Technological Management on Size-selective Catch in Tropical Tuna Purse Seine Fishery

（熱帯マグロ旋網漁業におけるサイズ選択漁獲に関わる技術管理）

Watcharapong CHUMCHUEN

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ABSTRACT

This research studied the size-selective catch by fishing gear and operation technique in tuna purse seine fishery in order to develop capture practices to avoid small-sized individuals of tropical tunas (i.e., skipjack, yellowfin and bigeye tunas) in catches, which were concerned by the tuna Regional Fishery Management Organizations (tRFMOs).

In Study I, size compositions of the three species captured by purse seine operation with fish aggregating devices (FADs) were analyzed to clarify the size distribution and proportion of small-sized individuals using data obtained by the cruises of M.V. SEAFDEC in the Eastern Indian Ocean from 1995 to 2003. Results indicated that most catch in these three species were commercial size, while a large proportion of immature yellowfin and bigeye were included.

In Study II, size compositions of the three species and selectivity curves of purse seine net calculated by a new established selectivity model were compared to assess the degree of selective capture in tuna purse seining around FADs using the same database as in Study I. It was indicated that purse seine net contributes to size selectivity, and the selectivity curve explains well the size distribution. From the results, it was concluded that exclusions of immature yellowfin and bigeye tunas in multi-species tuna purse seine fishery are difficult by the selectivity of the net.

In Study III, size-selective fishing by operation techniques was analyzed using fishing data from Thai tuna purse seiners operated in the Western Indian Ocean

during 2005-2007. Fishing operation was classified into four operation types, including free school (FS), FAD, natural log, and other floating objects. FS operation was found to be the most size-selective technique, which caught the fewest small-sized individuals, while the associated operations were less size-selective.

In Study IV, skippers' fishing strategies in operation type combinations was analyzed using the same fishing data as in Study III. Fishing strategy analysis showed that success rates represent the difficulty and differences between optimistic and actual values represent economic risk. Skipper's skills are believed to affect a skipper's fishing strategy, and specialist and generalist skippers were both identified in this analysis. FS operation holds the highest risk; however, it represents potentially high revenue fishing because of its ability to catch large-sized individuals and high-priced species. A specialist achieved high revenue by overcoming the risk of FS operation, while generalists distributed fishing efforts over operation types to avoid risks. Simulation results suggested that high- and moderate-skilled skippers can shift to FS operation with no revenue decline to respond to policies of tRFMOs, which increasingly promote FS operation.

This research suggested that size selectivity model is useful to regulate catch of small-sized individuals for resource utilization. The future study of school behaviour during the hauling procedure is needed to clarify the fish-net encounters for improving the accuracy of selectivity. FS operation is a highly recommended fishing technique for resource management.

熱帯マグロ旋網漁業におけるサイズ選択漁獲に関わる技術管理

本論文は、かつお・まぐろ類の地域漁業管理機関（tRFMOs）が懸念する、カツオ、キハダ、メバチに代表されるかつお・まぐろ類の小型個体の漁獲を回避する操業方法を検討するために、マグロ旋網漁業における漁具及び操業方法によるサイズ選択漁獲について評価した。

研究Ⅰでは、東部インド洋における流し浮き漁礁（FAD）を用いた熱帯マグロ旋網漁業における選択的漁獲を評価するために、1995-2003 年に商業網と類似の網を用いて操業試験の結果を元に、カツオ、キハダ、メバチの 3 種の漁獲物のサイズ組成を明らかにした。漁獲は商業サイズの個体から構成されるものの、キハダ、メバチの未成熟魚を多く含むことが示された。

研究Ⅱでは、研究Ⅰと同じデータを元に、カツオ、キハダ、メバチの 3 種の漁獲物のサイズ組成と、新たに開発した魚体と網目の遭遇時の保持確率に基づく施網選択性モデルを用いて計算した選択性曲線を比較した。当該漁具は片側選択性を有し、漁獲結果は商業サイズの個体を十分に選択的に保持していたが、漁獲に多く含まれるキハダ、メバチの未成熟魚の、漁具の選択性による排除は困難であると結論した。

研究Ⅲでは、西部インド洋でのタイ国マグロ施網漁船の 2005-2007 年操業資料から、操業法による選択的漁獲の可能性について分析した。素群れ操業、FAD 蝟集群操業、木付き群操業、その他の漂流物蝟集群操業のそれぞれで得られた漁獲物サイズ組成から、素群れ操業は付き物操業に比べてサイズ選択的であることが示された。

研究Ⅳでは、研究Ⅲと同じデータを元に、各船団の操業方法の組み合わせ（操業戦略）について分析した。素群れ操業は経済的リスクは大きいが潜在的操業収入は大きかった。素群れ操業成功率等で代表される技術力が操業戦略の決定要因であった。漁獲努力を多様な操業法に分散してリスクを回避しているジェネラリストがいたが、シミュレーションの結果、高・中位技術力の漁業者は、収入の減少なく素群れ操業の増加が可能であることが示された。

本研究より、漁具の選択性モデルを利用することで商業利用される漁獲小型個体の体長組成を制御できる可能性を示唆できた。操業中の網内での魚の対網行動を今後明らかにすることで、さらに選択性の精度を高められると考えられた。資源管理の観点からは、漁場での漁労長による操業手法の選択に素群れ操業を多く取り入れることが推奨されることが明らかとなった。

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ABBREVIATIONS

ANOVA	Analysis of Variance
cm	Centimeter
CPUE	Catch Per Unit Effort
DOF	Department of Fisheries (Thailand)
FAD	Fish Aggregating Device
FS	Free School
GT	Gross Tonnage
IOTC	Indian Ocean Tuna Commission
kg	Kilogram
LSD	Least Significant Difference
mm	Millimeter
NL	Natural Log
OFO	Other Floating Objects
PA	Polyamide
PE	Polyethylene
PES	Polyester
SD	Standard Deviation
SE	Standard Error
SEAFDEC	Southeast Asian Fisheries Development Center
SPSS	Statistical Package for Social Science
t	Metric Ton
TAC	Total Allowable Catch

TAE	Total Allowable Effort
tRFMO	Tuna Regional Fishery Management Organization
US$	United States Dollar
WCPFC	Western and Central Pacific Fisheries Commission

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Finally, I dedicate this research to my family for their unconditional love and understanding.

CHAPTER 1: GENERAL INTRODUCTION

Tunas belong to the Family Scombridae, consisting of about 50 species, and they are highly migratory fish with thunniform swimming behaviour that distinguishes them from most other fishes. They have widespread geographic distributions throughout the tropical, subtropical and temperate oceanic and coastal ecosystems between 45° North and South latitudes (Graham and Dickson, 2004).

Tunas are a significant source of protein food and economically important in fisheries (Pillai and Satheeshkumar, 2012), which accounted for more than 10% of the world seafood international trade ranked as second next to shrimp (Paquotte, 2003; Campling, 2012). The tuna fishery is distributed in the Pacific, Atlantic and Indian Oceans that it captures 23 stocks of the major commercial tuna species; namely, bluefin (*Thunnus orientalis*, *T. thynnus* and *T. maccoyii), albacore (T. alalunga),* bigeye (*T. obesus*), yellowfin (*T. albacores*) and skipjack (*Katsuwonus pelamis*) tunas. These species are caught by a variety of fishing gears such as pole and line, longline, troll line, gillnet and purse seine (Pillai and Satheeshkumar, 2012).

The average global catch of tunas from 2009 and 2013 was about 4.4 million t. It increased from less than 0.5 million t in the early 1950s to almost 4 million t in the late 1990s (Miyake *et al*., 2004). The increased global catch is mainly caused by the development of the tuna purse seine fishery, which captured three main tropical species (i.e., skipjack, yellowfin and bigeye tunas). Purse seine fishing took 63% of the average global catch of tunas in the above period equivalent to around 2.6 million t (ISSF, 2015).

Tuna purse seine has become an important fishing gear for commercial fishery for canneries before the 1950s (Scofield, 1951). Catches of small-sized individuals of the three species have increased historically together with the development of fishing techniques. These techniques can be categorized into free school (FS) and associated schools (tuna school associated with a natural or artificial floating object) operations (Misund *et al.*, 2002). In this research, associated school operations were categorized into fish aggregating device (FAD), natural log (NL) and other floating objects (OFO) operations. An FAD is an artificial floating object deployed by fishers (IOTC, 2012). An NL is a floating log or trunk (Davies *et al.*, 2014a). An OFO can be various type of flotsams, such as marine debris (Dagorn *et al.*, 2013), hawsers, crates, or old nets (Cayré *et al.*, 1993).

FS operation was the main fishing technique for catching tuna in the purse seine fishery from the mid-1940s to the mid-1950s (Orange *et al.*, 1957), though associated operations were also carried out even in these early times (Inoue, 1959). In the Indian Ocean, fishers started attaching radio buoys to floating objects and tracking them in the 1980s, which increased tuna production. FS operation was, however, still the main fishing technique, accounting for 80% of the total number of operations even in 1985 (Lopez *et al.*, 2014). The fishing technique was further developed as fishers created and distributed FADs over the various fishing grounds. The development of FAD fishing and buoy technology helped fishers to reduce searching time and decrease the number of unsuccessful operations (Murillas-Maza *et al.*, 2013). This resulted in an increasing number of associated operations. In 2009, use of associated operations increased to account for 75% of all operations in this fishery (Lopez *et al.*, 2014). This resulted in high catch rates of small-sized individuals of the concerned species because the associated operations were catching immature yellowfin and bigeye tunas (Taquet *et al*., 2007). A large amount of catches of immature tunas subsequently induced declines of their spawning stocks.

Consequently, the tRFMOs began to adopt policies to force and guide tuna purse seiners to catch tuna more selectively toward the goal of sustainable resource utilization. Policies included time-area closure, total allowable catch (TAC), total allowable effort (TAE) and discard ban (Chan *et al*., 2014). Therefore, selective methods are needed to capture tuna by purse seine for two main goals: to reduce unmarketable size of tunas and to reduce immature yellowfin and bigeye tunas (Hall and Roman, 2013). The main objective of this research was to study the size selective catch in the tropical tuna purse seine fishery, including size selectivity of purse seine net and fishing technique by operation type. The feasibility of improvement on the size selectivity from both fishing gear and fishing technique in purse seine fishing was evaluated and considered to be adapted for purse seiners in terms of commercial and management purposes.

The theoretical framework of this research was specified in Chapter 2 which composed of two main parts: (1) development of size selectivity model of purse seine net and feasibility of exclusion of immature tunas through gear selectivity; and (2) proving size-selective catch by fishing operation technique and adoptability of the selective technique for purse seiners.

This research was divided into four sub-studies to support the framework for achieving the main objective. In Study I (Chapter 3), the size distribution and proportion of small-sized individuals of the three species in the catches from purse seine fishing around FADs were clarified. In Study II (Chapter 4), size-selective catch by fishing gear for the three species in the purse seine fishery was developed through the size selectivity model, and evaluated the catch from a survey net on the exclusion of immature tunas. In Study III (Chapter 5), size-selective catch by fishing operation technique for the three species in the purse seine fishery was clarified by identifying the differences in catches among operation types, and found the selective operation type, which is the most effective to address in the concerned fishery. In Study IV (Chapter 6), fishing strategy analysis and simulation of revenue from fishing strategies with the most selective fishing technique was proposed in a model of fishing strategy on how to combine fishing operation types, including the most selective fishing technique. The simulation results might encourage skippers to shift their fishing efforts to the most selective fishing technique. The adoptability of the most selective fishing technique for skippers was evaluated with a concern on revenue decline from fishing strategies.

The results of this research are hoped to contribute to the improvement of catching practices particularly for the tuna purse seine fishery, and eventually influence the development of the world tuna fisheries for resource utilization and management.

CHAPTER 2: THEORETICAL FRAMEWORK

2.1 Development of size selectivity model of purse seine net and feasibility of exclusion of unmarketable size and immature tunas through gear selectivity

The purse seine net is a very large fishing gear composed of many net panels with different mesh sizes, thus its experiment on size selectivity is difficult to carry out in the field. Due to the same reason, it is not realistic to clarify selectivity curves of individual purse seine nets with a variety of designs experimentally for application of selectivity to resource use management.

This research proposed a new selectivity model of the purse seine net developed from assumptions on the underwater shape of an encircled net and fish shapes. The net shape is assumed to be a hemisphere after the pursing process, and a cross section of fish body at maximum body girth is assumed to be an ellipse. The model was based on the calculation from parameters of purse seine net and fish body. The model considered the probability of exclusion on the basis of the capture process in purse seining, focusing on a simulation of encountering between sizes and shapes of both meshes in a net and maximum body section of the three species. A survey purse seine net (similar to Thai commercial tuna purse seine nets) was used to clarify the size distribution in catches of the three species, to verify the selectivity curves obtained from the model and to evaluate the exclusion of unmarketable size and immature fish for the three species.

2.2 Proving size-selective catch by fishing operation technique and adoptability of size-selective fishing technique for purse seiners

Fishing operation techniques in the purse seine fishery are also considered as a way to selectively capture the three species, and it may be combined with size selectivity of the net for tuna resource management. Since catch results from tuna purse seine fishing have shown that the catches from FS operation were composed of larger fish than the catches from associated operations; however, the differences in species and size compositions related to canneries (the main sector in the supply chain of tuna purse seine fishing) are needed to clarify among operation techniques. Catch data from commercial tuna purse seiners were used to clarify the catch compositions and prove the most size-selective fishing technique.

The size-selective fishing technique was considered on adoptability for skippers' fishing strategies. A simulation of revenue from different skippers' fishing strategies and skills levels was conducted on the basis of a fishing strategy model, including combinations of operation techniques, species and size compositions, CPUEs, fish prices and skipper's skills represented by success rates. The simulation result was determined to evaluate the adoptability of the size-selective fishing technique with a concern on the revenue decline for skippers.

CHAPTER 3: SIZE DISTRIBUTION IN THREE TROPICAL TUNA SPECIES CAUGHT BY PURSE SEINE FISHERY AROUND FISH AGGREGATING DEVICES (FADs)

3.1 Introduction

Several decades ago, FADs were introduced to tuna purse seine fishery as mentioned in Chapter 1. The use of FADs accelerated exploitation of tuna resources and increased tuna production (Hallier, 1995; Miyake *et al*., 2004). In the Indian Ocean, the catch of tuna dramatically increased from 87,123 t in 1985 to 241,754 t in 1990 (Pillai and Satheeshkumar, 2012) as a result of FADs fishing, and it became the most important technical element for the success of tuna fishing operations in this ocean (SEAFDEC/TD, 2004).

However, mixed schools of tunas around a FAD include small-sized individuals of yellowfin and bigeye tunas (Taquet *et al*., 2007). The caught fish smaller than the industrially marketable size, 40 cm (Fonteneau *et al*., 2013), and the cannery accepted size, 1.8 kg (Désurmont and Chapman, 2000) are considered as bycatch in terms of the commercial purposes, because they have little or no economic value (Hall, 1996). For the three species, the bycatch of small-sized individuals are immature (Hallier, 1995), where fork lengths at the matured stage are 43 cm for skipjack, 85 cm for yellowfin and 102 cm for bigeye tunas (ISSF, 2015). Small-sized bycatch of tunas has not been a great interest to canneries in the past, but presently they are being processed (Hallier, 1995). Consequently, catching immature yellowfin and bigeye tunas around FADs in the purse seine fishery has become a concern (IOTC, 2013).

In this chapter, a series of survey fishing was conducted with a purse seine net which was similar to general commercial nets. The objective of this chapter was to clarify the size distribution and the proportion of small-sized individuals of the three species caught in the vicinity of FADs.

3.2 Materials and Methods

3.2.1 Tuna purse seine fishery data

Survey fishing was conducted by the research vessel of the Southeast Asian Fisheries Development Center (SEAFDEC), M.V. SEAFDEC, from 1995 to 2003 in the Eastern Indian Ocean, encompassing the area from 10°S to 2°N and 78°E to 98°E (Fig. 3.1).

The operations of survey fishing were conducted around commercial FADs. There were various designs of FADs; however, the main structures were iron pipe frame, bamboo poles, old net webbing and sinkers (Chanrachkij and Loon-on, 2003).

Fish samples were randomly scooped from the bunt while the net was being hauled. Tuna samples were identified for species. Body weights of all the samples were weighed by a spring balance, and their fork lengths were measured by a measuring board. The catches amounts of the three species from each operation were obtained from fishing logbooks.

3.2.2 Data analysis

Since the amount of samples from an operation was fixed as one scoop, the sampling rate q for each operation was calculated from quantities of samples Q_s and catches Q_c in weight from the operation as:

$$q = \frac{Q_s}{Q_c} \qquad \text{...... (3.1)}$$

In the analysis, the numbers n_c of catches in size classes of a species from each operation were estimated from the number n_s of the concerned samples as:

$$n_c = \frac{n_s}{q} \qquad \text{...... (3.2)}$$

Frequency distributions of fork length and body weight in numbers from estimated catches of the three species were plotted in histograms with the class interval decided following the Sturges rule (Sturges, 1926).

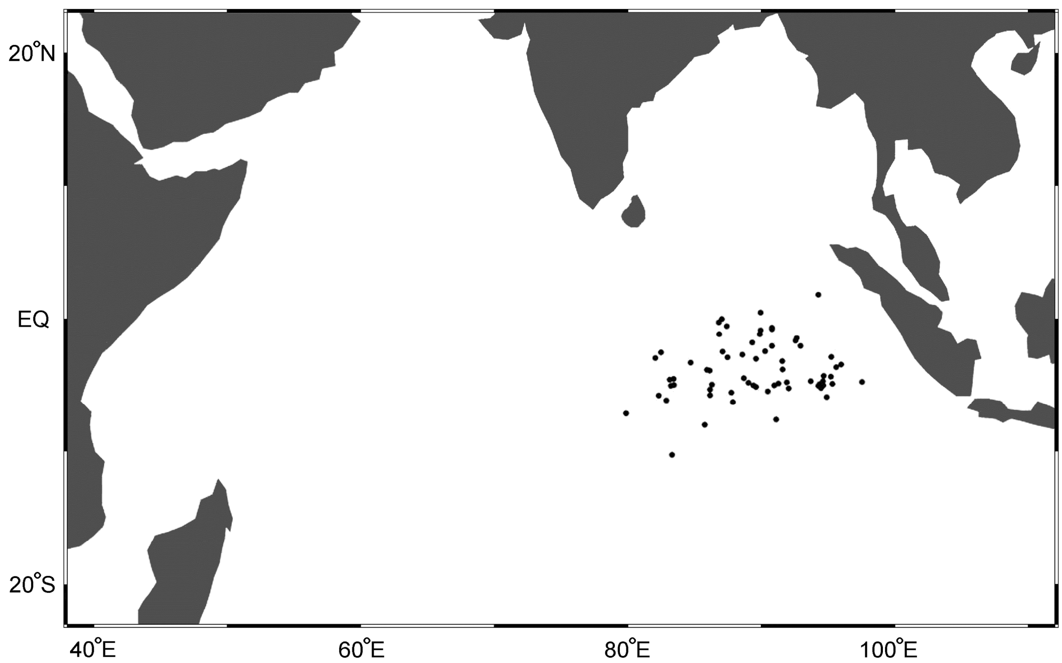

Figure 3.1 Locations of survey tuna purse seine operations by M.V. SEAFDEC

3.3 Results

The numbers of tuna samples obtained from 65 operations around FADs in the survey fishing are shown in Table 3.1. The sampling rate q ranged from 0.2% to 100% of the catch, and the average sampling rate q was 12.7±22.4 % (mean ± SD). Skipjack, yellowfin and bigeye tunas were major tuna species in the samples, of which skipjack tuna was caught in the highest numbers.

Table 3.1 Fishing data from survey operations obtained by M.V. SEAFDEC

Species	n
Skipjack tuna	9,669
Yellowfin tuna	2,031
Bigeye tuna	1,814
Total	13,514

3.3.1 Size distribution in catches

Figure 3.2 shows the histograms of fork length and body weight distributions in the catches estimated by Equations (3.1) and (3.2) of the three species. The sizes where catch distributions sharply declined on the left side of the modes in the histograms appeared at similar sizes (around 42 ~ 46 cm and 1 ~ 2 kg for the three species). The class of the smallest size in fork length appeared between the classes of 23 cm and 31 cm, while that in body weight appeared at the same class as 0.5 kg for the three species. These finding meant that the small-sized individuals of the three species in the catches were the similar size. The correlation of similar sizes of fish seeing sharp declines with the results of these smallest-sized classes in the three species were hardly due to size distributions in the populations of the three species, since they are species of different sizes biologically. From these results, it was conjectured that the size distributions of the catches were affected by the selectivity of the fishing gear.

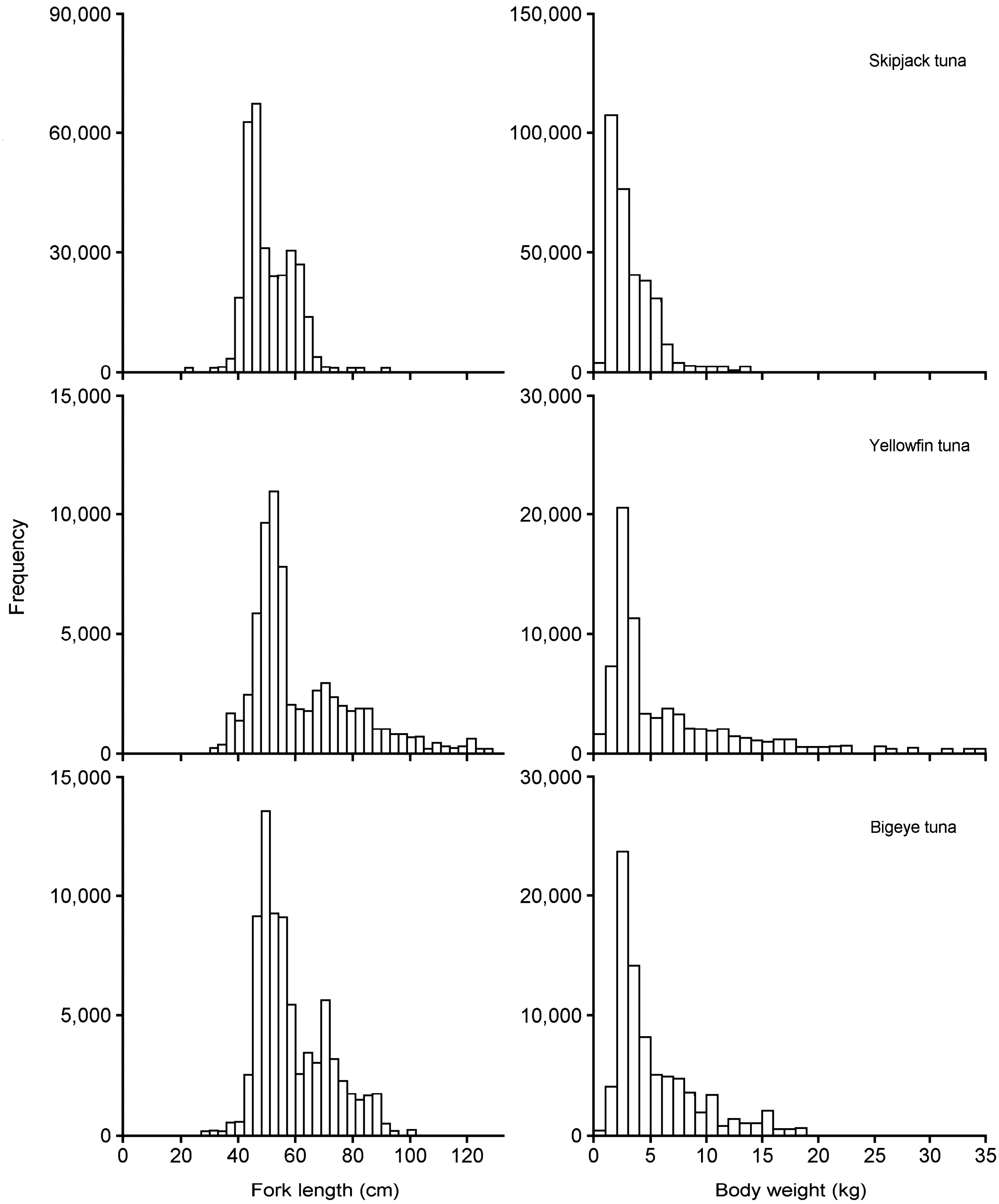

Figure 3.2 Fork length and body weight distributions of skipjack, yellowfin and bigeye tunas in catches

3.3.2 Marketable size proportions in catches

The criteria of marketable sizes for the three species were adopted from Fonteneau *et al*. (2013), and Désurmont and Chapman (2000). The industrially marketable size for the three species is 40 cm and the cannery accepted size is 1.8 kg. The proportions in number of the estimated catches that were smaller than the industrially marketable size were small in the three species (Fig. 3.3). The proportions of catches that were smaller than the cannery accepted size were less than 10% in yellowfin and bigeye tunas, and about 21% in skipjack tuna (Fig. 3.4). The reason why the proportions in the latter analysis were higher than those in the former analysis was that the criterion of cannery accepted size is larger than the industrially marketable size, because the latter category includes a variety of miscellaneous utilizations. The results indicated that most catches were marketable, and commercial sizes of fish were selectively caught.

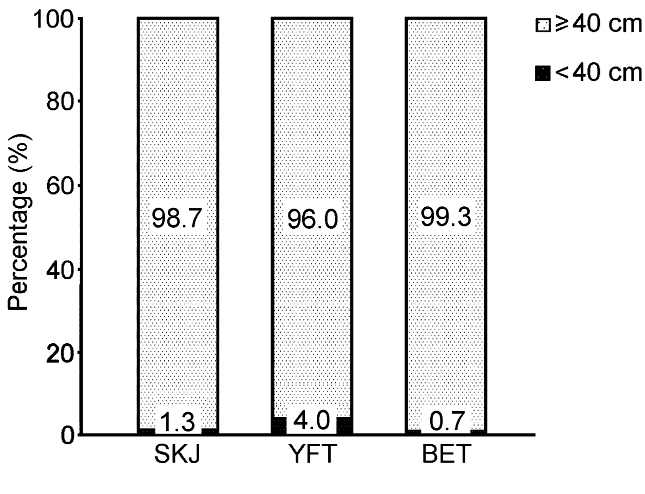

Figure 3.3 Proportion in numbers of industrially marketable size of skipjack (SKJ), yellowfin (YFT) and bigeye (BET) tunas in catches

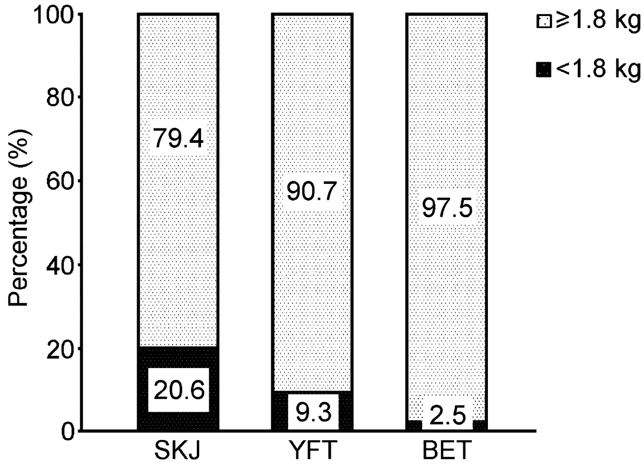

Figure 3.4 Proportion in numbers of cannery accepted size of skipjack (SKJ), yellowfin (YFT) and bigeye (BET) tunas in catches

3.3.3 Maturity size proportions in catches

Sizes of the estimated catches were compared to the maturity sizes in the three species, where the maturity sizes were adopted from ISSF (2015). For these species, fork lengths at their matured stage are 43 cm for skipjack, 85 cm for yellowfin and 102 cm for bigeye tunas. There were immature fish of the three species in the catches (Fig. 3.5). All of bigeye and 90% of yellowfin tunas in the catches were immature fish, while immature skipjack tuna accounted for less than 9%. Despite the selective catches suitable for commercial purposes as indicated above, the selectivity did not satisfactorily avoid catches of immature fish particularly for bigeye and yellowfin tunas.

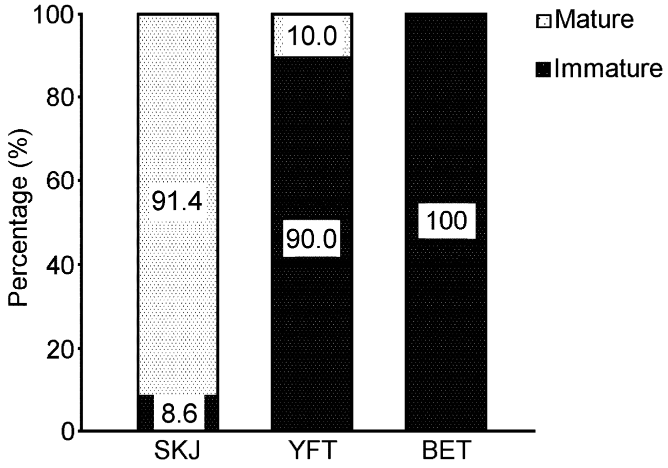

Figure 3.5 Proportion in numbers of maturity size of skipjack (SKJ), yellowfin (YFT) and bigeye (BET) tunas in catches

The analysis is summarized as the catches of the three species from the survey net were acceptable for commercial purposes, because most of the catches were commercial sizes and bycatch of small-sized individuals which were unmarketable size were small proportions. However, high proportion of immature yellowfin and bigeye tunas were involved in the catches.

3.4 Discussion

Most estimated catches of the three species caught by the survey net were larger than the cannery accepted size. The remainder can be sold in other industrial markets. In this study, the proportions of bycatch in the three species with the sizes smaller than industrially marketable size were minor. Fonteneau *et al.* (2013) reported that a total bycatch rate in FAD fishing was about 5–10% of the retained tuna catch, and bycatch on small-sized individuals of tunas in the retained tuna catch in the Indian Ocean was 3.2%. The bycatch proportions from the survey net were smaller than the above rate. These proportions are conjectured to be a very small quantity in comparison to their population. Therefore, the proportions of bycatch caught by the survey net should be acceptable as a bycatch quota in tuna purse seine fishing, and the catches by the survey net were acceptable for commercial purposes.

The proportions of immature tunas in the catch found in this study were relatively low for skipjack tuna, but very high for yellowfin and bigeye tunas, which are the species of concern on stock management (IOTC, 2013). Catches of the three species around FADs are mainly comprised of small-sized individuals (Langley *et al.*, 2009). In FADs fishery, skipjack tuna was the main species, and it was caught together with immature yellowfin and bigeye tunas (ISSF, 2015; Fonteneau *et al.*, 2000).

Through the survey fishing results, the similar distributions of particularly small-sized individuals in the three species of differently sized tunas suggested that the purse seine net selectively caught fish. However, the catch cannot prove the selectivity of the net, since the catch is the result of multiplication of the encountered population of fish and selectivity. Therefore, a selectivity study is needed to assess the catch.

In conclusion, catches from FADs operation included small-sized individuals of the three species. The catches from the survey net around FADs were composed of a high proportion of marketable sized fish; however, immature fish of the three species, particularly yellowfin and bigeye tunas were included. The size distribution of the catches was presumed to be a result of purse seine net selectivity. Therefore, a study on size selectivity of the purse seine net is needed to develop the size-selective catch by fishing gear in the purse seine fishery.

CHAPTER 4: SIZE-SELECTIVE CATCH BY FISHING GEAR FOR THREE TUNA SPECIES AROUND FISH AGGREGATING DEVICES (FADs)

4.1 Introduction

Since the catches from purse seine fishing were composed of small-sized individuals of the three species or bycatches. In some cases, bycatch tunas are discarded at sea thus wasting the resources because of economical reasons; however, there is a measure of "No discards" or "Discard ban" to reduce the discarding (Hall *et al*., 2000; Uhlmann *et al*., 2014). This measure pressured fishers to fish selectively by developing selective fishing technology, and by avoiding periods, areas or times which result in high bycatch (Hall *et al*., 2000; Catchpole *et al*., 2005).

Consequently, a selectivity study on tuna purse seine is needed to determine the appropriate net design required to exclude the small-sized bycatch. Purse seine selectivity has, however, not been well documented. There were few researches which tried to estimate the selectivity of the purse seine (Prado, 1992), where only the selective functions by the mesh perimeter (Sukramongkol, 2002) and by the mesh opening at the bunt part (Resma *et al*., 2006) were studied.

The selectivity of a whole purse seine net is still not reported. One of the reasons of the limited advances in this research field is that the purse seine net is a very large fishing gear and experimental verification of a theoretical model is difficult. Due to the same reason, it is not realistic to clarify selectivity curves of individual purse seine nets with a variety of designs experimentally for application of selectivity to resource use management.

In this chapter, a new model was developed for estimating the purse seine selectivity to consider if exclusion of small-sized individuals of the three species by size selectivity of the purse seine net is possible or not. The model considers the probability of the exclusion on the basis of the capture process in purse seine fishing, focusing on a simulation of encountering between sizes and shapes of meshes in a net, and sizes and shapes of maximum body sections of the three species. The objectives of this chapter were to develop the size selectivity model and to evaluate the catch from a sampling net (similar to general commercial purse seine nets) on the exclusion of unmarketable size and immature tunas.

4.2. Materials and Methods

4.2.1 Tuna purse seine fishery data

Fishing data were obtained from the survey fishing as same as the data set in the Chapter 3. The survey purse seine net in this study was 1,267 m long and 231 m deep (Fig. 4.1 and Table 4.1). Most major panels of the body were composed of 210 mm and 105 mm meshes, together with 105 mm in the major parts of the wings, and 90 mm in the bunt and the end of a wing adjacent to the bunt (SEAFDEC/TD, 2004). It was similar to Thai tuna commercial purse seine nets composed of 210 mm mesh in the body and wing and 90 mm in the bunt (Yingyuad and Chanrachkij. 2010).

In order to verify the selectivity curves with catches for the three species, the maximum body girths of the three species were measured by a measuring tape from some samples used in Chapter 3.

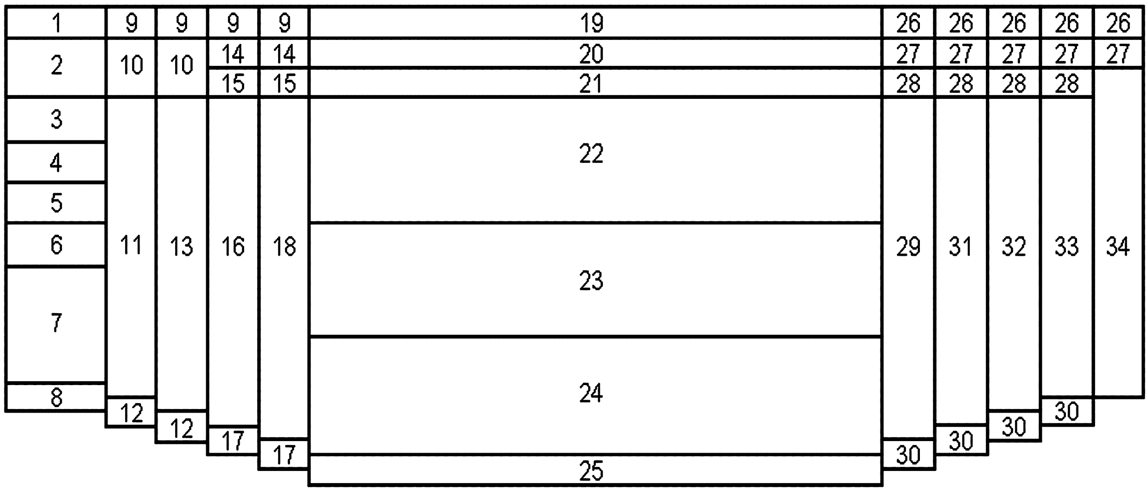

Figure 4.1 Plan of tuna purse seine net used for survey by M.V. SEAFDEC

Table 4.1 Specifications of panels of tuna purse seine net used for survey by M.V. SEAFDEC

Part	Number	Material	Mesh size (mm)	Thickness (Ply)	Length (m)	Hanging ratio (%)	Mesh depth (no. of meshes)
Bunt	1	PE	150	320	105.0	70	5
	2	PA	90	224	105.0	70	200
	3	PA	90	180	105.0	70	200
	4	PA	90	160	105.0	70	200
	5	PA	90	140	105.0	70	200
	6	PA	90	120	105.0	70	300
	7	PA	90	90	105.0	70	800
	8	PA	90	120	105.0	70	100
Wing	9	PE	150	320	54.0	72	5
	10	PA	90	120	54.0	72	200
	11	PA	90	60	54.0	72	1,800
	12	PA	90	90	54.0	72	100
	13	PA	90	60	54.0	72	1,900
	14	PA	105	90	54.0	72	100
	15	PA	105	90	54.0	72	100
	16	PA	105	40	54.0	72	1,700
	17	PA	105	90	54.0	72	100
	18	PA	105	40	54.0	72	1,800
Body	19	PE	150	320	610.5	74	5
	20	PA	105	90	610.5	74	100
	21	PA	105	60	610.5	74	100
	22	PA	105	60	610.5	74	500
	23	PES	210	60	610.5	74	300
	24	PES	210	70	610.5	74	400
	25	PA	105	90	610.5	74	100
Wing	26	PE	150	320	55.5	74	5
	27	PA	105	90	55.5	74	100
	28	PA	105	60	55.5	74	100
	29	PA	105	40	55.5	74	1,800
	30	PA	105	90	55.5	74	100
	31	PA	105	40	55.5	74	1,700
	32	PA	105	40	55.5	74	1,600
	33	PA	105	60	55.5	74	1,500
	34	PA	105	90	55.5	74	1,600

(PA: Polyamide, PE: Polyethylene and PES: Polyester)

4.2.2 Body section measurement

The body width, height and girth of fish at the section of maximum body girth were necessary for calculating size selectivity of a purse seine net, because the selectivity analysis in this study was conducted by assuming the maximum body section as an ellipse, and the fish sizes were represented by the maximum body girths. The data obtained from survey fishing did not provide the body widths and heights; therefore, the morphological data such as body width, height and girth were obtained from specimens of skipjack and yellowfin tunas which were measured by a measuring board and a measuring tape at the fishing port in Kagoshima, Japan. The data of bigeye tuna were acquired from Sakai *et al.* (2007) because there was no bigeye tuna specimen at the fishing port. This data set, however, lacked details on the maximum body girth.

4.2.3 Size selectivity model

The size selectivity of the survey net was estimated on the basis of a simplified model as follows. It was assumed that the size selectivity of a purse seine net functions after completion of pursing procedure and confinement of fishes within the net. The underwater shape of the survey net during the above process is approximated as a hemisphere with pleats, in other words, the horizontal length of the net on the foot-rope end was assumed to be zero. The length of meridian of the above-mentioned hemisphere was 772 m because the meridian found according to the model below was 193 m, while the length of the net’s float line was 1,267 m.

Therefore, the float line is not fully stretched and net webbing is ruffled. It was assumed, however, that the length of a meridian of the ruffled part can be approximated with that of the hemisphere's meridian (Fig. 4.2). Since the twine in the net webbing is assumed to be rigid when a sufficiently large tensile force works during the pursing and hauling procedure, the shapes of diamonds representing the meshes are presumed to be unchanged when fish encounter them with their swimming force.

The length of meridian of the presumed hemisphere is determined by the sum of the heights of meshes, which change along the meridian. The breadth $2B$ and height $2H$ of a diamond of each mesh of planar net webbing is easily calculated on the basis of a mesh size M and hanging ratio (Fig. 4.3). The underwater breadth $2B'$ and heights $2H'$ of a diamond mesh located at the position v distant from the float-line end along a meridian of the hemispherical net can be calculated with Equations (4.1) and (4.2);

$$B' = B \cdot \cos\left(\frac{\pi}{2} \cdot \frac{v}{V}\right) \qquad \text{...... (4.1)}$$

$$H' = \sqrt{\left(\frac{M}{2}\right)^2 - B'^2} \qquad \text{...... (4.2)}$$

where V is the length of the meridian and v is the distance between the float-line end and a certain mesh on the meridian. V is given by Equation (4.3) and v_J at the J-th mesh is given by Equation (4.4).

$$V = 2\sum_j H_j \qquad \text{...... (4.3)}$$

$$v_J = 2\sum_{j}^{J} H_j \qquad \text{…… (4.4)}$$

The maximum body section of a fish was represented by an ellipse with the width 2*b*, height 2*h* and girth *G*, which is approximated by Equation (4.5) (Fig. 4.3);

$$G = \pi \cdot (b+h) \cdot \left(1 + \frac{3 \cdot C}{10 + \sqrt{4 - 3 \cdot C}}\right) \qquad \text{...... (4.5)}$$

$$C = \left(\frac{b-h}{b+h}\right)^2 \qquad \text{...... (4.6)}$$

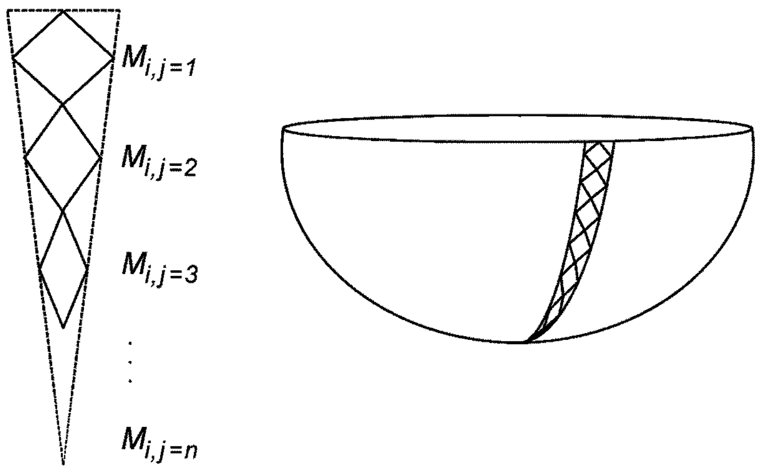

Figure 4.2 Model of net and mesh shapes after pursing procedure

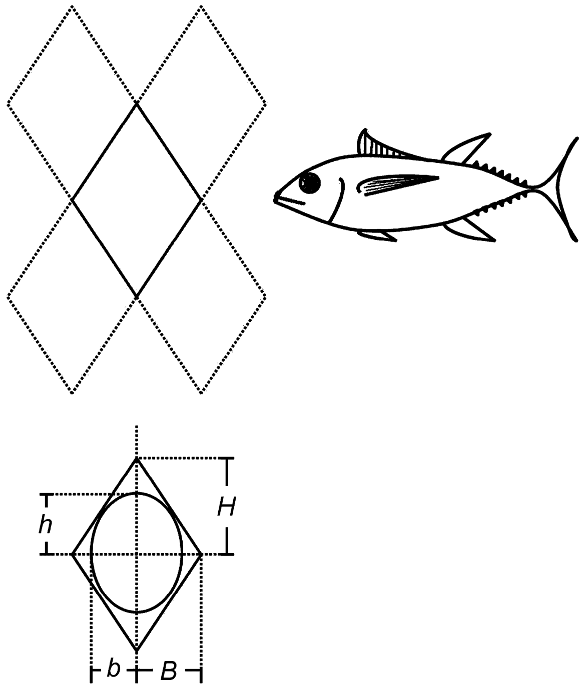

Figure 4.3 Diagram of mesh and section of maximum body girth as parameters in selectivity calculation

Size selection by a purse seine net is determined by the probabilities of a fish of a certain maximum body section that can pass through meshes of which the sizes and shapes are different from one position to another in a net. Only one case was taken into consideration, where both of the longitudinal axes of a diamond represented a mesh and an ellipse represented a maximum body section of a fish are parallel. This corresponds to the relative positions where a fish can most easily pass through a mesh. On the basis of the early assumption where a mesh shape is unchanged by encountering of fish, the above phenomenon can be simplified into a model to consider if a line segment of a diamond and an ellipse (of which centers are both located at the origin of a coordinate system) will overlap or not. An ellipse and a line segment in the second quadrant of a diamond are represented by Equations (4.7) and (4.8), respectively;

$$\begin{cases} \left(\frac{x}{b}\right)^2 + \left(\frac{y}{h}\right)^2 = 1 & \text{...... (4.7)} \\ y = \frac{H}{B}x + H & \text{...... (4.8)} \end{cases}$$

Positive solutions for the discrimination equation of the simultaneous Equations (4.7) and (4.8) show that the ellipse overlaps with the diamond geometrically where the maximum body section of a fish exceeds the mesh diamond, thus the fish is retained. On the other hand, negative solutions show that the ellipse does not overlap with the diamond where the maximum body section of fish falls in the mesh diamond, thus the fish is excluded.

The probability of retention of fish for a mesh located at a horizontally *i*-th and vertically *j*-th position is denoted as p_{ij}, which is either 1 or 0 (retained or excluded). The area A_{ij} of *i*-th and *j*-th positioned mesh is $2B'_{ij} \cdot H'_{ij}$, where $2B'_{ij}$ and $2H'_{ij}$ are the breadth and height of the *i*-th and *j*-th positioned mesh. Under an assumption that fish encounter the whole area of the net webbing with a uniform probability, the probability R of whether fish are retained in the net is described as Equation (4.9);

$$R = \frac{\sum_i \sum_j A_{ij} \cdot p_{ij}}{\sum_i \sum_j A_{ij}} \quad \text{...... (4.9)}$$

When fish-net encountering occurs for multiple times (Fig 4.4), the same mechanism as the above works for fish retained at the previous encounter; therefore, the probability S of fish retention is described as Equation (4.10) (Matsuoka, 2008);

$$S = R^{k} \qquad ...... (4.10)$$

where k is the number of encounters.

The probability S changes according to a set of b and h, and hence, G changes; therefore, it is denoted as S (G), which is the selectivity of the concerned net with a parameter of G. This parameter, which gives 0%, 50% and 100% selectivity, was denoted as G_0, G_{50} and G_{100}, respectively.

The length V of a meridian and the distance v from the float line to a certain mesh are not given a priori in the above model. In the actual calculation, they were approximated asymptotically as follows. Firstly, the breadth $2B$ and height $2H$ of each mesh in a planar net were calculated from the mesh size M and hanging ratio, and then V and v were calculated by Equations (4.3) and (4.4). Secondly, assuming that the underwater breadth $2B'$ of a mesh positioned at v changes according to a ratio of $(V - v)/V$, the underwater heights $2H'$ of the meshes were calculated, and new values of V and v were obtained accordingly. Thirdly, the new V and v were applied to Equations (4.1) and (4.2) to recalculate $2B'$ and $2H'$, and the V and v were also recalculated. This process means that asymptotic approximations of mesh shapes were carried out as consequently assuming the underwater form of the net as a cylinder first, then a cone, and finally a hemisphere (Fig. 4.5). Theoretically, the above recalculations of $2B'$ and $2H'$ by Equations (4.1) and (4.2) need repetition until V converges; however, a test calculation of repetition made no difference greater than 1% in comparison to the V values from the first calculation in the third step.

Therefore, it was decided to adopt the results from the above three steps as solutions in sufficient convergence.

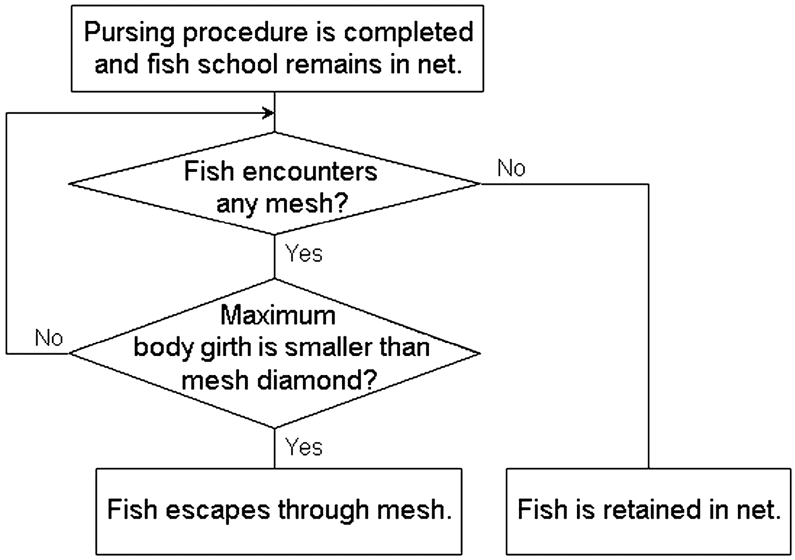

Figure 4.4 Flowchart of fish retention and exclusion process in purse seine fishing, where selectivity function of purse seine net starts after completion of pursing procedure

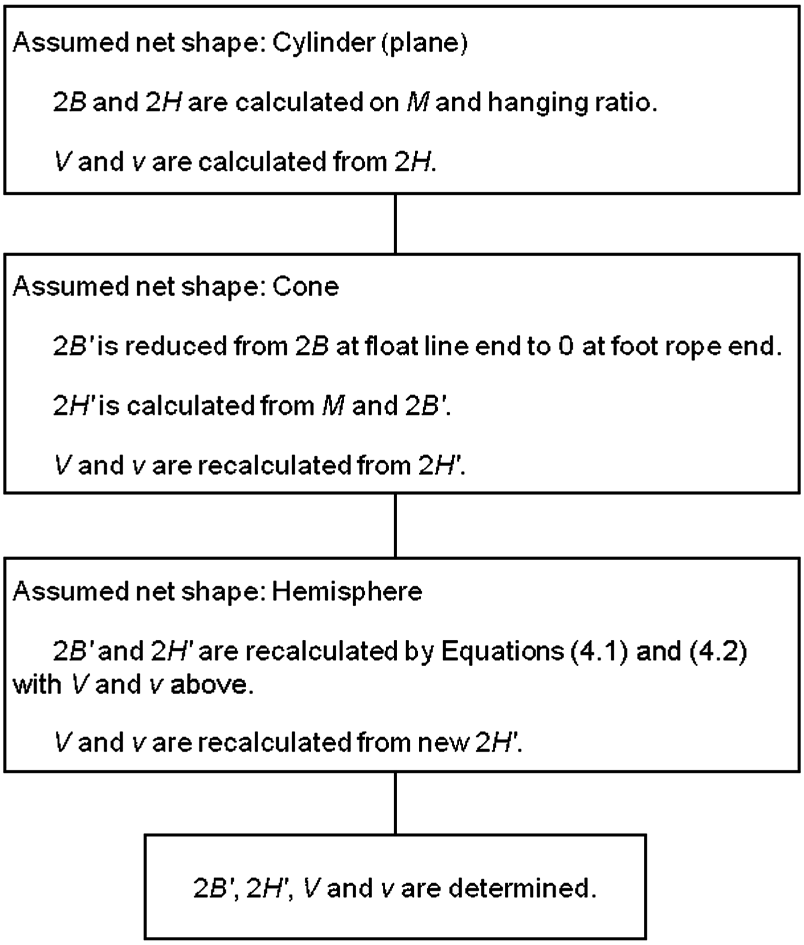

Figure 4.5 Steps in estimation of mesh shapes in survey net: $2B'$ and $2H'$ are breadth and height of each mesh included in survey net, V is distance between float-line and foot-rope along net panel, and v is distance from float-line to certain mesh along net panel. M is mesh size, and $2B$ and $2H$ are breadth and height of mesh in planar net.

4.3 Results

Numbers of the girth data samples for the three species, which measured from some samples obtained from the survey fishing data in Chapter 3, are shown in Table 4.2.

Table 4.2 Number of samples for maximum body girth data obtained from M.V. SEAFDEC

Species	n
Skipjack tuna	4,720
Yellowfin tuna	1,251
Bigeye tuna	1,070
Total	7,041

4.3.1 Fish morphology and estimation of girth

In order to apply the new selectivity model of purse seine gear proposed in this study to the survey net and the three species, the girth-measurement data were analyzed first. The numbers of fish morphology specimens are shown in Table 4.3. Body widths $2b$ of skipjack, yellowfin and bigeye tunas were 6.1 – 9.1 cm, 8.0 – 10.6 cm and 19.0 – 35.0 cm, respectively, and their body heights $2h$ were 8.4 – 13.9 cm, 12.3 – 15.3 cm and 26.0 – 50.0 cm, respectively. The average of h-b ratios were 1.50 ± 0.22 for skipjack, 1.50 ± 0.04 for yellowfin and 1.37 ± 0.22 for bigeye tunas. There was no correlation between the h-b ratios and body lengths in the three species ($P > 0.05$). It indicated that the h-b ratios are not changed even though the body lengths represented the fish sizes are changed from small to large. From these results, it was assumed that the body section shapes of each species changed symmetrically.

Relationships between measured girths and girths of the ellipse calculated on b and h were analyzed by simple linear regression. Due to the lack of girth data for bigeye tuna, as explained in the Materials and Methods section, only the relationships of skipjack and yellowfin tunas are shown (Fig. 4.6). The relationships had high correlation coefficients (r) for both skipjack ($r = 0.988$, $P < 0.001$) and yellowfin (r = 0.964, P < 0.001) tunas. The results indicated that the calculated girths can represent actual girths.

Table 4.3 Number of morphology specimens used to find relationship between body width 2b and height 2h and for calculating ellipse

Species	*n*
Skipjack tuna	51
Yellowfin tuna	30
Bigeye tuna	22*
Total	103

*Sakai *et al*. (2007)

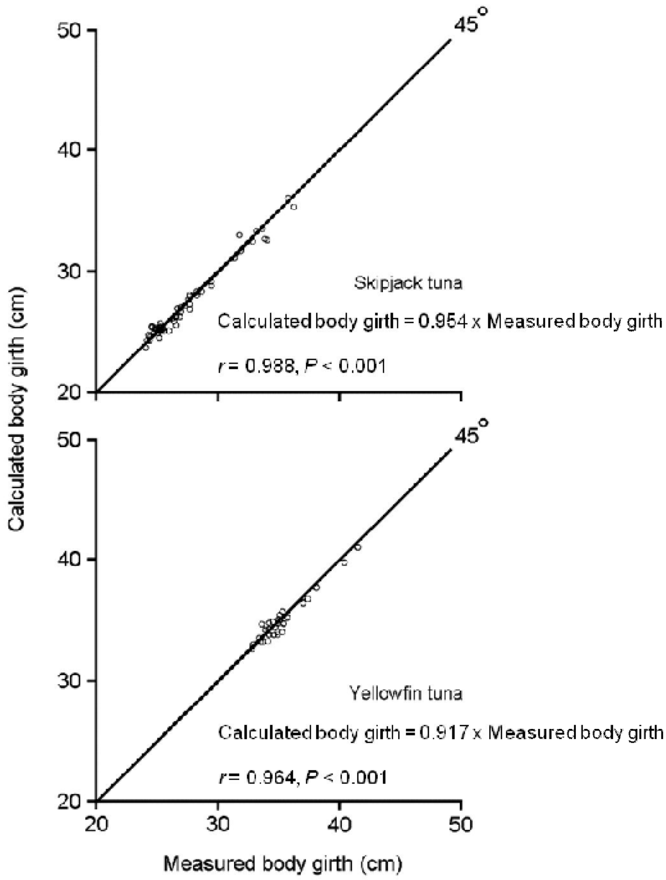

Figure 4.6 Relationship between measured girths and girths calculated on ellipse: 45° line indicates the 1:1 ratio between two girths

4.3.2 Estimation of size selectivity

The ratios between *b* and *h* obtained from the above analysis were applied to calculate the selectivity of the survey net for the three species. Fig. 4.7 shows the selectivity curves obtained from different times of fish-net encounters, which were one-tail curves with a knuckle in the slope and an edge at the shoulder of a curve regardless of species and encounter times. The selectivity curves shifted downwards with increasing encounter times. G_0 and G_{50} values increased as a result of the curves shifted downwards, though changes in G_0 and G_{50} values became small with increasing encounter times. The G_{100} values did not change for any encountering times. This is attributed to the fact that when the maximum body section of a fish is greater than the diamond of the largest meshes in the net, the fish cannot pass through any mesh regardless of encounter times.

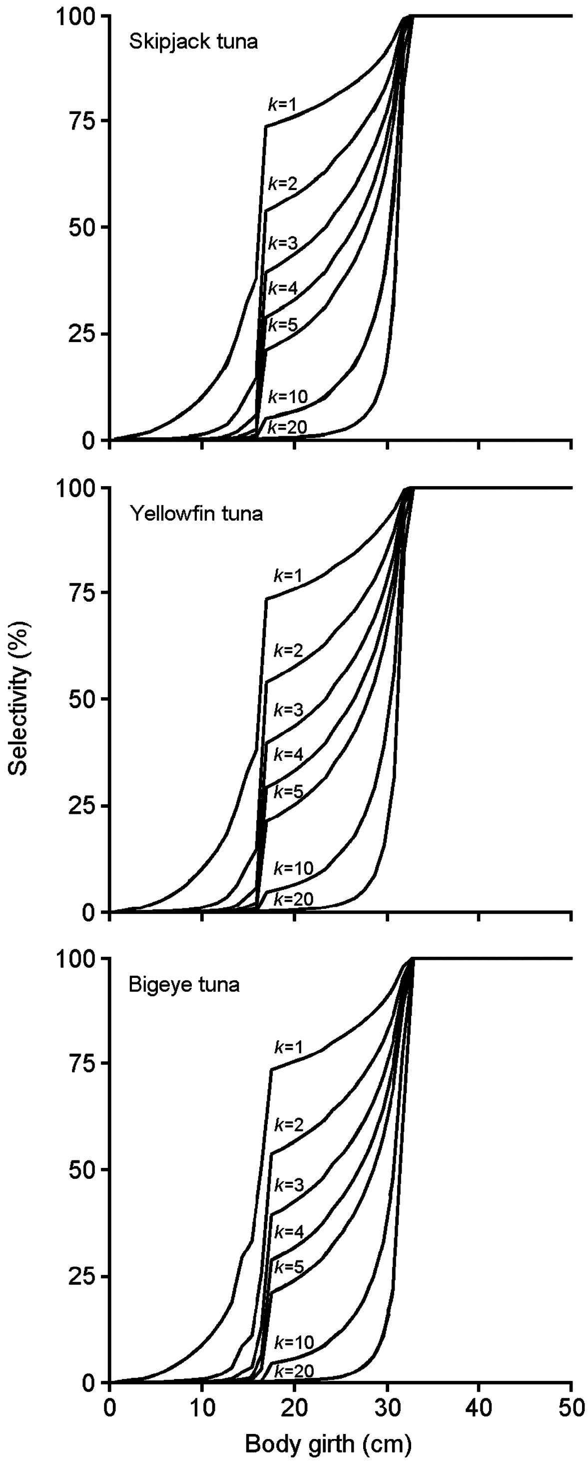

Figure 4.7 Selectivity curves for three tuna species simulated by fish-net encounter for 1 to 20 times, where *k* is the number of encounters

Assuming that the size at sharp decline between classes on the left side of the mode in the histogram of the maximum body girth was due to the sharp drop around G_{50} in the selectivity curve, the sharp decline in the histogram was compared to the G_{50}. The class of the smallest size was compared to the G_0 value. This comparison was made for the cases of 1 to 20 encounters for the three species. Sharp decline appeared at 28 cm, 30 cm and 31 cm for skipjack, yellowfin and bigeye tunas, respectively. Due to the low resolution of the sharp decline size, the G_{50} values were searched in the range of the sharp decline size ±1 cm (Table 4.4). The size at sharp decline for skipjack tuna fell between G_{50} values at 5th and 6th encounters. The size for yellowfin tuna fell between G_{50} values at the 7th and 13th encounters. The size for bigeye tuna fell among G_{50} values at cases of encounters more than eight times. From these results, the curves from the 8th encounter were adopted as the cases that provide G_{50} values relatively closer to the sharp decline sizes for the three species. G_0 found from the curves at the 8th time an encounter occurred was 16.4 cm for all the three species, which was slightly smaller than classes of the smallest sizes in the catch (i.e., 19.0 cm, 17.0 cm and 19.0 cm for the three species, respectively). G_{100} found for the three species was 31.9 cm, 31.9 cm, and 32.2 cm, respectively.

Table 4.4 Sizes at sharp decline between classes of three tuna species and G_{50} values obtained from selectivity curves

Species	Sizes at sharp decline between classes (cm)	G_{50} values at encountering time (cm)								
		5th time	6th time	7th time	8th time	9th time	10th time	11th time	12th time	13th time
Skipjack tuna	28.0	28.0	28.9	29.5	29.9	30.2	30.4	30.6	30.7	30.8
Yellowfin tuna	30.0	28.0	28.9	29.5	29.9	30.2	30.4	30.6	30.7	30.8
Bigeye tuna	31.0	28.5	29.3	29.9	30.3	30.6	30.8	30.9	31.1	31.2

Comparisons of frequency distributions of the maximum body girth in the estimated catches and the selectivity curve from the 8th time of encounter for the three species as shown in Fig. 4.8. There was a good correspondence between the sizes at sharp decline in frequency on the left side of the mode and G_{50} values for the three species, though G_{50} was about one class larger than the size at sharp decline for skipjack tuna. G_{100} appeared around the peaks of histograms for all the three species. It was conjectured that the declining frequency distributions of fish smaller than the peaks was attributed to the selective capture of fish smaller than G_{100}. G_0 was not very far from the classes of the smallest size.

According to these results, the stimulatory calculation of selectivity on the new model in this study adequately represents the selectivity of the survey net, though encountering times remained unknown. This insufficiency was assumed to reflect the slight differences between the G_{50} and the sharp decline size for skipjack tuna when a uniform encountering time was adopted for the three species—despite the fact that encountering time, which gave good correspondence between the two values for skipjack tuna, was different from the other two species, as explained in the previous paragraph.

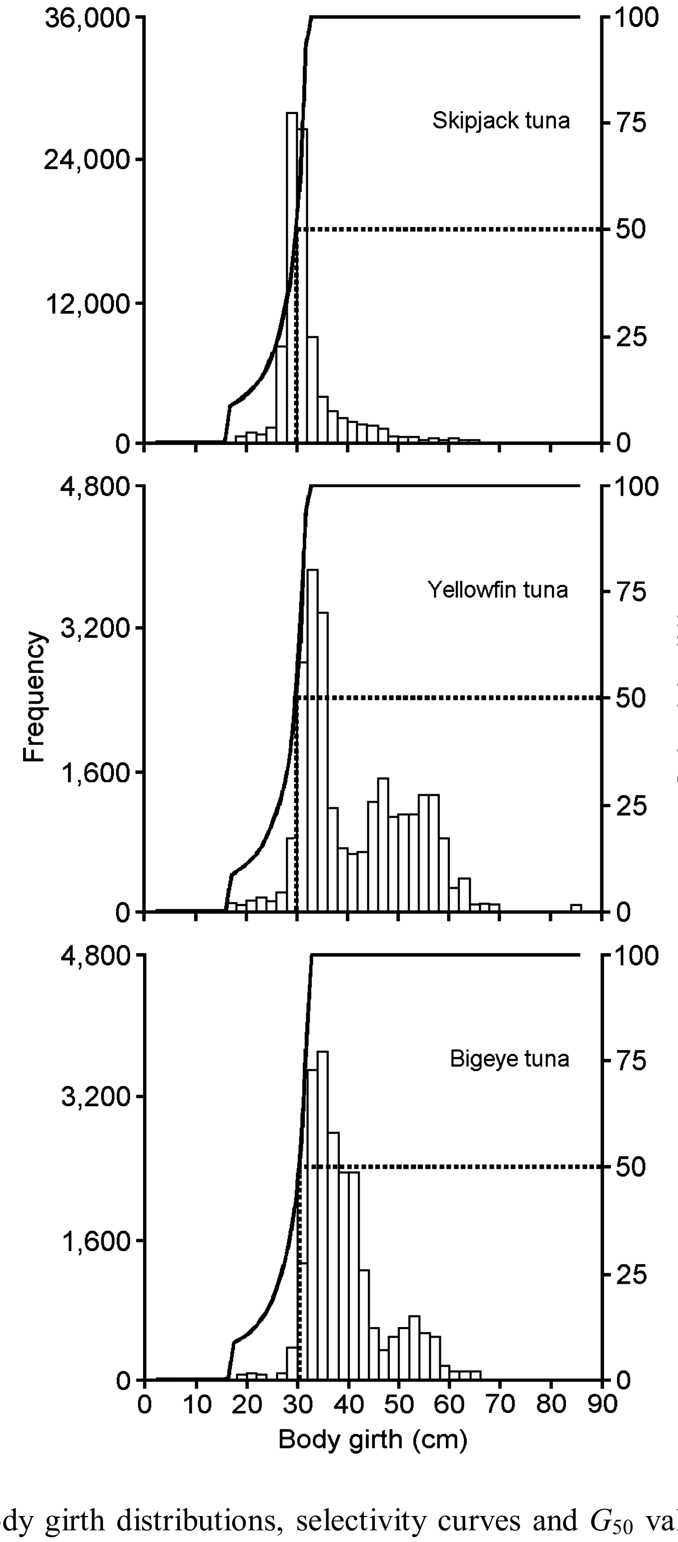

Figure 4.8 Body girth distributions, selectivity curves and G_{50} values at the time of the 8th encounter with a survey net in three tuna species

4.3.3 L_{50} and W_{50} values of three tuna species

In order to convert G_{50} to L_{50} and W_{50}, the girth-length and girth-weight relationships for the three species were analyzed using 7,041 samples, of which girths were measured from the samples shown in Table 3.1 (Fig. 4.9). The relationship equations and correlation coefficients are shown in Table 4.5. It was considered that the equations can be used for the conversion because of the high correlations.

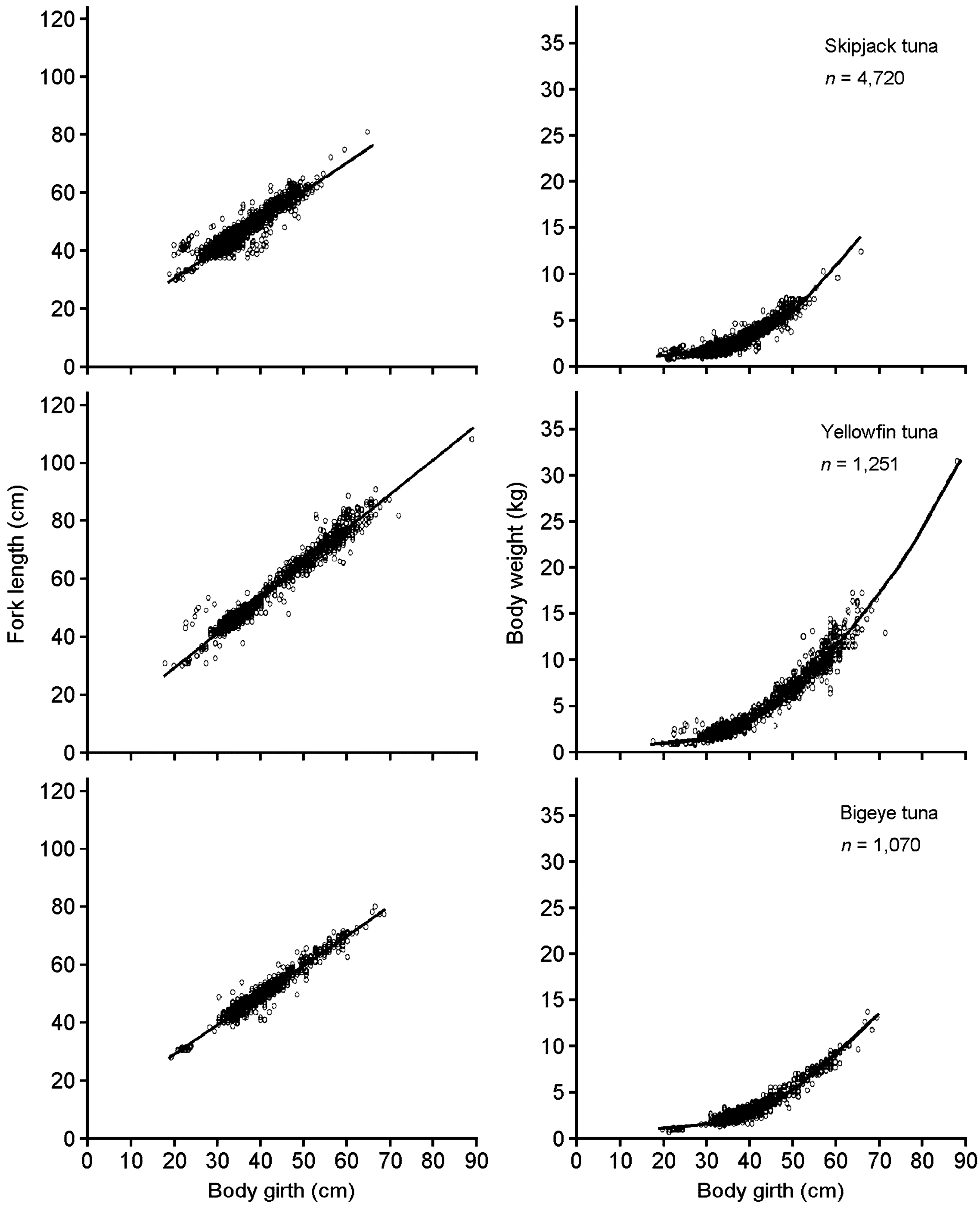

Figure 4.9 Relationships of girth-length and girth-weight of skipjack, yellowfin and bigeye tunas

Table 4.5 Relationship equations of girth-length and girth-weight for skipjack, yellowfin and bigeye tunas

Relationship	Species	Equation	r	P value
Girth-length	Skipjack tuna	$L = 1.23G + 8.43$	0.930	<0.001
	Yellowfin tuna	$L = 1.46G + 1.67$	0.982	<0.001
	Bigeye tuna	$L = 1.25G + 5.16$	0.974	<0.001
Girth-weight	Skipjack tuna	$W = 1.89 \times 10^{-4} G^{2.70}$	0.899	<0.001
	Yellowfin tuna	$W = 1.02 \times 10^{-4} G^{2.88}$	0.969	<0.001
	Bigeye tuna	$W = 1.64 \times 10^{-4} G^{2.78}$	0.953	<0.001

Table 4.6 shows the L_{50} and W_{50} values converted from the G_{50} values by using the obtained equations for the three species. L_{50} values of the three species were considerably larger than the industrially marketable size. W_{50} values of all the three species were the same to or larger than the cannery accepted size. The results indicated that the survey net had the capacity for size selectivity, which functioned to retain catches of the three species for the commercial purposes, especially for canneries.

Table 4.6 L_{50} and W_{50} values for skipjack, yellowfin and bigeye tunas converted from G_{50} values from the 8th encounter

Species	G_{50} (cm)	L_{50} (cm)	W_{50} (kg)
Skipjack tuna	29.9	45.2	1.8
Yellowfin tuna	29.9	45.3	1.8
Bigeye tuna	30.3	43.2	2.2

Numbers of catches with the size smaller than L_{50} and W_{50} values in the three species were measured in proportions (Fig. 4.10 and Fig. 4.11). The proportions of fish of sizes smaller than the L_{50} and W_{50} values were larger than those of industrially marketable size, shown in Figure 3.3, while similar to those of cannery accepted size, shown in Figure 3.4. These results corresponded well to the previous analysis where the 50% selectivity sizes of the survey net for the three species were similar to the cannery accepted size. The proportions of the three species with fork lengths and body weights smaller than 50% selectivity sizes were considered as bycatch or the unexpected size of fish caught through the net selectivity. The bycatches of the survey net were the high proportions from the viewpoint of cannery accepted size, particularly for skipjack tuna; however, most of them had fork length larger than 40 cm, which were acceptable in the industrial market.

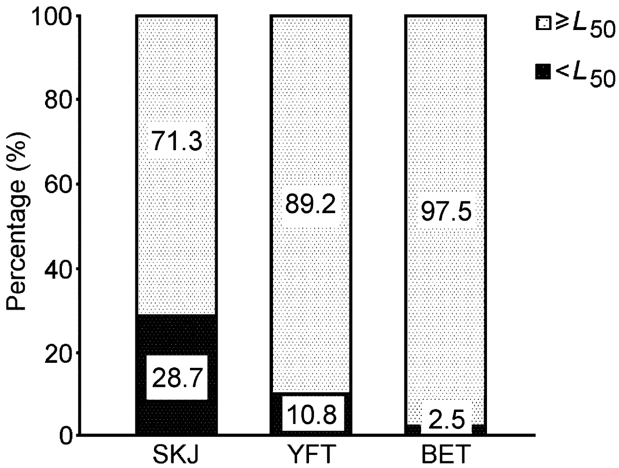

Figure 4.10 Proportion in number of skipjack (SKJ), yellowfin (YFT) and bigeye (BET) tunas in catch with sizes smaller than L_{50} in selectivity

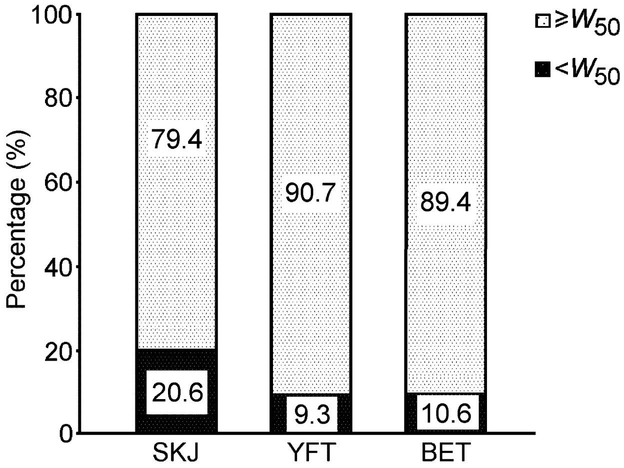

Figure 4.11 Proportion in number of skipjack (SKJ), yellowfin (YFT) and bigeye (BET) tunas in catch with sizes smaller than W_{50} in selectivity

L_{100} values for the three species were converted also from G_{100} values, and were compared to the maturity sizes of the three species (Table 4.7). The L_{100} values for yellowfin and bigeye tunas were smaller than their maturity sizes; therefore, immature yellowfin and bigeye tunas cannot be avoided even with size selectivity of the survey net.

Table 4.7 G_{100}, L_{100} and fork length L at maturity size for three tuna species

Species	G_{100} (cm)	L_{100} (cm)	L at maturity size (cm)*
Skipjack tuna	31.9	47.7	43
Yellowfin tuna	31.9	48.2	85
Bigeye tuna	32.2	45.4	102

*ISSF (2015)

The results of this study indicated that the survey net had size selectivity function, and the frequency distributions in the catches for the three species were a result of the selectivity of the net. Size selectivity of the survey net was suitable for commercial purposes that sizes at 50% selectivity for the three species were larger than the industrially marketable size. However, large proportions of immature fish in the catches were attributable to the fact that sizes at 50% selectivity for the three species as well as sizes at 100% selectivity for yellowfin and bigeye tuna were smaller than maturity sizes.

4.4 Discussion

This study proposed the size selectivity model for the whole net of purse seine. The assumptions were that the selectivity function of the purse seine net starts when the pursing procedure has finished, and fish randomly encounter the net webbing. Kim *et al*. (2008) reported that the swimming behaviour of skipjack tuna schools during purse seine operations consist of very complex movements with changes in speed and direction related to the nets or purse seiner. Tuna schools commonly keep away from an encircling net and swim through the space between wing ends or dive under the purse line and escape during the entire process of shooting and pursing a net (Kim *et al*., 2008; Hosseini *et al*., 2011; Hosseini and Ehsani, 2014). During my onboard observation on a tuna purse seiner in the Indian Ocean, a tuna school slowly swam inside the net after completion of the pursing procedure and some fish became enmeshed during the hauling procedure of the net. This demonstrates that fish-net encounters do occur during the hauling procedure.

Misund *et al.* (1992) reported that the schools of mackerel displayed "explosion behaviour" when they escaped through meshes. The behaviour of skipjack tuna schools inside the net is similar to that of mackerel schools (Kim, 2007). The basic assumptions for the selectivity model are supported by the above evidences.

There are two main types of size selectivity curves for most fishing gear. The first is a modal curve or two-tail type, and the second is a logistic curve or one-tail type (De Alteris and Riedel, 1996; Langley *et al.*, 2009; Millar, 1992). The selectivity curves obtained in this study had two distinctive characters; namely, a knuckle in the slope and an edge at the shoulder of the curve. The appearance of a knuckle is not generalized for purse seine nets because the knuckle is attributed to the net panel configuration, i.e., using two largely different mesh sizes in the body. The edge at a shoulder of the curve is due to numerical simulation, and it could be rounded in the field. Therefore, the selectivity curve of purse seine net is conjectured to be in the category of a one-tail logistic curve.

Comparison between the obtained size distributions of catches and selectivity curves sufficiently explained the characteristic size distributions in the catches; therefore, the present selectivity model for the purse seine net is proved to be effective. However, the varying encounter times is needed in the simulation, since the number of fish encountering a purse seine net is unknown. For the simplest model, the number of fish encounters with the whole area of the net webbing with a uniform probability was presumed in this study; however, it is more plausible that the probability of encountering of fish and meshes changes dynamically (Misund and Beltestad, 1994) due to the varying degrees of stimulation that fish encounter throughout the hauling procedure. The behaviour of an enclosed school in a purse seine net is, however, still unknown and further studies are needed to improve the model of selectivity of purse seine.

The fact that the 50% selectivity sizes for the three species were close to the cannery accepted size supports that the catches by the survey net were acceptable for commercial purposes. The survey net is, therefore, assessed as having the appropriate size selectivity for commercial tuna purse seine fishery. However, this study proved that it is impossible to avoid immature yellowfin and bigeye tunas by using the net, even though it has the appropriate selectivity to catch commercial sizes of the three species. The size selectivity of the purse seine net cannot satisfy both commercial and management purposes. Therefore, other operation techniques, such as free schools operation, must be considered to avoid or minimize the catches of immature yellowfin and bigeye tunas.

In conclusion, purse seine gear is assessed to have the size selectivity which can be applied for commercial purposes, but the selectivity is not sufficient to utilize as a tool for resources management in multi-species tuna purse seine fishery. The management of fishing techniques must be considered.

CHAPTER 5: SIZE-SELECTIVE CATCH BY FISHING OPERATION TECHNIQUE FOR THREE TUNA SPECIES

5.1 Introduction

It was proven that the size selectivity of purse seine net is applicable for commercial purposes that the proportion of unmarketable size in the three species can be reduced through gear selectivity; however, it is insufficient for tuna resource management because the exclusion of immature yellowfin and bigeye tunas is difficult in the multi-species tuna purse seine fishery. In order to solve the problem of catching immature tunas, particularly for yellowfin and bigeye tunas, the use of selective operation should be considered as a tool for resource management in the concerned fishery.

In this chapter, the fishing operation techniques in the purse seine fishery were considered as a way to selectively capture the three species for management purposes. Since catch results from tuna purse seine fishing have shown that the catches from FS operation were composed of larger fish than associated operations (FAD, NL or OFO); however, the differences in species and size compositions related to canneries are needed to be clarified among operation techniques. The objectives of this chapter were to clarify the difference in catches among operation types and to clarify the types of selective operation available for tropical tuna purse seine fishery.

5.2 Materials and Methods

5.2.1 Fishing data

In order to analyze differences in the catch among operation types in the tuna purse seining, fishing data were obtained from logbooks of the Thai tuna purse seine fleet composed of six fishing vessels during the period from September 2005 to April 2007. The six vessels were all ocean-going large purse seiners of the Asian standard (Kawamoto, 2014), with overall lengths ranging from 72.5 to 85.0 m, and gross tonnage ranging from 1,413 to 2,660 GT (Table 5.1) (http://www.iotc.org/vessels "Accessed 22 July 2015"). The fishing grounds for the six vessels were almost the same in the Western Indian Ocean, reaching from 8°S to 11°N and 48 to 70°E (Fig. 5.1). The data set of each operation (one deployment of the purse seine net) obtained from logbooks was composed of the operation type and catch data of tuna species. The operation types were categorized into FS, FAD, NL and OFO operations, as explained earlier. The catch data were composed of catch amounts in size classes for the three species. The sizes of skipjack tuna were further categorized into three classes, while those of yellowfin and bigeye tunas were categorized into two classes in relation to the cannery market (Table 5.2).

Table 5.1 Length overall and gross tonnage of six Thai tuna purse seiners from which fishing data were collected in this study

Vessel	Length overall (m)	Gross tonnage (GT)
A	79.0	2,027
B	72.5	1,413
C	79.0	2,027
D	79.0	2,027
E	85.0	2,660
F	85.0	2,660

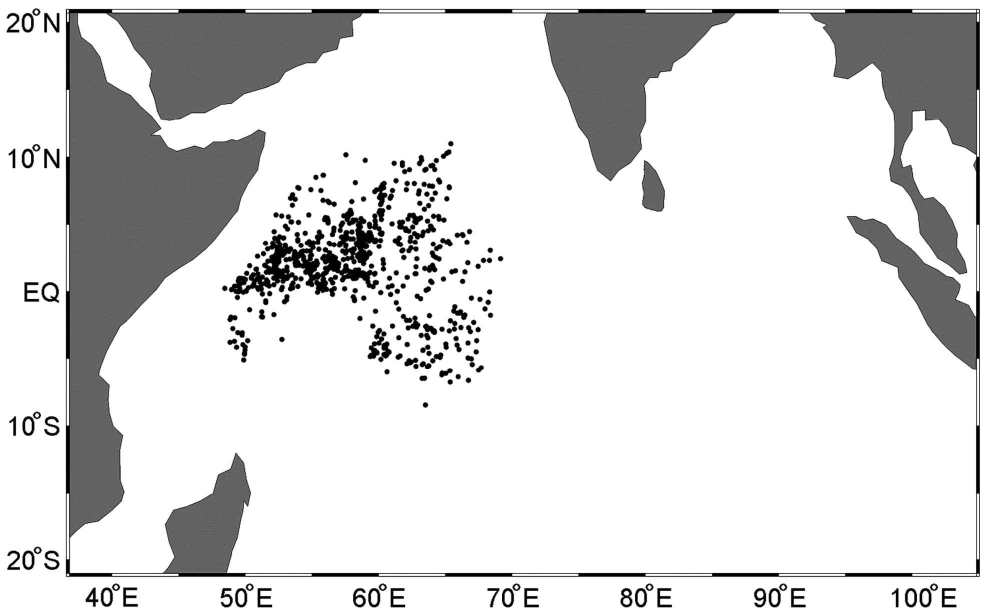

Figure 5.1 Fishing grounds for Thai tuna purse seiners in the Western Indian Ocean during this study

Table 5.2 Size classes of three tuna species from Thai tuna purse seiners' logbooks

Species	Sizes	Body weight (kg/individual)
Skipjack tuna	Large	>3.4
	Medium	1.8 – 3.4
	Small	<1.8
Yellowfin and bigeye tunas	Large	>10
	Small	≤10

5.2.2 Statistical analyses

The obtained catch amounts from the operations were categorized into successful operations (large quantity catch) and unsuccessful operations (small quantity or no catch). The operations were deemed successful on the basis of distribution of catch amount per operation. Data from the successful operations were used for clarifying the difference in catches among operation types in order to avoid bias by operations of small quantity or no catch.

The four operation types, FS, FAD, NL and OFO, were set as independent variables for comparison analyses. Species and size compositions were compared among the four operation types by contingency-table analysis and Tukey-type multiple pairwise comparisons for proportions. A significant level of 0.05 was considered for all the statistical analyses.

5.3 Results

The operation numbers of the four operation types obtained from the logbooks are shown in Table 5.3.

The catch weights of the three species from each operation ranged from 0 to 255 t; however, the distribution was extremely positively skewed (Fig. 5.2). Catches were less than 50 t in most operations, but more than 100 t in some operations. The frequency was the highest in the class of the smallest-quantity catch (less than 10 t).

Table 5.3 Numbers of operations of each operation type

Operation type	*n*
Free school (FS)	147
Fish aggregating device (FAD)	256
Natural log (NL)	365
Other floating objects (OFO)	108
All operation types	876

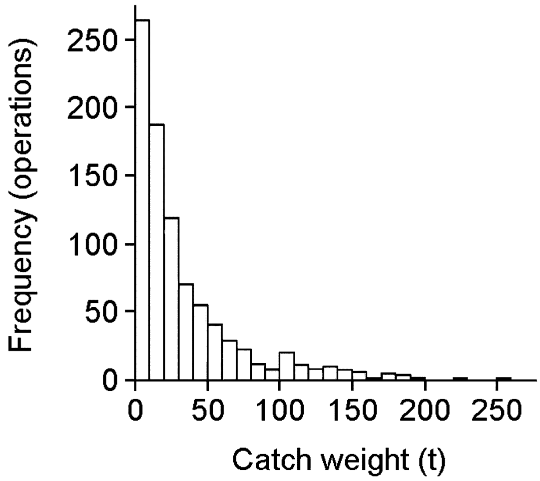

Figure 5.2 Distribution of catch weight of tuna per operation by Thai tuna purse seiners

5.3.1 Successful operation

The catch weights from all operations were ranked from the largest to smallest values (Fig. 5.3). The accumulated total of 556 operations produced 95% of the total catch, while the remaining 320 operations produced only 5% of the total catch, including 108 operations of no catch. The 556th largest quantity of catch was 10 t; therefore, it was considered as the criterion of successful operation. This was the same as the criterion recommended by Fuller and Schafer (2014).

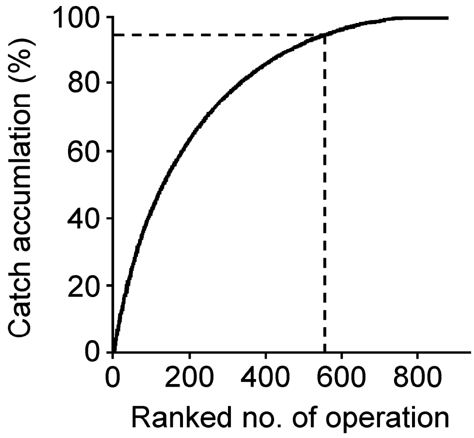

Figure 5.3 Accumulated catch and criterion of successful operation; the dashed line indicates that the accumulated catch at 95% of total catch appeared at the 556th largest catch quantity (10 t)

5.3.2 Species composition

The catch weight compositions of the three species from successful operations in the four operation types showed significant differences (χ^2 = 632.22, $P < 0.0001$ for skipjack; χ^2 = 2,294.17, $P < 0.0001$ for yellowfin and χ^2 = 471.09, $P < 0.0001$ for bigeye tunas) (Fig. 5.4). The majority of catch in all operation types was skipjack tuna. The proportion of skipjack tuna was the highest in NL operation, while it was the lowest in FS operation. The proportion of yellowfin tuna was the highest in FS operation, while it was the lowest in FAD operation. In contrast, the proportion of bigeye tuna was the highest in FAD operation, while it was the lowest in FS operation.

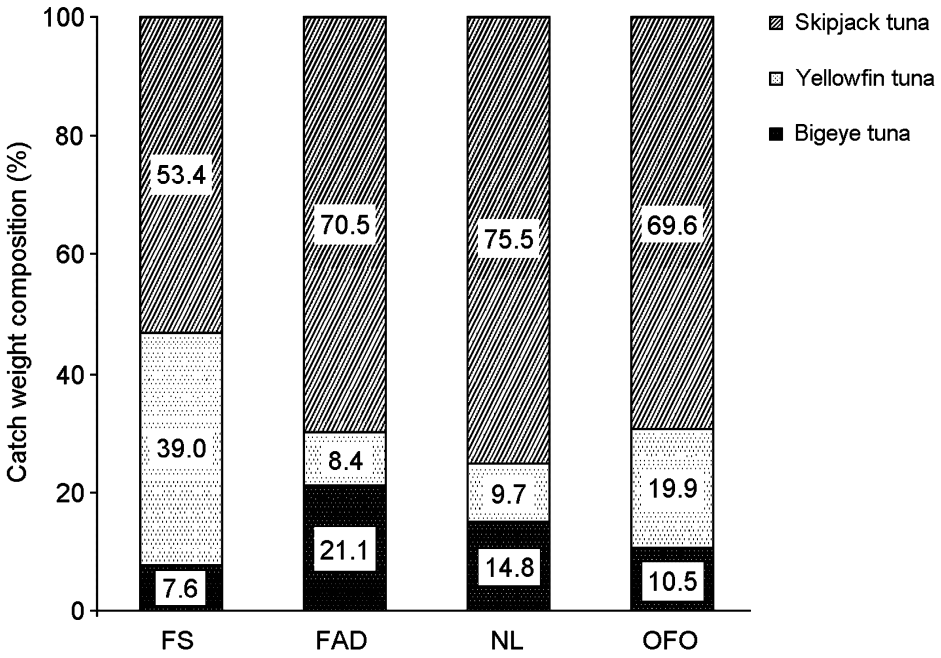

Figure 5.4 Proportion in catch weight of three tuna species from successful operations in four operation types (FS: free school, FAD: fish aggregating device, NL: natural log, OFO: other floating objects)

5.3.3 Size composition in each species

There were significant differences in the size compositions of skipjack tuna from successful operations among the four operation types ($\chi^2 = 1{,}783.18$, $P < 0.0001$ for small size; $\chi^2 = 956.93$, $P < 0.0001$ for medium size and $\chi^2 = 2{,}216.28$, $P < 0.0001$ for large size) (Fig 5.5). The proportion of small-sized skipjack tuna was the lowest in FS operation, while it was the highest in OFO operation. The proportion of large-sized skipjack tuna was the highest in FS operation. Those in the three associated operations were less than 50% in comparison to FS operation. The results indicated that FS operation avoided the catch of small-sized skipjack tuna.

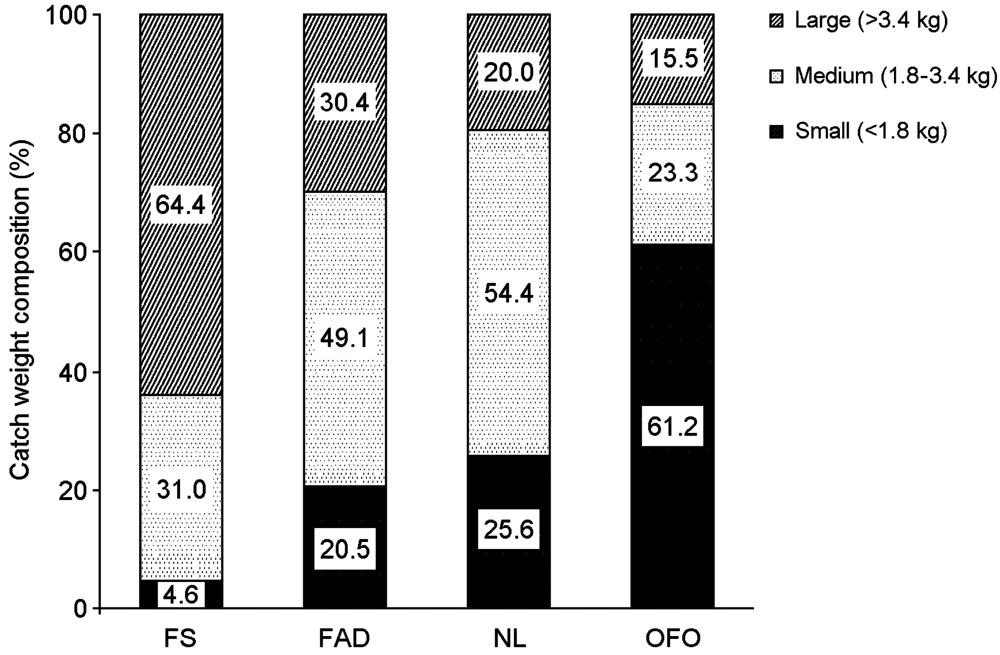

Figure 5.5 Proportion in catch weight from successful operations for skipjack tuna in four operation types (FS: free school, FAD: fish aggregating device, NL: natural log, OFO: other floating objects)

The same analysis was applied to yellowfin tuna, where size compositions among the four operation types showed significant differences (χ^2 = 697.24, $P < 0.0001$ for small size and χ^2 = 697.24, $P < 0.0001$ large size) (Fig 5.6). The proportion of small-sized yellowfin tuna was low in FS and FAD operations with no significant difference between them, while it was the highest in NL operation. The results indicated that FS and FAD operations avoided the catch of small-sized yellowfin tuna in comparison to NL and OFO operations.

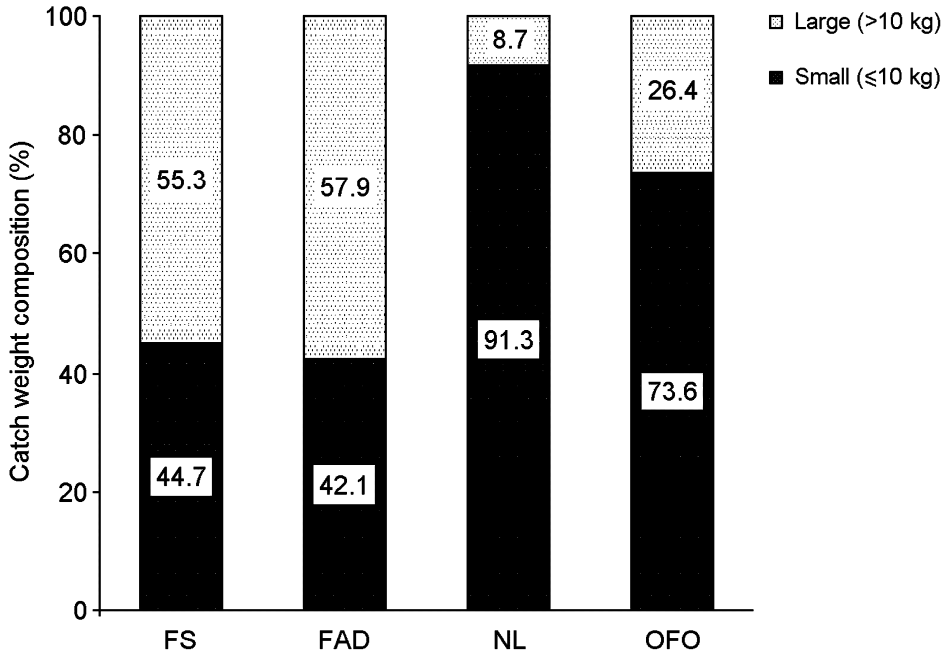

Figure 5.6 Proportion in catch weight from successful operations for yellowfin tuna in four operation types (FS: free school, FAD: fish aggregating device, NL: natural log, OFO: other floating objects)

Figure 5.7 shows the size compositions of bigeye tuna from successful operations in the four operation types. There were significant differences among operation types ($\chi^2 = 823.61$, $P < 0.0001$ for small size and $\chi^2 = 823.61$, $P < 0.0001$ for large size). The proportion of small-sized bigeye tuna was lowest in FS operation, while it was very high in all the associated operations with no significant difference among them; therefore, FS operation avoided the catch of small-sized bigeye tuna.

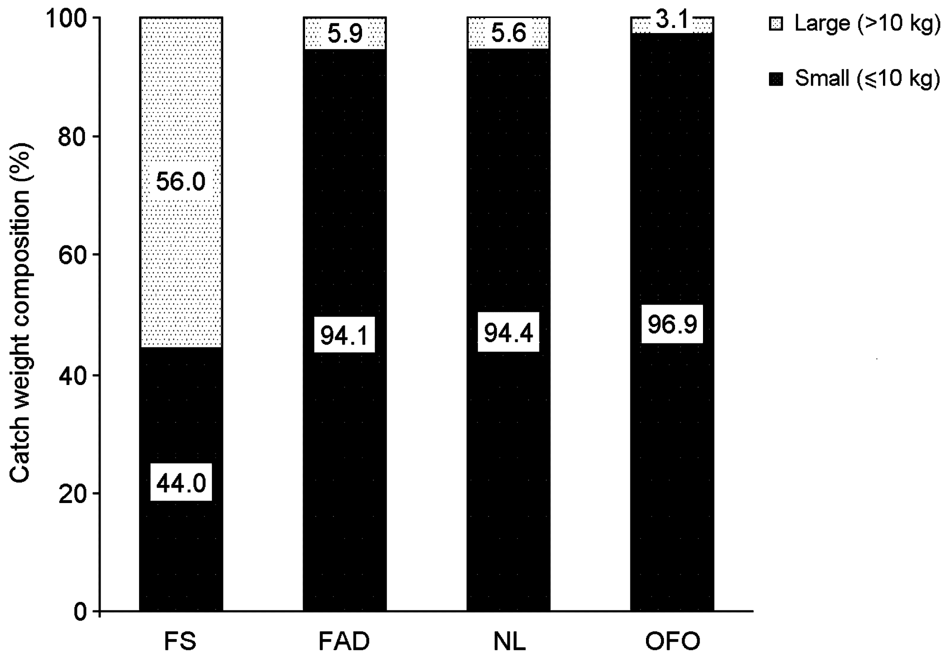

Figure 5.7 Proportion in catch weight from successful operations for bigeye tuna in four operation types (FS: free school, FAD: fish aggregating device, NL: natural log, OFO: other floating objects)

The results of catch size composition analysis indicated that all the four operation types caught small-sized tunas; however, FS operation had the catch results with the lowest compositions of small-sized individuals of the three species in comparison among the four operation types. It was considered that FS operation is the most size-selective fishing technique to avoid small-sized tunas among the four operation types.

5.4 Discussion

The four operation types recorded in this study can be categorized to FS and associated operations according to the distinctive characters of FS operation in catch results in comparison to the others. Misund *et al.* (2002) also categorized tropical tuna purse seine operations in the Pacific, Atlantic and Indian Oceans into free-swimming school and associated school operations.

Bycatches of small-sized yellowfin and bigeye tunas are particularly the concern of tRFMOs. The study on the size selectivity of the purse seine net found that the gear selectivity is functional to catch tunas of commercially appropriate sizes; however, catching immature yellowfin and bigeye tunas cannot be avoided through the selectivity of the fishing gear in the multi-species tuna purse seine fishery. Consequently, the selective catch by fishing techniques should be considered to reduce fishing pressure on immature yellowfin and bigeye tunas. In this study, the analyses of catch compositions from operation types proved that FS operation is the most size-selective fishing technique. Therefore, it gives lower fishing pressure on small-sized individual of the three species in comparison to the associated operations. Skippers should be persistently encouraged to adopt this operation type. FS operation revealed in this study, however, accounted for only 17% of all the operations. This is extremely lower than FS operation ratio of 80–85% achieved by the Japanese tuna purse seine fleet in the Western and Central Pacific Fisheries Commission (WCPFC) areas (Nakamae, pers. comm., 2013). Therefore, the mechanism to induce low FS operation ratio found in this study and its solutions must be considered.

In conclusion, the four operation types in the purse seine fishery involved with small-sized individuals of the three species in the catches; however, FS operation is the most size-selective fishing technique which should be adopted by skippers in the concern fishery.

CHAPTER 6: FISHING STRATEGY ANALYSIS AND SIMULATION OF REVENUE FROM FISHING STRATEGIES WITH SIZE-SELECTIVE FISHING TECHNIQUE

6.1 Introduction

The history of fishing technique in purse seine fishery showed that purse seiners have moved their directions of fishing efforts from FS operation to associated operations since they found the advantage on the gathering of fish schools around floating objects. Consequently, purse seine fishing is involved with small-sized individuals of tunas in the catches as mentioned in previous chapters. Selective fishing methods are needed in the tropical tuna purse seine fishery to avoid catching of unmarketable size and immature tunas. The size selectivity of the purse seine net can satisfy only commercial purposes, while size-selective catch by FS operation is proved to be the most size-selective fishing technique and a tool for management purposes. Therefore, FS operation must be considered in the fishing strategy by existing skippers in the tropical tuna purse seine fishery.

As mentioned above, most purse seiners changed their fishing strategy by increasing the proportion of associated operations; therefore, FS operation must be adoptable by decision-making on the fishing strategy of skippers. The decision-making is related to four main factors, environment conditions, school features, economic incentives and skipper's skills. Among these factors, the economic factor is a dominant driver (Van Putten *et al.*, 2012), including fish prices (Gaertner *et al.*, 1999; Squires *et al.*, 2006), fishing costs and investment on fishing equipment (Murillas-Maza *et al*., 2013; Morón, 2006). The skipper's skills are also an essential factor in choosing the operation type and in handling fishing operation procedures. The skipper's skills are proportional to the catch results (Ruttan and Tyedmers, 2007), which related to revenue; therefore, skilled skippers can become successful with high revenue through their fishing strategies.

In this chapter, FS operation was considered on adoptability for skippers to take it into their fishing strategies. A simulation of revenue from different skippers' fishing strategies and skill levels was conducted on the basis of a fishing strategy model, including combinations of operation techniques, species and size compositions, CPUEs, fish prices and skipper's skills represented by success rates. The objectives of this chapter were to propose a model of fishing strategy that demonstrates how to combine the four operation types to encourage skippers to shift their fishing efforts to FS operation and to evaluate the feasibility of its adoption by skippers into their fishing strategies.

6.2 Materials and Methods

6.2.1 Fishing data and fish prices

In order analyze the fishing strategy and simulate revenue, fishing data set of the six Thai tuna purse seiners from Chapter 5 were used in this chapter, including catch compositions, successful operations and catch amount per operation (Catch Per Unit Effort: CPUE). The three species with different sizes shown in Table 5.2 were considered as different fish prices. The monthly fish prices of the species and size classes during the period of this study were obtained from a cannery group in Thailand (Thai Union Group Public Co., Ltd.). This cannery group is the largest canned tuna producer in Thailand, with a market share of 37% (Kuldilok *et al*., 2013). The obtained price data were composed of price records of the medium-sized skipjack tuna, which is the standard for price determination for the tuna canning industry and is referred to as the market price, as well as equations to decide the prices of the other species and size classes on the basis of the market price.

6.2.2 Fishing strategy model

Each skipper is conjectured to have his own fishing strategy in combination of operation types to maximize and/or stabilize his revenue from fishing. Skippers choose a school to pursue according to the fishing strategy when they find multiple schools of different types, or may even ignore a certain type of school. A presumption of this study was that the fishing strategy depends mainly on revenue from fishing and skipper's skills. The revenue is determined by the prices of species and size categories of the three species, combinations of which vary among operation types. Fishing vessel performance and equipments such as sonar, echo-sounders, and bird radar affect fishing capability; however, these were not taken into consideration because all the studied vessels were oceangoing, large tuna purse seiners in a similar size range. Although gear modification techniques (e.g., for increasing sinking speed of a net) are assumed to be linked with the performance of a fishing vessel, they were not dealt with as an independent factor in this study and were instead considered as included facets of a skipper's overall skill set.

Under the presumption above, revenue differences among the four operation types and their influences on the total revenue and fishing strategy with various rates of combination of the four operation types were modeled as follows. A partial CPUE (C_{ijk}, t/operation) of fish in the size class *j* of species *k* in the operation type *i* of either a vessel (skipper) or all vessels is defined as Equation (6.1);

$$C_{ijk} = \frac{1}{N_i} \sum c_{ijk} \qquad \ldots\ldots \quad (6.1)$$

where c_{ijk} is the catch amount (t) in the size class *j* of species *k* per operation in the operation type *i*, and N_i is the number of operations in the operation type *i*.

The CPUE (C_i, t/operation) in the operation type *i* is derived as Equation (6.2);

$$C_i = \sum_{j,k} C_{ijk} \qquad \ldots\ldots \quad (6.2)$$

The revenue from an operation type regardless of the operation cost is affected by different prices of species and sizes; therefore, the average revenue (US$/operation) I_i from the operation type *i* is described as Equation (6.3);

$$I_i = \sum_{j,k} C_{ijk} \cdot V_{jk} \qquad \ldots\ldots \quad (6.3)$$

where V_{jk} is the fish price (US$/t) in the size class *j* of species *k*.

The average revenue I from all operations under a certain combination of operation types is described as Equation (6.4)

$$I = \sum_{i} R_i \cdot I_i \qquad \ldots\ldots \quad (6.4)$$

where R_i is the component rate of the operation type i in all operations.

6.2.3 Data analyses and simulation on fishing strategy model

A success rate s_i was defined as the rate of successful operations in all operations in number in the operation type i. s_i was accessed to clarify the technical difficulties among the four operation types. C_i and I_i were evaluated in two cases, i.e., optimistic and actual values. The optimistic value was calculated using the catch results from only successful operations, while the actual value was calculated using the catch results from all operations. The values in the two cases were compared to consider the economic risk in the four operation types. Eventually, I for the skippers who operated with different combinations of the four operation types were compared based on the fishing strategy model.

Simulation was conducted on the basis of the above model to assess I in Equation (6.4) with parameters of skipper's skills and fishing strategies. In the simulation, skipper's skills were represented by the success rate s_i in FS operation, and the fishing strategies were represented by the component rate of each operation type R_i.

6.3 Results

6.3.1 Fishing strategies

Success rates

The success rate s_i in each operation type was computed and compared among the four operation types by contingency-table analysis and Tukey-type multiple pairwise comparisons for proportions (Figure 6.1). There were significant differences among the four operation types ($\chi^2 = 57.39$, $P < 0.0001$). FS operation had the lowest success rate, while FAD operation had the highest rate. There was no significant difference between OFO and NL operations. Therefore, FS operation is the most difficult fishing technique, and skippers need higher skills to choose this operation type. In contrast, FAD operation is the simplest fishing technique and does not require advanced skills to be successful.

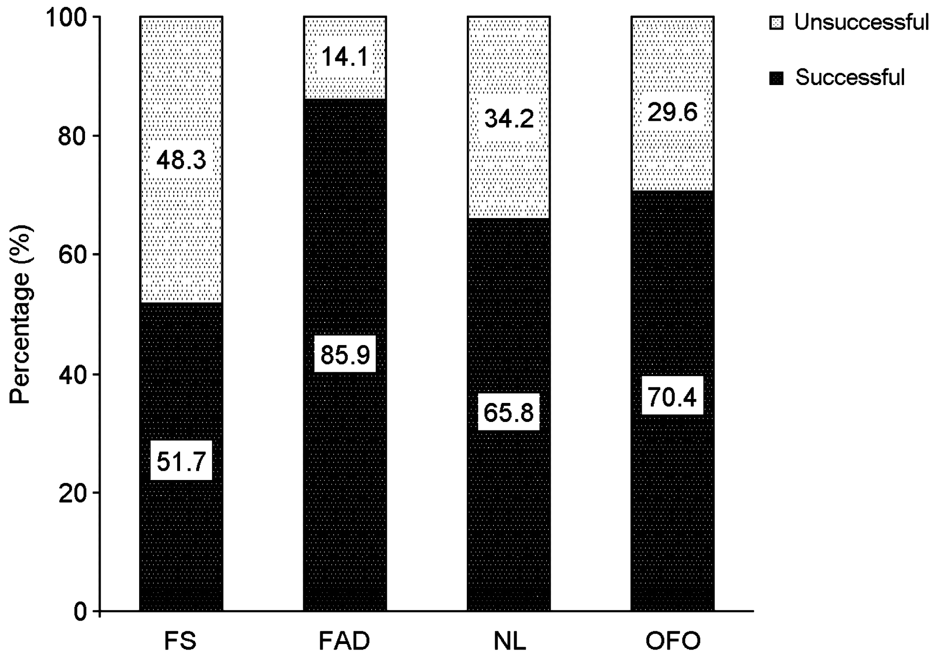

Figure 6.1 Proportions of successful and unsuccessful operations in four operation types (FS: free school, FAD: fish aggregating device, NL: natural log, OFO: other floating objects)

CPUEs

The optimistic and actual CPUEs in the four operation types were calculated (mean±SE) according to Equation (6.2) and compared among the four operation types by Kruskal-Wallis one-way analysis of variance (ANOVA) and Fisher's least significant difference (LSD) multiple pairwise comparisons using the SPSS statistical program (Table 6.1). FS operation had the highest optimistic CPUE, followed by OFO operation; however, there was no significant difference among the four operation types ($\chi^2 = 5.11$, $P = 0.16$). The actual CPUEs from four operation types were significantly different ($\chi^2 = 52.29$, $P < 0.0001$). FAD operation had the highest actual CPUE, while

FS operation had the lowest.

The actual CPUE from FS operation was 47% smaller than the optimistic CPUE, while the actual CPUE from FAD operation was only 12% smaller than its optimistic CPUE. The differences between actual and optimistic CPUEs in NL and OFO operations were 32% and 28%, respectively. The largest difference between optimistic and actual CPUEs in FS operation reflects its difficulty in fishing technique as mentioned above, and it was considered as the economic risk to choose this operation type for skippers.

Table 6.1 Optimistic and actual CPUEs (mean ± SE) in four operation types

Operation type	CPUE (t/operation)		Actual CPUE / optimistic CPUE
	Optimistic (successful operations)	Actual (all operations)	
Free school (FS)	49.5 ± 5.19^{ns}	26.4 ± 3.33^{a}	0.53
Fish aggregating device (FAD)	40.9 ± 2.13^{ns}	35.8 ± 2.00^{b}	0.88
Natural log (NL)	40.9 ± 2.53^{ns}	28.0 ± 1.91^{a}	0.68
Other floating objects (OFO)	49.0 ± 5.50^{ns}	35.4 ± 4.36^{ab}	0.72

ns = not significant difference ($p > 0.05$); values with different superscripts in the same column are significantly different ($p < 0.05$)

Fish prices

The market price for the tuna cannery industry was inconsistent; however, it was relatively stable between 740 US$/t and 1,025 US$/t with an average of 915 US$/t during the catch data collection period (Fig 6.2).

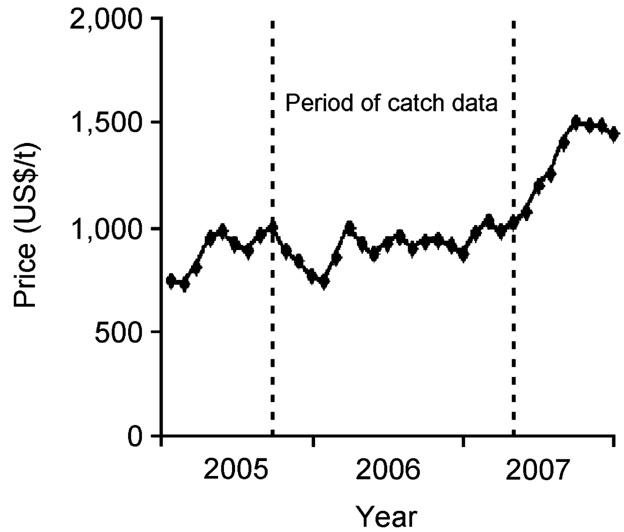

Figure 6.2 Monthly price of medium-sized skipjack tuna with body weight ranging from 1.8 – 3.4 kg/individual (market price) during period of catch data

The average prices of other species and size classes during the catch data collection period were calculated by the equations obtained from the cannery (Table 6.2). The highest price category was that of large-sized yellowfin tuna, while the lowest one was for small-sized skipjack tuna. Prices of small- and large-sized bigeye tuna were not different, because size difference in this species was not greatly appreciated, and they were purchased as “mixed-size” by the cannery.

Table 6.2 Equations used to decide prices of species and sizes on the basis of price of medium-sized skipjack tuna (market price) and average prices of species and sizes of tuna

Species	Sizes	Fish price equation (US$/t)	Average price (US$/t)
Skipjack tuna	Large	MP + 50	965
	Medium	Market price (MP)	915
	Small	MP – 250*	665
Yellowfin tuna	Large	MP + 200	1,115
	Small	MP + 100	1,015
Bigeye tuna	Large	MP + 50	965
	Small	MP + 50	965

*The constant -250 is the average of -350 for body weight < 1.4 kg/individual and -150 for 1.4 – 1.7 kg/individual obtained from the cannery

Average revenue from catch in operation types

Table 6.3 shows the optimistic and actual revenues in the four operation types estimated by catch results and fish price data according to Equation (6.3). FS operation had the highest optimistic revenue. Its superiority was clearer than that in the optimistic CPUE. This is attributable to the largest component of large-sized catches of the three species among the four operation types. For the actual revenue, FAD and OFO operations were higher than FS operation. NL operation had the lowest both optimistic and actual revenues.

The ratios between the actual revenue and the optimistic revenue in the four operation types were almost the same as those between the actual and optimistic CPUEs. This was attributed to the compositions of species and size classes from successful operations and all operations in each operation type were not much different.

The difference between optimistic and actual revenues was believed to affect a skipper's fishing strategy. Some skippers may prefer FAD operation because it provides the highest actual revenue; however, FS operation has the potentiality of high revenue when operations are successful.

Table 6.3 Average optimistic and actual revenues in four operation types estimated by catch results and fish prices

Operation type	Average revenue (US$/operation)		Actual revenue / optimistic revenue
	Optimistic (successful operations)	Actual (all operations)	
Free school (FS)	48,970	26,108	0.53
Fish aggregating device (FAD)	37,353	32,731	0.88
Natural log (NL)	36,503	24,989	0.68
Other floating objects (OFO)	41,323	29,976	0.73

Difference in revenue and fishing strategy among skippers

Fishing results from the six fishing vessels (skippers) were compared, focusing on revenues I_i from the catch results and the success rate s_i (Table 6.4). The average actual revenue for each skipper was calculated using Equation (6.4). The revenue was high for Skippers A–D (more than 30,000 US$/operation), while it was low for Skippers E and F (less than 17,000 US$/operation). Skippers A–D also recorded success using FS operation, while Skippers E and F recorded no success in this operation type. It was assumed that high success rates in FS operation are reflections of the advanced skills among these skippers. It was concluded, therefore, that the skilled skippers generated higher revenues, while low-skilled skippers generated less revenue.

Skipper A recorded a very high proportion of FS operations in his operations. On the other hand, the proportions of FS operations for Skippers B–E were relatively low. Skipper A and Skippers D–F conducted no FAD operations. They may not have been prepared to release their FADs. The results indicated that among the skilled skippers, Skipper A was a specialist of FS operation, while Skippers B–D were generalists who performed both FS operation and associated operations according to their fishing strategies. It was assumed that the relatively small size of the vessel used by Skipper B shown in Table 5.1 did not affect this analysis very much because of his high success rate in FS operation.

Table 6.4 Composition of fishing operation types and average actual revenues among skippers that appeared in catch data obtained from Thai tuna purse seiners

Operation type	Skipper					
	A	B	C	D	E	F
Free school (FS) (*n*)	83	9	11	27	14	3
Fish aggregating device (FAD) (*n*)	0	185	71	0	0	0
Natural log (NL) (*n*)	41	19	24	75	5	201
Other floating objects (OFO) (*n*)	0	0	0	40	68	0
All operations (*n*)	124	213	106	142	87	204
Average actual revenue (US$/operation)	36,443	33,378	39,557	30,378	16,735	14,619
% Success rate in FS operation	69.9	55.6	36.4	33.3	0.0	0.0
% FS operation	66.9	4.2	10.4	19.0	16.1	1.5

6.3.2 Simulation of revenue from fishing strategies

Component rates R_i from the four operation types were calculated in order to simulate the fishing strategies from the combination of the four operation types (Table 6.5). The component rate of FS operation was 0.17, while the majority was attributed to the associated operations, particularly NL operation.

Table 6.5 Component rate of each operation type

Operation type	Component rate in all operations	Component rate in associated operations
Free school (FS)	0.17	—
Fish aggregating device (FAD)	0.29	0.35
Natural log (NL)	0.42	0.51
Other floating objects (OFO)	0.12	0.14
All operation types	1.00	1.00

The influences of various fishing strategies and skill levels on revenue were simulated on the basis of the proposed model. Under assumptions that the partial optimistic CPUE C_{ijk} defined in Equation (6.1) and fish prices are constant as recorded in this study, the simulated average revenue $\hat{I}_i$ from the operation type i was calculated by Equation (6.5);

$$\hat{I}_i = s_i \cdot I_i \qquad \ldots\ldots \quad (6.5)$$

where I_i is the optimistic revenue in the operation type i, which is defined in Equation (6.3), and the observed values are shown in Table 6.5. The simulated average revenue $\hat{I}$ from all operation types was calculated by substituting $\hat{I}_i$ and the component rates R_i of the four operation types, which were changed into Equation (6.4) as shown below.

In order to represent the fishing strategy, R_i of FS operation was changed from 0.0 to 1.0, while R_i of the associated operations was changed from 1.0 to 0.0, leaving the component rates among the three associated operations shown in Table 6.5 unchanged. The success rate s_i in FS operation that represents skill levels was set for five levels at 30%, 40%, 50%, 60% and 70%, while the constant average success rates s_i from all vessels shown in Figure 6.1 were applied to the three types of associated operations.

The results indicated that the revenue decreases with increasing component rates R_i of FS operation where success rates s_i in FS operation are low (representing low-skilled skippers), whereas it increases where success rates s_i in FS operation are high (representing high-skilled skippers) (Fig. 6.3). This implies that the best fishing strategy to maximize revenue for high-skilled skippers is to increase the proportion of FS operations as FS operation specialists. The simulation also indicated that the revenue is not much affected by the combination of operation types and is relatively unchanged at a certain level of skills or around 50–60% success rate in FS operation. This is one of the mechanisms through which generalists exist. Generalists are conjectured to distribute their fishing efforts to associated operations to avoid the risk in FS operation as a fishing strategy. For low-skilled skippers, it is unavoidable to decrease the component rate R_i of FS operations in order to maintain their revenue.

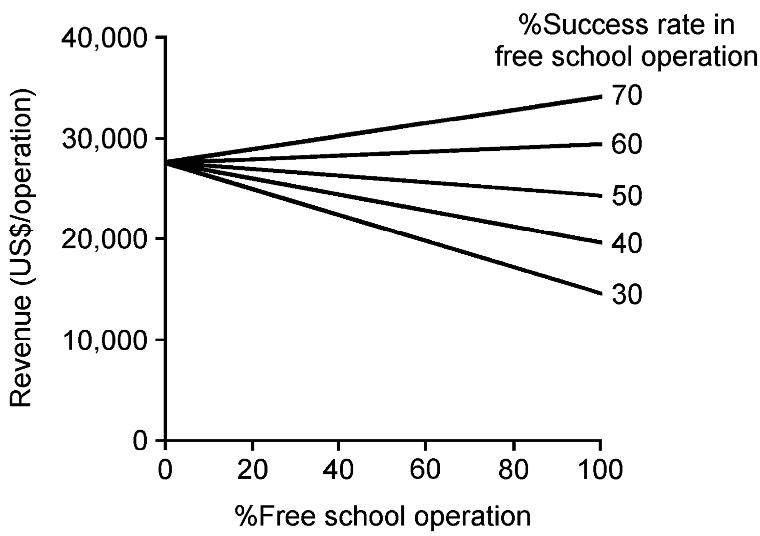

Figure 6.3 Simulated revenue at varied skill levels represented by success rates in free school operation and increasing rate of FS operation in all operation types

The above simulation focused on the component rate of FS operation as the representative factor of fishing strategy, remaining average success rate, component rate, as well as species and size compositions for the associated operation types unchanged. These factors were, however, different from skipper to skipper.

Therefore, the present simulation does not necessarily explain the revenues for the six skippers shown in Table 6.4.

An important finding revealed through this study was that associated operations are avoidable with no revenue decline for skippers who have success rates in FS operation higher than a certain level. Therefore, FS operation is adoptable for high- and moderate-skilled skippers.

6.4 Discussion

6.4.1 Skipper's fishing strategy toward selective fishing technique

Technical difficulty and economic risk

It has been empirically known that the success rate is low in FS operation. This study proved that the success rate in FS operation is the lowest among operation types. It indicates that FS operation is the most difficult fishing technique. The differences between optimistic and actual CPUEs as well as between optimistic and actual revenues were the largest in FS operation. It was presumed that the success rates as well as differences between optimistic and actual values are reflected in the risk, which skippers feel in each operation type. FS operation has, therefore, the highest risk. These findings support the work by Guillotreau *et al.* (2011), who reported that FS operation carried a higher risk than associated operations on the basis of success rates.

Skipper's skills and revenue

A skipper needs higher skills to perform FS operation than they do for associated operations. Morón (2006) emphasized the importance of the skipper's skills, and Ruttan and Tyedmers (2007) noted that skills may contribute significantly to variations in CPUE. Skippers' skills are more important in achieving high revenue from the catch results, such as the high-skilled skipper in this study, who gained high actual revenue because of the high success rate in FS operation and high price fish in the catch. Skippers are assumed to be able to estimate the risk in FS operation based on the revenue expected due to past experiences and fish price information from the market. The simulation indicated that high-skilled skippers can overcome the risk in FS operation, while moderate-skilled skippers try to avoid the risk by distributing their fishing efforts over various operation types.

Fishing strategy

The results of the fishing strategy analysis among skippers indicated that the revenue from fishing is a function of the success rate in FS operation which represents the skipper's skills, composition of operation types including species and sizes of their catches, and fish prices. This function influences the skipper's fishing strategy. Therefore, different fishing strategies among skippers to maximize their revenue are based on the skipper's skills. These results support the simulation model, which considered a skipper's skills as the major factor determining revenue. Salas and Gaertner (2004) also explained that fishers are not homogeneous and may differ in their operation techniques. This coincides with that the fishing strategy was different among even high-skilled skippers, such as between Skippers A and B in this study.

Strategic shift to FS operation

Skippers were identified as specialists and generalists according to their fishing strategies in this study. Skipper A in this study recorded no FAD operation and did not likely invest in making and tracking FADs. He concentrated his work in FS operation and obtained high revenues. This is his fishing strategy, and he is identified as a FS operation specialist. On the other hand, the generalists mix operation types with short-term economic perspective. This supports the idea that high-skilled generalists in this study (particularly Skippers B and C) achieved quite high revenues. The high-skilled generalists in this study distributed the most fishing efforts into associated operations. This is conjectured as one of the fishing strategies to manage the risk of FS operation. Tsitsika and Maravelias (2008) explained that purse seiners adapted their fishing strategies to minimize risk rather than maximize catches. This explains why high-skilled generalists were found in this study. The simulation proved, however, that high- and moderate-skilled generalists can shift their fishing strategies to FS operation with no revenue decline. It should be noted that FS operation specialists can also reduce potential cost and labor force to make and use FADs. This is one of the merits of FS operation in reducing the investment risk.

For low-skilled skippers, it is still difficult to change the fishing strategy immediately, because revenue decline is inevitable if they increase the component rate of FS operation, as the simulation result indicated. However, technical innovations can help a skipper's transition into FS operation. Kawamoto (2010) reported technical innovations that helped skippers move toward higher success rates in FS operation, which was developed in a project conducted in Yamagawa, Japan. He recommended enlargement of meshes, increasing power of a purse winch and operations for boat-associated schools. The enlargement of meshes increased the sinking speed of a net for more successful encircling of a school. Empowerment of a purse winch reduced the time of the pursing procedure by more than 50% in comparison to an ordinary purse winch. The last recommendation was to use a boat for free school to induce temporary association in which the mobility of the fish was lower than that of a free school. He reported that the success rate in FS operation was increased from 14% to 40% (Kawamoto's criterion for successful operation was 30 t of catch). Eventually, the composition ratio of FAD operation in all operations was reduced from 87% to 16%. Further technological studies to increase the success rate in FS operation should be promoted to support low-skilled skippers in shifting to FS operations.

6.4.2 Effects of tRFMO's policy to Motivate skippers to change fishing strategy

Policies of tRFMOs are considered as both direct and indirect tools to stop increasing associated operations and to motivate skippers to shift their fishing efforts to FS operation.

The policy on time-area closure against FAD operation was set forth by the WCPFC in 2009. All associated operations in tuna purse seining were prohibited in the WCPFC convention area between 20°S and 20°N from August to September (WCPFC, 2008). The WCPFC is examining this policy towards extension of the closed period or reduction of the numbers of associated operations (WCPFC, 2015). The Indian Ocean Tuna Commission (IOTC), on the other hand, closed the area from 0 to 10°N and from 40 to 60°E from purse seining in November from 2011 to 2014 (IOTC, 2012) in order to protect immature tunas. This policy was evaluated as likely to be ineffective (IOTC, 2015). It can be explained based on the study of Davies *et al.* (2014b) that the purse seine fleet was forced to move out from the closed area during the restricted month; however, the associated operations were dominant from August to October in the IOTC closed area. In order to effectuate the IOTC closed area, the realistic approach is that the IOTC should allow FS operations during the closure period, while extending the regulation period to reduce associated operations.

The TAC system has been adopted in the policies of tRFMOs to manage tuna resources; such as for Atlantic bluefin tuna by the International Commission for the Conservation of Atlantic Tunas, for bluefin tuna by the Inter-American Tropical Tuna Commission, and for Southern bluefin tuna by the Commission for the Conservation of Southern Bluefin Tuna. Catching fish of high value is a way to increase the total revenue under the TAC system. In Chapter 5, it was proven that FS operation is the most selective technique to catch large-sized skipjack and yellowfin tunas which had high prices. Therefore, encouraging FS operation is one method of encouraging adoption of the TAC system. Wilen (1979) also reported that the fishers' fishing behaviour (which should be the actualizations of fishing strategies of skippers) was affected by the TAC system. The TAE system, such as that adopted by the IOTC and the Parties to the Nauru Agreement, is assumed to have the same effect.

The policy on a discard ban against tunas in the purse seine fishery was adopted in 2010 by the IOTC. This policy was enforced in January 2014 (IOTC, 2013) and has guided the purse seiners towards more selective technologies (Chan *et al*., 2014). According to this policy, skippers should catch large-sized individuals of tunas. This study proved that FS operation selectively catches large-sized individuals of tunas more successfully in comparison to the associated operations. Therefore, encouraging FS operations is also an important means of achieving policy adoption of the discard ban. This is especially true when the discard ban is presented together with the allocation systems (e.g., TAC and TAE systems).

In conclusion, FS operation has the potential to generate high revenue; however, it is a technically difficult fishing technique and has a high economic risk. High- and moderate-skilled skippers are, however, able to adopt FS operation in their fishing strategies with no revenue decline, while the technical innovation is needed for low-skilled skippers to adopt FS operation. It is very important for purse seiners to shift to FS operation, thus aligning with the policies of tRFMOs in their efforts to improve sustainable management of the tuna purse seine fishery.

CHAPTER 7: GENERAL DISCUSSION AND CONCLUSION

The tuna purse seine is an important fishing gear to capture tunas that takes the highest catches among fishing gears. However, catches of the three species from this fishing gear included bycatch of small-sized individuals of tunas which were immature fish. Since associated operations were introduced to purse seine fishery, catching immature tunas became an issue and concerned by tRFMOs.

This research clarified that FAD operation results in catching of small-sized individuals of tunas. The selectivity of purse seine net can solve the issue of catching small-sized individuals which are unmarketable size through gear design or modification. The size selectivity model in this research was simple in calculation; however, the knowledge of tuna schools behaviour on fish-net encounters during the hauling procedure is still needed to improve the model. Further study on number of fish-net encounters should be performed; therefore, selectivity curves for the three species from the improved model can become more precise.

The study on size-selective catch by fishing operation techniques indicated that all operation types caught immature yellowfin and bigeye tunas; however, FS operation was proved to be the most size-selective fishing technique, which has the least catch of small-sized individuals of the three species. The issue of catching immature tunas, particularly for yellowfin and bigeye tunas, can be solved for management purposes. The analysis of fishing strategy indicated that FS operation is the most difficult fishing technique, and it has the highest economic risk in comparison among the four operation types; however, FS operation has potentially high revenue that skilled skippers can achieve. The simulation also proved that the adoption of FS operation for high- and moderate-skilled skippers is possible without revenue decline, but it is impossible for low-skilled skippers, who need to improve their skills to adopt this fishing technique. In order to improve the skills, a low-skilled skipper can learn from a high-skilled skipper on how to handle and become successful in FS operation, because skipper's skills is a kind of knowledge that can be transferred from a high-skilled skipper to a low-skilled skipper. Moreover, the technical innovations as mentioned in Chapter 6 can help low-skilled skippers through publications or trainings. It is a challenge in tuna resource management to increase skippers' capability of FS operation. However, the policies of tRFMOs significantly tend to shift to FS operation in the management of the tuna purse seine fishery for resources utilization and conservation.

As a recommendation, one of the improvements on the fishing gear is net modification by enlarged mesh sizes in some net panels. It can reduce bycatch of unmarketable size through the selectivity function of the net. Besides, it can increase the sinking speed of the net during the shooting procedure to help skippers on the success rate in FS operation.

The main objective of this research was achieved, and the results suggested that size selectivity of purse seine net and fishing operation technique can be used to satisfy commercial and management purposes in terms of tuna resource utilization and management. Purse seiners should take it into account to improve the size selectivity of their fishing gears and to start the adoption of FS operation for their fishing strategies. Resources managers should also encourage skippers to catch tunas by selective methods through the policies of tRFMOs.

REFERENCES

Campling, L. 2012. The tuna 'commodity frontier': Business strategies and environment in the industrial tuna fisheries of the Western Indian Ocean. *J Agrar Change* 12:252–278

Cayré, P., J.B. Amon Kothias, T. Diouf and J.M. Stretta. 1993. Biology of tuna. In: Fonteneau, A. and J. Marcille (eds) Resources, fishing and biology of the tropical tunas of the Eastern Central Atlantic. FAO, Rome, pp 147–244

Catchpole, T.L., C.L.J Frid and T.S. Gray. 2005. Discards in North Sea fisheries: causes, consequences and solutions. *Mar Policy* 29:421–430

Chan, V., R. Clarke and D. Squires. 2014. Full retention in tuna fisheries: benefits, costs and unintended consequences. *Mar Policy* 45:213–221

Chanrachkij, I. and A. Loon-on. 2003. Preliminary report on ghost fishing phenomena by drifting FADs in Eastern Indian Ocean. SEAFDEC, Samut Prakan

Dagorn, L., K.N. Holland, V. Restrepo and G. Moreno. 2013. Is it good or bad to fish with FADs? What are the real impacts of the use of drifting FADs on pelagic marine ecosystems? *Fish Fish* 14:391–415

Davies TK, Mees CC, Milner-Gulland EJ. 2014a. The past, present and future use of drifting fish aggregating devices (FADs) in the Indian Ocean. *Mar Policy* 45:163–170

Davies, T.K., C.C. Mees and E.J. Milner-Gulland. 2014b. Modelling the spatial behaviour of a tropical tuna purse seine fleet. *Plos One*. doi: 10.1371/journal.pone.0114037

De Alteris, J. and R. Riedel. 1996. Effect of size selection within and between fishing gear types on the yield and spawning stock biomass per recruit and yield per unit effort for a cohort. *J Northw Atl Fish Sci* 19:73–82

Désurmont, A. and L. Chapman. 2000. The use of anchored FADs in the area served by the Secretariat of the Pacific Community (SPC): regional synthesis. In: Le Gall, J. *et al* (eds) Proceedings of the international symposium on tuna fishing and fish aggregating devices. IFREMER, Plouzané, pp 108–140

Fonteneau, A., E. Chassot and N. Bodin. 2013. Global spatio-temporal patterns in tropical tuna purse seine fisheries on drifting fish aggregating devices (DFADs): taking a historical perspective to inform current challenges. *Aquat Living Resour* 26:37–48

Fonteneau, A., J. Ariz, D. Gaertner, V. Nordstrom and P. Pallares. 2000. Observed changes in the species composition of tuna schools in the Gulf of Guinea between 1981 and 1999, in relation with the fish aggregating device fishery. *Aquat Living Resour* 13:253–257

Fuller, D.W. and K.M. Schaefer. 2014. Evaluation of a fishing captain's ability to predict species composition, sizes, and quantities of tunas associated with drifting fish-aggregating devices in the eastern Pacific Ocean. *ICES J Mar Sci*. doi: 10.1093/icesjms/fsu012

Gaertner, D., M. Pagavino and J. Marcano. 1999. Influence of fishers' behaviour on the catchability of surface tuna schools in the Venezuelan purse-seiner fishery in the Caribbean Sea. *Can J Fish Aquat Sci* 56:394–406

Graham, J.B. and K.A. Dickson. 2004. Tuna comparative physiology. *J Exp Biol* 207:4015-4024

Guillotreau, P., F. Salladarré, P. Dewals and L. Dagorn. 2011. Fishing tuna around fish aggregating devices (FADs) *vs* free swimming schools: skipper decision and other determining factors. *Fish Res* 109:234–242

Hall, M.A. 1996. On bycatches. *Rev Fish Biol Fish* 6:319–352

Hall, M. and M. Roman 2013. Bycatch and non-tuna catch in the tropical tuna purse seine fisheries of the world. FAO, Rome

Hall, M.A., Alverson, D.L., Metuzals, K.I. 2000. By-catch: problems and solutions. *Mar Pollut Bull* 41:204–219

Hallier, J.P. 1995. Tropical tuna fishing with purse seine and log. *INFOFISH Int* 4:53–58

Hosseini, S.A., C.W. Lee, J.S. Kim, J. Lee and G.H. Lee. 2011. The sinking performance of the tuna purse seine gear with large-meshed panels using numerical method. *Fish Sci* 77:503–520

Hosseini, S.A. and E. Ehsani. 2014. An investigation of reactive behavior of yellowfin tuna schools to the purse seining process. *Iran J Fish Sci* 13:330–340

Inoue, M. 1959. On the relation of behaviours of skipjack and tuna shoals to their catch inferred from the data for seine fishery. *Bull Jpn Soc Sci Fish* 25:12–16 (in Japanese with English abstract)

IOTC. 2012. Report of the sixteenth session of the Indian Ocean Tuna Commission. IOTC, Victoria

IOTC. 2013. Report of the seventeenth session of the Indian Ocean Tuna Commission. IOTC, Victoria

IOTC. 2015. Report of the nineteenth session of the Indian Ocean Tuna Commission. IOTC, Victoria

ISSF. 2015. ISSF tuna stock status update, 2015: status of the world fisheries for tuna. ISSF, Washington DC

Kawamoto, T. 2010. Considerations on fishing strategy in overseas purse seine fishery. *Discuss Pap Ser Jap Soc Fish Econ* 5:36–55 (in Japanese)

Kawamoto, T. 2014. Drastic international changes around overseas purse seine fishery and required enlargement of fishing vessels. *Discuss Pap Ser Jap Soc Fish Econ* 6:1–6 (in Japanese)

Kim, Y.H. 2007. Complex movements of skipjack schools based on sonar observations during pelagic purse seining. *J Fish Sci Technol* 10:220–225

Kim, Y.H., M.C. Park and S.W. Ha. 2008. Simulation and three-dimensional animation of skipjack behavior as capture process during purse seining. *J Fish Sci Technol* 11:113–123

Kuldilok, K.S., P.J. Dawson and J. Lingard. 2013. The export competitiveness of the tuna industry in Thailand. *Brit Food J* 115:328–341

Langley, A., A. Wright, G. Hurry, J. Hampton, T. Aqorua and L. Rodwell. 2009. Slow steps towards management of the world's largest tuna fishery. *Mar Policy* 33:271–279

Lopez, J., G. Moreno, I. Sancristobal and J. Murua. 2014. Evolution and current state of the technology of echo-sounder buoys used by Spanish tropical tuna purse seiners in the Atlantic, Indian and Pacific Oceans. *Fish Res* 155:127–137

Matsuoka, T. 2008. A review of bycatch and discard issue toward solution. In: Tsukamoto, K. *et al* (eds) Fisheries for global welfare and environment. TERRAPUB, Tokyo, pp 169–180

Millar RB, 1992. Estimating the size-selectivity of fishing gear by conditioning on the total catch. *J Am Stat Assoc* 87:962–968

Misund, O.A. and A.K. Beltestad. 1994. Size-selection of mackerel and saithe in purse seine. ICES, Copenhagen

Misund, O.A., J. Kolding and P. Fréon. 2002. Fish capture devices in industrial and artisanal fisheries and their influence on management. In: Hart, P.J.B. and J.D. Reynolds (eds) Handbook of fish biology and fisheries: volume 2, fisheries. Blackwell Publishing, Oxford, pp 13–36

Misund, O.A., W. Diskson and A.K. Beltestad. 1992. Optimization of purse seines by large-meshed sections and low lead weight. Theoretical considerations, sinking speed measurements and fishing trials. *Fish Res* 14:305–317

Miyake, M.P., N. Miyabe and H. Nakano. 2004. Historical trends of tuna catches in the world. FAO, Rome

Morón, J. 2006. Tuna fishing capacity: perspective of the purse-seine fishing industry on factors affecting it and its management. In: Bayliff, W.H. and J. Majkowski (eds) Methodological workshop on the management of tuna fishing capacity: stock status, data envelopment analysis, industry surveys and management options. FAO, Rome, pp 117–127

Murillas-Maza, A., G. Morenoa and J. Murua. 2013. A socio-economic sustainability indicator for the Basque tropical tuna purse-seine fleet with a FAD fishing strategy. *Economía agraria y recursos naturales*. doi: 10.7201/earn.2013.02.01

Orange, C.J., M.B. Schaefer and F.M. Larmie. 1957. Schooling habits of yellowfin tuna (*Neothunnus macropterus*) and skipjack (*Katsuwonus pelamis*) in the Eastern Pacific Ocean, as indicated by purse seine catch records, 1946-1955. *Inter-Am Trop Tuna Comm Bull* 2:83–126

Paquotte, P. 2003. Tuna in the international market for seafood. In: Bridges, C.R. *et al* (eds) Domestication of the bluefin tuna *Thunnus thynnus thynnus.* CIHEAM, Zaragoza, pp 159–163

Pillai, N.G. and P. Satheeshkumar. 2012. Biology, fishery, conservation and management of Indian Ocean tuna fisheries. *Ocean Sci J* 47:411–433

Prado, J. 1992. List of references of the selectivity of various fishing gears and methods; research in this field. FAO, Rome

Resma, S.E., J.T. De Alteris and M.A, Rice. 2006. Size selectivity of purse seines in the Southern Philippines multispecies tuna fisheries. *J Aquat Sci* 3:1–21

Ruttan, L.M. and P.H. Tyedmers. 2007. Skippers, spotters and seiners: analysis of the “skipper effect” in US menhaden (*Brevoortia* spp.) purse-seine fisheries. *Fish Res* 83:73–80

Sakai, H., S. Wu, D. Shiode, K. Uchida, Y. Miyamoto, Y. Mine and Y. Koike. 2007. Releasing force of fishhook on caught tuna in longline fishery. In: Matsushita, O. *et al* (eds) Cruise reports no.15: report of the Umitaka-maru cruise in 2005 fiscal year. TUMSAT, Tokyo, pp 76–78 (in Japanese)

Salas, S. and D. Gaertner. 2004. The behavioural dynamics of fishers: management implications. *Fish Fish* 5:153–167

Scofield, W.L. 1951. Purse seines and other roundhaul nets in California. Department of Fish and Game, California

SEAFDEC/TD. 2004. Tuna purse seine. SEAFDEC, Samut Prakan

Squires, D., T. Kim, Y. Jeon and R. Clarke. 2006. Price linkages in Pacific tuna markets: implications for the South Pacific Tuna Treaty and the Western and Central Pacific region. *Environ Dev Econ* 11:747–767

Sturges, H. 1926. The choice of a class interval. *J Am Stat Assoc* 21:65–66

Sukramongkol, N. 2002. Preliminary result on by catch from tuna purse seine fishery in the Eastern Indian Ocean. SEAFDEC, Samut Prakan

Taquet, M., G. Sancho, L. Dagorn, J. Gaertner, D. Itano, R. Aumeeruddy, B. Wendling and C. Peignon. 2007. Characterizing fish communities associated with drifting fish aggregating devices (FADs) in the Western Indian Ocean using underwater visual surveys. *Aquat Living Resour* 20:331–341

Tsitsika, E.V. and C.D. Maravelias. 2008. Fishing strategy choices of purse seines in the Mediterranean: implications for management. *Fish Sci* 74:19–27

Uhlmann, S.S., A.T.M. Van Helmond, E.K. Stefánsdóttir, S. Sigurðardóttir, J. Haralabous, J.M. Bellido, A. Carbonell, T. Catchpole, D. Damalas, L. Fauconnet, J. Feekings, T. Garcia, N. Madsen, S. Mallold, S. Margeirsson, A. Palialexis, L. Readdy, J. Valeiras, V. Vassilopoulou and M.J. Rochet. 2014. Discarded fish in European waters: general patterns and contrasts. *ICES J Mar Sci* 71:1235–1245

Van Putten, I.E., S. Kulmala, O. Thébaud, N. Dowling, K.G. Hamon, T. Hutton and S. Pascoe. 2012. Theories and behavioural drivers underlying fleet dynamics models. *Fish Fish* 13:216–235

WCPFC. 2008. Conservation and management measure for bigeye and yellowfin tuna in the Western and Central Pacific Ocean. WCPFC, Pohnpei

WCPFC. 2015. Conservation and management measures (CMMs) and resolutions of the Western Central Pacific Fisheries Commission (WCPFC). WCPFC, Pohnpei

Wilen, J.E. 1979. Fisherman behavior and design of efficient fisheries regulation programs. *J Fish Res Board Can* 36:855–858

Yingyuad, W. and I. Chanrachkij. 2010. Purse seine fisheries of Thailand. SEAFDEC/TD, Samut Prakan