.96	

Remarks: The M, F, and P stand for Male, Female, and Pooled sex, respectively, and AM, GT, ML, and TH were the Andaman Sea, Gulf of Thailand, Malaysia, and Thailand, respectively.

Table C3. Comparison of growth parameters between *Scoliodon laticaudus* and other related elasmobranch species.

Species	Area	Sex	L_{∞}	K	$t_{\max}$	Φ'	References
<i>Scoliodon laticaudus</i>	MY/AM	All	52.54	0.86	3.47	3.38	This study
<i>Scoliodon laticaudus</i>	India	P	75.53	0.54	5.15	3.49	Sen et al. (2019)
<i>Rhizoprionodon terraenovae</i>	USA	P	94.0	0.73	ND	3.81	Carlson and Baremore (2003)
<i>Mustelus canis</i>	USA	M	105.17	0.44	10	3.69	Conrath et al. (2002)
		F	123.57	0.29	16	3.65	

Remarks: The M, F, and P stand for Male, Female, and Pooled sex, respectively, and AM, and MY were the Andaman Sea, and Myanmar, respectively.

Table C4. Comparison of growth parameters between the *Brevitrygon heterura* and *Telatrygon zugei* with other related elasmobranch species.

Species	Area	Sex	L_{∞}	K	$t_{\max}$	Φ'	References
<i>Telatrygon zugei</i>	ML/SC	M	25.04	0.89	3.16	2.75	This study
		F	31.14	0.51	5.74	2.7	
	TH/GT	M	32.83	0.35	8.01	2.58	
		F	28.02	0.85	3.41	2.82	
<i>Brevitrygon heterura</i>	ML/AM	P	30.01	1.00	2.82	2.95	
	TH/GT	M	23.80	0.64	4.36	2.53	
		F	29.40	0.21	12.89	2.26	
	ML/AM	M	24.90	0.53	5.30	2.58	
		F	30.77	0.55	4.97	2.72	
	TH/AM	M	26.79	0.82	3.24	2.77	
		F	24.67	0.59	4.75	2.55	
	Colombia	M	15.50	0.65	8	2.19	
<i>Urotrygon rogersi</i>		F	20.10	0.22	11	1.95	Mejía-Falla et al. (2014)

Remarks: The M, F, and P stand for Male, Female, and Pooled sex, respectively, and AM, GT, ML, SC, and TH were the Andaman Sea, Gulf of Thailand, Malaysia, South China Sea, and Thailand, respectively.

Table C5. Comparison of growth parameters between the *Neotrygon kuhlii* with other related elasmobranch species.

Species	Area	Sex	L_{∞}	K	$t_{\max}$	Φ'	References
<i>Neotrygon kuhlii</i>	ML/SC	M	31.87	0.61	4.70	2.91	This study
		F	30.03	0.51	5.50	2.67	
	ML/AM	M	27.97	0.89	3.11	2.74	
		F	30.00	0.81	3.46	2.86	
	TH/AM	M	29.89	0.51	5.49	2.66	
		F	43.06	0.18	15.54	2.51	
<i>Neotrygon kuhlii</i>	Australia	M	38.52	0.20	10	2.47	Pierce and Bennett (2009)
		F	46.58	0.13	13	2.45	
<i>Neotrygon kuhlii</i>	Australia	M	43.86	0.08	10	2.19	Jacobsen and Bennett (2010)
		F	44.06	0.08	14	2.19	

Remarks: The M, F, and P stand for Male, Female, and Pooled sex, respectively, and AM, GT, ML, SC, and TH were the Andaman Sea, Gulf of Thailand, Malaysia, South China Sea, and Thailand, respectively.

Table C6. Comparison of growth parameters between *Maculabatis gerrardi* and other related elasmobranch species.

Species	Area	Sex	L_{∞}	K	$t_{\max}$	Φ'	References
<i>Maculabatis gerrardi</i>	ML/SC	P	73.60	0.11	28.27	2.77	This study
	ML/AM	M	77.97	0.13	24.07	2.89	
		F	93.86	0.06	53.22	2.71	
<i>Dasyatis pastinaca</i>	Mediterranean	P	121.50	0.09	10	3.12	Ismen (2003)
<i>Dasyatis pastinaca</i>	Aegean Sea	M	188.49	0.06	10	3.33	Yigin and Ismen (2012)
		F	119.96	0.09	16	3.11	
<i>Malacoraja senta</i>	USA	M	75.40	0.12	15	2.83	Natanson et al. (2007)
		F	69.60	0.12	14	2.76	
<i>Malacoraja senta</i>	Canada	M	57.10	0.15	23.10	2.69	McPhie and Campana (2009)
		F	64.70	0.10	34.66	2.62	

Remarks: The M, F, and P stand for Male, Female, and Pooled sex, respectively, and AM, ML, SC, and TH were the Andaman Sea, Malaysia, South China Sea, and Thailand, respectively.