Received: 13 October, 2011

Performance of different length information on stock assessment of bigeye tuna from the Indian Ocean by length-based yield per recruit analysis

Lin, yu-jia[1], Yu-Min Yeh[2], Chiee-Yuan Chen[3] and Chien-Chung Hsu[1,*]
[1]Institute of Oceanography, National Taiwan University, 1, Section 4, Roosevelt Road, Taipei, Taiwan 106
[2]Department of Tourism Managment , NanHua University, No. 55, Sec. 1, Nanhua Rd., Zhongkeng, Dalin Township, Chiayi County 62240, Taiwan
[3]Department of Marine Environmental Engineering, National Kaohsiung Marine Technology and Science, 142, Hai-Chuan Road, Nan-Tzu District, Kaohsiung City, Taiwan 800

The report submitted to 2011 Indian Ocean Tuna Commission Working Parties on Tropical Tunas workshop, Paradise Island Resort, Lankanfinolhu, North Malé Atoll, Maldives, 16-23 October 2011. Please do not be cited without consult with authors.

Abstract

Catch at size of longline fishery was estimated from both on board measurements and Taiwan logbook data in 2006 and 2007, and this sort of monthly catch at size was combined with those of purse seine fishery for the corresponding time period into a complete catch at size matrix. The finalized catch at size matrix is a representative of the bigeye tuna stock in the Indian Ocean, and was used to evaluate the fishing pressures of the stock and to estimate biological reference points. First, the von Bertalanffy growth curve was estimated from the catch at size matrix. Second, the estimated von Bertalanffy growth parameters were used to estimate total mortality coefficients by length converted catch curve. Third, the biological reference points were then estimated using yield per recruit and spawning stock biomass per recruit models analysis. And finally, a multi-gear yield per recruit was applied to estimate the biological reference points by gears. The current stock status was evaluated by the estimated biological reference points. Results of multi-gear yield per recruit model analysis indicated that the purse seine fishery competed with longline fishery by harvesting different sizes, and results of spawning stock biomass per recruit model analysis tend to be reduced with increases in fishing mortality rates of both longline and purse seine fisheries, indicating that the spawning biomass percentages will be reduced more greatly when harvested by two or more fisheries simultaneously.

1 Introduction

Length frequency data are essential on fishery stock assessment. Estimation of catch-at-age matrix, age-structured models analysis and length-based approaches are based on represented length frequency distributions. Unfortunately, to obtain a well-represented length frequency distribution is nearly unlikely because fishing gear selectivity, poor sampling techniques, incorrect measuring or recording and predomination of certain species. Particularly, those reasons always occur in commercial fisheries, the tuna fisheries as the real case.

Bigeye tuna, *Thunnus obesus*, is a large mesopelagic tuna distributing in the tropical and temperate waters between 45°N and 45°S (Collette & Nauen, 1983). There was one bigeye tuna stock in the Indian Ocean (Appleyard et al., 2000; Chiang et al. 2006) for the assessment and management purposes. Bigeye tuna is the most economically productive over 300,000 US dollars annually among the scombridae worldwide, and over 120,000 mt in the Indian Ocean (IOTC 2006). The sub-adult and adult bigeye tuna was taken mainly by longline fishery, and juvenile and sub-adult bigeye tuna was caught with skipjack and juvenile yellowfin tuna as by-catch by purse seine fishery.

The stock status in the Indian Ocean has been evaluated and monitored regularly the national scientists through the coordination of Indian Ocean Tuna Commission (IOTC) (e.g. Nishida and Shono, 2006; Shono et al., 2006; Hillary, 2008). Mainly, the age-structured production model analysis (Nishida and Shono 2006), stock synthesis II (Shono et al. 2006), and surplus production model analysis (Hillary. 2008) were applied on standardized catch per unit effort of Japanese longline fishery as abundance index during the stock assessment analyses. Incorporating with the models analysis, Tankevich (1982) estimated the sex-specific von Bertalanffy growth parameters and Stéquert and Conand (2004) re-estimated the parameters, using small-size fish caught by purse seiner fishery; The standardized catch per unit effort of purse seine fishery (Dorizo et al. 2008; Soto et al. 2008) was also made available in 2008 working session (Bankok, Thailand, October 11-23, 2008). However, the assessed results obtained are still preliminary and the stock status is still in high uncertainty because the standardized catch per unit effort derived from longline fishery (Hsu 2006; Okamoto et al. 2006) and purse seine fishery (Arrizabalaga 2008; IOTC 2008; Pianet et al. 2008) was not satisfactorily available for all fleets that targeted full size range of the harvest stock. The catch at age data, used in age-structured models analysis, was biased also because the length measurements submitted by main fisheries may be under-represented. Moreover, estimated biological reference points, such as maximum sustainable yield (MSY) and maximum fishing mortality ($F_{\max}$) and $F_{0.1}$ etc. were based on doing so. And more importantly, the stock status through the effects of the harvest juveniles only from purse seine fishery on the bigeye tuna stock are not satisfied, because the effect of sub-adult taken by longline fisheries is not investigated.

Therefore, the objectives of this study was to use size data of bigeye tuna obtained from different sources that were sampled and measured during 2006 and 2007 fishing seasons, to estimate growth parameters, selectivity, and to estimate biological reference points by fleets and combined fleets by means of yield per recruit model and stock biomass per recruit model analyses. And the multi-gear yield and spawner-biomass per recruit profiles were also pursued to investigate the effects of simultaneous longline and purse seine fishery on the yield and spawner-biomass per recruit in order to examine the limiting biological reference points by fleets.

2 Materials and Methods

2.1 Data collection

2.1.1 *Nominal Catch*

Because length frequency distribution was compiled mainly from different sources and different fisheries, nominal catch is used as a weight to combine those length frequencies in one for the corresponding time scale. Nominal catch of bigeye tuna (*Thunnus obesus*) were obtained from the database managed by the Indian Ocean Tuna Commission (IOTC) secretariat, who is the organization for Indian Ocean tuna assessment and management, in which fisheries were classified into longline (LL), purse-seine (PS) and others (ART). The annual catch is illustrated in Fig. 1. According to IOTC database, the fleets from Taiwan and Japan contributed the majority of catches from longline fishery, and the rest were made by other fleets from Belize, China, France-Reunion, Indonesia, Kenya, Republic of Korea, Madagascar, Mauritius, Malaysia, Oman, Philippines, Portugal, Seychelles, Thailand, Tanzania, Uruguay, South Africa and those with various flags. For purse-seine fishery, catches were mostly taken by Spain, France and her associated territory, and few taken by fleets from Indonesia, Iran, Islamic Republic, Japan, Mauritius, Seychelles, Thailand and those with various flags.

2.1.2 *Fish samples and length distributions*

Three sets of length data were available in the analysis. First, bigeye tuna were sampled and measured from four Taiwan longline vessels operated in the Indian Ocean from April to December in 2006 and from July to December in 2007. Those measurements were measured to the nearest 1 cm by the onboard assistants. Almost the folk length of all bigeye tuna caught were measured in the nearest 1 cm as possible except being depredated, totally 5,682 and 11,509 bigeye tuna were measured in 2006 and 2007 fishing seasons, respectively. Those length measured data for January to March in 2006 and January to June in 2007 were not available because the sample vessels' operation was not scheduled. Second, the monthly length distributions was obtained from log-books, which the actual sizes in FL were sampled and measured by fishermen of Taiwanese longline fishing vessels operated in the Indian Ocean during the corresponding months, and those sizes measured were submitted to the Fisheries Agency, and compiled and provided by the Oversea Fisheries Development Council (OFDC), Taiwan. A total of 154,953 and 267,889 bigeye tuna were reported to the nearest 1 cm in 2006 and 2007, respectively. And third, the size composition of bigeye tuna caught by purse-seine fisheries was also extracted from IOTC databases for 2006 and 2007. Those size measurements of bigeye tuna, ranged from 10 to 200 cm FL, were submitted by the nations fished with purse seiners.

Because different fisheries target different sized fish, and making the length frequency distribution compiled for the current analysis can represent the bigeye tuna stock in the Indian Ocean as possible, a common approach is to compile a length frequency distribution by combining the actually measured length frequency, and raising to its corresponding catches for each fishery, respectively.

Firstly, to estimate the catch at size for each fishery (h, $h = LL$ for longline fishery and $h = PS$ for purse seine fishery), the proportions of size interval, L, for the monthly size frequency distribution sampled were estimated by:

$$\hat{p}_{h,ijk} = \frac{f_{hijk}}{\sum_{k=1}^{96} f_{h,ijk}}$$

where $\hat{p}_{h,ijk}$ is the proportion and f_{hijk} is the frequency of 2 cm length-class interval k (k = 1 to 96) in month j (j = 1 to 12) in year i (i = 2006 to 2007) for gear h.

The estimated length frequency distribution (i.e. catch at size) for each class interval in month j and year i was raised by the monthly catch for gear h, $C_{h,ij}$ by:

$$\hat{f}_{h,ijk} = \hat{p}_{h,ijk} \times C_{h,ij}$$

where $C_{h,ij}$ is the catch in number for month j (j = 1 to 12) in year i (i =

2006 or 2007) for gear h obtained from the IOTC Data Summary No. XX for catch and effort data (CE data) and catch at size data of bigeye tuna in the Indian Ocean for the longline and purse seine fisheries, respectively.

Since the monthly catch at size for each gear ($\hat{f}_{h,ij}$) was obtained by raising actual size frequency with nominal monthly catch each year, both the catch at size could be combined into one complete catch at size by month and by year by summing both length frequency distribution (i.e. catch at size, $\hat{f}_{LL,ij}$ for longline fishery and $\hat{f}_{PS,ij}$ for purse seine fishery) for each class interval k in month j and year i as:

$$\hat{f}_{ijk} = \hat{f}_{LL,ijk} + \hat{f}_{PS,ijk}$$

To check the representative and to evaluate the fidelity of estimating catch at size combined from both fisheries, the monthly catch and annual catch in weight were obtained by multiplying the estimated catch at size for each length interval with the estimated mean weight derived from mean length at its length interval by the length weight relationship. The length-weight relationship (gilled and gutted weight to fork length) is

$$W_{\bar{L}} = 1.13 \times 1.59207 \times 10^{-5} \times \bar{L}^{3.04154}$$

where is the mean round weight $W_{\bar{L}}$ in kg at mean fork length $\bar{L}$ in cm for a length interval, and 1.13 is a conversion factor to convert a gilled and gutted body mass into a round weight.

As it was doing so, the estimated monthly catch in weight ($\hat{C}_{ij}$) for month j and year i was computed by

$$\hat{C}_{ij} = \sum_{k=1}^{96} \hat{f}_{ijk} \times W_k$$

And the estimated annual catch in weight for the year i was computed by summing the 12 monthly catches:

$$\hat{C}_i = \sum_{j=1}^{12} \hat{C}_{ij}$$

2.2 Estimation of von Bertalanffy growth parameters

The growth of bigeye tuna was expressed by von Bertalanffy growth function

(VBGF):

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

where L_t is the length at age t, L_∞ is the asymptotic length, K is the Body growth coefficient and t_0 is the hypothesized length at age zero (Quinn & Deriso, 1999).

VBGF parameters were estimated using ELEFAN-I, which is a modal progression fitting subroutine in FiSAT II (version 3.0, ICLARM 2006) for the three sets of length frequency distribution. The maximal length ($L_{,max}$) of the population was estimated according to Formacion et al. (1991) using L_∞ as the initial setting for the asymptotic length. Then this initial setting for L_∞ was used to the ELENFAN-I procedure to search the K value given the highest scores, which was used as the initial estimate of K. After that the response surface was plotted around the initial estimates of L_∞ and K. The combination of (L_∞, K) with highest score in the response surface was used as the final estimate of L_∞ and K. Once L_∞ and k were estimated, t_0 was estimated using the empirical formula from Pauly (1979):

$$\log(-t_0) = -0.3922 - 0.2752 \log(L_\infty) - 1.038 \log(K).$$

2.3 Estimation of mortality rates

The estimated catch at size data from the longline and purse-seine were separated and then length-converted catch curve was used to estimate Z (King 2007):

$$\ln[\frac{C_{(L_1 - L_2)}}{\Delta t}] = a(\text{constant}) - Z[\frac{(t_{L_1} + t_{L_2})}{2}]$$

where $C_{(L_1 - L_2)}$ is the catch in number between length L_1 and L_2 (the upper and lower limits of the length class, respectively), t_{L_1} and t_{L_2} is the age corresponding to L_1 and L_2, and Δt is the time taken for the species to grow through a particular length class. In which the ages used in length-converted catch curve were converted by the von Bertalanffy growth equation estimated herein before by

$$t = -\frac{1}{K} \ln(1 - \frac{L_t}{L_\infty})$$

where Δt in a length class with a upper limit of L_1 and lower limit of L_2 was estimated from above equation:

$$\Delta t_{(L_1-L_2)} = \frac{1}{K}\ln(\frac{L_\infty - L_1}{L_\infty - L_2})$$

Once Δt was calculated, the length-converted catch curve was drawn by plotting $\ln(\frac{C_{L_1-L_1}}{\Delta t})$ against mean relative age $t_{L_1-L_2}$. A regression was fitted using the data points excluding the points in the initial ascending data, points with very small sample sizes and closed to L_∞. The estimate of Z is indicated by the slope of this regression line (King, 2007).

Because M was highly related to growth coefficient (L_∞ and k) and sea surface temperate (*SST*), M was estimated using Pauly's empirical formula (Pauly, 1982):

$$\log(M) = 0.1228 - 0.1912\log(L_\infty) + 0.7485\log(K) + 0.1291\log(SST)$$

and F was thus estimated by $Z - M$.

2.4 Estimation of gear selectivity

Gear selectivity curves of longline and purse-seine were estimated using estimated catch a length data. Logistic curve was applied to represent the selection curve of longline:

$$S_t = \frac{1}{1+e^{(T_1+T_2t)}} ,$$

or the linear form is:

$$\ln(\frac{1}{S_t} - 1) = T_1 + T_2 \times t ,$$

where T_1 and T_2 are parameters and $\frac{T_1}{T_2}$ is the age at 50 % maturity.

The selection curve of longline was estimated also using length-converted catch curve from the estimated catch at length data. In the estimation of selection curve, the initial data points before fully-exploited were used (Sparre and Venema, 1992). The estimated population size was estimated by:

$$\hat{N}_{L_1-L_2} = \Delta t * e^{(a-Z*t_{L_1-L_2})}$$

and the observed selectivity was thus:

$$S_{obs,L_1-L_2} = \frac{C_{L_1-L_2}}{\hat{N}_{L_1-L_2}}$$

Then T_1 and T_2 were estimated using the linearized form of logistic select curve: $\ln(\frac{1}{S_{obs,L_1-L_2}} - 1) = T1 - T2 * t_{L_1-L_2}$ that the intercept and the slope was the estimate of

T_1 and T_2 , respectively.

On the other hand, the selection curve of purse seine was closed to normal and therefore catch at size was used to represent the selection curve according to Hovgård (2000):

$$S_l = \frac{C_l}{\max\limits_{l}\{C_l\}}$$

or

$$S_a = \frac{C_a}{\max\limits_{a}\{C_a\}}$$

where S_l and S_a, is the selectivity at length class l (l = 1,2,…L, the maximal observed length in the catch) and at age a (a = 1, 2, …, A, the maximal age).

2.5 Yield and spawner-biomass per recruit models analysis

The simulation models of yield per recruit (YPR) and spawner-biomass per recruit (SPR) of bigeye tuna under exploitation were calculated as:

$$YPR = \sum_{a=1}^{A} \frac{[1 - e^{-(M_a + S_a F)}] \times S_a F_a}{M_a + F_a} \times e^{-\sum_{i=t_r}^{a-1}(M_i + S_i F)} \times W_a$$

and

$$SPR = \sum_{a=1}^{A} p_a \times e^{-\sum_{i=t_r}^{a-1}(M_i + S_i F)} \times W_a ,$$

where S_a, M_a, and W_a is the selectivity, natural mortality rate and mean total weight at age a, (a = 1, 2, …, A), p_a is the proportion of bigeye tuna being sexually matured, which is 0 for age 0 to 2, 0.5 at age 3 and 1 for age over 4 (IOTC, 2008) and F is the fishing mortality rate, being the sum of all gears. S_a, M_a, and W_a were assumed to be temporally and spatially constant and only varied with fish age. F was further assumed to be constant among fish age (Knight, 2007).

Biological reference points (BRPs) were calculated to indicate current exploitation status. $F_{\max}$, the F value at which the YPR is at maximal, $F_{0.1}$, the F value at which the slope of YPR is 10 % of its initial value, $F_{30\%}$ and $F_{40\%}$, the F value at which the SPR is 30 % and 40 % of its initial value, were calculated from YPR and SPR models to indicate the effect of changing fishing mortality on the YPR and SPR.

However, bigeye tuna was mainly harvested by longline and purse seine fishery, which contributed collectively 95 % in catches in number and more than 98 % in weight (IOTC, 2008). Therefore simultaneous consideration of these two gears might result in conclusion closer to reality. To incorporate the effects of exploitation by multiple gears, a multi-gear yield and spawner per recruit (YPR_M and SPR_M) were calculated according to Booth (1999):

$$YPR_M = \sum_{a=1}^{A} \frac{[1-e^{-(M_a+\sum_j S_{aj}F_j)}]\times\sum_j S_{aj}F_j}{M_a+\sum_j S_{aj}F_j}\times e^{-\sum_{i=t_r}^{a-1}(M_i+\sum_j S_{ij}F_{ij})}\times W_a$$

and

$$SPR_M = \sum_{a=1}^{A} p_a \times e^{-\sum_{i=t_r}^{a-1}(M_i+\sum_j S_{ij}F_{ij})}\times W_a\,,$$

where F_j is the fishing mortality for gear, j = 1 for longline and 2 for purse seine..

Isopleths of YPR_M and SPR_M along with changing in fishing mortalities from longline and purse seine were plotted to reveal the interaction between these two fisheries on YPR_M and SPR_M.

3 Results

3.1 Nominal Catch and estimated catch at size

During 1981 to 1990, As figure 1 indicate that the annual catches of bigeye tuna by longline fishery were around 800 thousands to 1 million (30 to 60 thousand tons); The purse seine fishery started from 1983 and the annual catch of bigeye tuna gradually increased to more than 1.3 million individuals (4 to 12 thousand tons) caught in a year. The catch of bigeye tuna peaked during 1997 to 1999, which was more than 2.6 to 3 million individuals (110 to 112 thousand tons) and 4 to 8 million individuals (28 to 40 thousand tons) annually by longline and purse seine fisheries, respectively. The catches decreased gradually to about 1.67 million individuals (85 thousand tons) in 2006 and 1.78 million individuals (92 thousand tons) in 2007 for the longline fishery, and 1.67 million individuals (85 thousand tons) in 2006 and 1.78 million individuals (92 thousand tons) in 2007 for purse seine fishery (Fig.1).

Longline fishery targeted bigeye tuna with fork lengths mostly between 100 and 170 cm. Length distribution of bigeye tuna obtained from logbooks used in the present study (length distributions for January to March, 2006 and January to June, 2007) generally smoothed and appeared with only one peak, while those from on board sampling (length distributions for April to December, 2006 and July to December, 2007) fluctuated more greatly with multiple peaks and greater variation between months. On the other hand, the purse seine fishery targeted smaller tuna with fork lengths from 30 to 80 cm. Bigeye tuna with fork lengths from 120 to 160 cm appeared in the purse seine catches in January to September, 2006, but those large sized fish disappeared in the subsequent months.

3.2 Estimation of von Bertalanffy growth parameters

The catch at size data from longline and purse seine were pooled to estimate parameters of von Bertalanffy growth function using ELEFAN-I procedure in FiSAT II. First, the maximum length (L_{max}) was estimated as 210.86cm with 95 % confidence intervals of 204.24 to 217.48cm. Second, the estimated L_{max} was used as the initial value of L_∞ to scan the initial value of K given the highest score, which was 0.15 year^{-1}. Third, a response surface was plotted around the initial values of L_∞ and K to find the best combinations of (L_∞, K), which was at L_∞ = 211 cm and K = 0.15 year^{-1}. The t_0 was estimated as -0.67 year using Pauly's empirical formulae. The expected lengths at age were smaller than the growth curve from otolith (Stéquert and Conand 2003) until age 9 and smaller than Tankevish (1982) for all ages, but were larger than the growth curve obtained from tagging study (IOTC, 2007) at all ages (Fig. 2).

3.3 Estimation of instantaneous mortality coefficients

To calculate the length-converted catch curve, the combined catch at size of bigeye tuna sampled from 2006 and 2007 by longline and purse seine fisheries were used. As figure 3 indicates that two patterns with different slopes were found, i.e., one located at relative ages from 1.5 to 3.5 year, corresponding to the fork lengths of 40 to 80 cm; and the other was at the region with relative ages from 6.2 to 16 years, corresponding to fork lengths from 130 to 190 cm (Fig. 3). These two patterns may represent the fishery status of the bigeye tuna stock by purse seine and longline fisheries. Further, two regression lines were plotted for each pattern to estimate the instantaneous mortality coefficients (Z). Consequently, the Z values were estimated as 1.63 and 0.73 year^{-1} for purse seine and longline, respectively. Moreover, the natural mortality coefficient was approximately estimated using the Pauly's empirical formulae (Pauly 1984) as 0.25 year^{-1}. Therefore the current fishing mortality of bigeye tuna stock was computed by substracting the estimated natural mortality coefficient from total mortality coefficients as 0.38 and 1.48 year^{-1} for longline and purse seine fisheries, respectively (Table 1).

3.4 Estimation of gear selectivity

The gear selectivity of the longline was estimated using logistic curve from length-converted catch curve, and that of purse seine was estimated using observed catch at size data (Fig. 5). The selectivity of longline increased at relative age 4 and reached maximum when relative age was older than 7 years. Estimated 50 % age at selectivity was 5.3 years for longline fishery. Meanwhile, the selectivity of purse seine increased from relative age 1 and reached its maximum at relative age 1.5. After relative age 1.5, the selectivity decreased substantially and remained around 0.03 to 0.06 for relative age 5 to 10 (Fig. 5). Then the age-specific selectivity of longline and purse seine was calculated as in Table 2, which lengths were converted to ages using von Bertalanffy growth equation.

3.5 Yield and spawning biomass per recruit models analysis

Isopleths and response surface of Multi-gear yield per recruit (YPR_M) and relative spawning biomass per recruit ($\%SPR_M$) with different values of multiplier on fishing mortality rate of longline and purse seine were illustrated in Figures 6 and 7, respectively. YPR_M indicates that a reverse tendency is observed between the changes of fishing efforts suffered by longline and purse seine gears. (Figure 6). So long as SPR_M decreased faster as fishing mortality both from longline and purse seine increase (Figure 7), indicating the interaction of fishing efforts by different fisheries on YPR_M and SPR_M was observed. When the purse seine fishery was ignored (i.e. fishing mortality of purse seine = 0) and under the current fishing mortality of longline (fishing mortality of longline = 1), YPR_M of longline (7.2 kg ind^{-1}) did not reach its maximum, and the relative SPR_M was 17.4 %, indicating the growth overfishing did not occur and the spawning biomass was just below to the suggested 20 % level of recruitment overfishing. However, under the current exploitation (i.e. fishing mortality of both purse seine and longline = 1), YPR_M and SPR_M became much smaller, being 1.1 kg ind^{-1} and 2 %, respectively. Therefore, ignoring the exploitation of one gear would overestimate both YPR_M and SPR_M and resulted in optimistic conclusions.

Relative changes in YPR_M ($\%YPR_M$) compared to the current fishing mortality and SPR_M relative to unexploited status were shown in Tables 3 and 4, which $\%YPR_M$ was defined as 0 % under the current fishing mortality rate (black circle in Table 3) and % SPR_M was defined as 100 % when there is no exploitation. Reductions of the fishing mortality rate from purse seine are expected to result in substantial improvements in YPR_M. It increased about 97 to 191 % when M_{PS} reduced to 0.4 to 0.6, and the increase of YPR_M was much significant under low M_{PS} (Table 3, Figure 6). Meanwhile, it is important to protect spawning biomass, that $\%SPR_M$ was expected to remain above 20 % when from the light green zone in Table 4 and the isocline of 20 in Fig. 7. These results implied that exploitation by purse seine seemed having greater impact on YPR_M and might result in lower $\%SPR_M$.

4 Discussion

4.1 Estimation of catch at size

Data from on board observer directly represented the actual catch at size for sampled fleets. Since the gear types were similar between Taiwan and Japan longline fleets, data from observers were superior to data from logbook and probably more plausible to estimate the catch at size of bigeye tuna from longline fishery in the Indian Ocean. However, the sample sizes from observers were small, and consequently the distributions of estimated catch at size from observer data were inevitably more variable with more noises and greater degree of scattering than from logbook data. Catch at size from purse seine fishery was estimated from IOTC database, which included more than 40 % of total catch in numbers and has been examined by IOTC secretariat (IOTC, 2008). Therefore, it is considered to plausible to represent the whole catch at size data from purse seine.

4.2 Growth curve

The estimation of von Bertalanffy growth curve of bigeye tuna in the Indian Ocean was computed using catch at size applied to simulate modal progresses. The result was compared with reported previously using vertebrae, scale, otoliths and tag-recapture experiments (Tankevich, 1982; Stéquert & Conand, 2004; Eveson &

Million, 2008, Figure 2). The current estimate is within the range of those estimated previously, implying that the estimated growth curve was probably realistic for Indian bigeye tuna. Estimated value of L_∞ (in cm fork length) of this study (211 cm) was larger than those in recent two studies (169 cm for Stéquert and Conand (2004) and 160 cm for Eveson and Million (2008)). Because the maximum observed length was highly positively correlated to L_∞ (Froese & Binohlan, 2000), therefore the higher L_∞ in this study was possibly due to higher maximum fork length in the sample (200 cm in this study, 165 cm in Stéquert and Conand, 2004 and 110 cm in Eveson and Million, 2008). However, the maximum observed length in Tankevich was 183 cm, and L_∞ was the highest, which might be due to the higher lengths-at-age for the young age individuals (Whitelaw and Unnithan, 1997) than data used for other studies, consequently, those data may result in smaller K value, and consequently higher L_∞ than the others.

4.3 Mortality

The total mortality rate (Z) of bigeye tuna was estimated using length-converted catch curve. Z is high for purse seine fishery (1.63 year^{-1}) and relatively low for longline fishery (0.63 year^{-1}). Because the purse seine fishery targeted mainly on juveniles of about ages 1 to 2, the empirical estimate of natural mortality rate from von Bertalanffy growth parameters might be low to represent the high natural mortality rate of juveniles. Nishida & Shono (2006) used a natural morality of 0.8 year^{-1} for age 0+ to 1+ in and 0.4 in subsequent age classes during analysis using age structured production model, and Lorenzen (2000) suggested that the natural mortality was during their early life stage. The high estimated total mortality of purse seine fishery might possibly due to the high juvenile catch level, and therefore, estimates of the current fishing mortality of purse seine fishery might be overestimated if the natural mortality was as estimated in the present study.

On the other hand, Shono et al. (2006) estimated the fishing mortality rate of the longline fishery was 0.22 to 0.49 year^{-1}, Nishida and Shono (2006) as 0.2 year^{-1}, which were close to our estimate of 0.38 year^{-1}. However, there is still some uncertainty about exact natural mortality rate. Because our empirical estimate is lower than the one used in Shono et al. (2006) and Nishida and Shono (2006), following estimate of the current fishing mortality rate of longline fishery might be slightly overestimated.

4.4 Yield and spawning biomass per recruit models analysis

Apparently, when a fish stock were exploited by two or more fisheries simultaneously, the stock status evaluated from only one among them and ignored the others might technically result in an underestimation of the actual exploitation to indicate that the stock assessment was too optimistic. Moreover, harvesting different age classes by different fisheries probably resulted in competition among fisheries. The fishing mortality rate of purse seine was found to reduce the yield per recruit when the fishing mortality rate from longline remained (Figure 6). Immature juvenile bigeye tuna are targeted by purse seine fishery. Those juveniles might contribute to produce maximal yield per recruit, and therefore influence the potential yield of longline fishery in the future.

On the other hand, the spawning stock biomass per recruit decreased with increasing fishing mortality of both longline and purse seine fisheries that targeted on adults and juveniles, respectively. Our model did not consider the effects of different body sizes on the quality and survival of future progeny, nor was the reduced population stability due to selectively harvesting the large spawner (Anderson et al., 2008) examined.

The recent stock assessment studies (Nishida & Shono, 2006; Shono et al., 2006; Hillary, 2008) indicated that overfishing for the bigeye tuna was not observed. Hillary (2008) used Japanese longline CPUE to fit the surplus production model and suggested that the current harvest rates of longline fishery was still below the harvest rate given the maximum sustainable yield (MSY), and the stock biomass in 2007 was likely greater than B_{MSY}, with probability of 86.3 %. However, the effects of purse seine fishery on the bigeye tuna were not considered, which was found to compete the catchable bigeye tuna resources with longline fishery and also considerably reduce the juveniles that grow and recruit to spawning stock biomass. Thus, the multi-gear approach might simulate the relation of both fisheries and may provide the stock status results much closer to reality.

5 Acknowledgements

The authors thank National Science Council provide financial support to conduct this research (NSC96-2313-B-002-039-MY3) to C.C. Hsu. And appreciation is indebted to the Fisheries Agency, Council of Agriculture who supported a two-year sampling project to collect the actual sizes of bigeye tuna in the Indian Ocean. Thanks are extended to Mr. Chen, Chin-Tien, who is the boat-owner of Yu-you No. 127 and 137 for his great helps to allow researchers to measure the catches on board in 2006 and 2007.

6 References:

Anonymous. 2008. Growth of tropical tunas using the Laslett, Polacheck and

Eveson (LEP) method. A document presented to the Indian Ocean Tuna Commission Working Party on Tropical Tunas in 2008. IOTC-2008-WPTT-09.

Appleyard, S.C., R. D. Ward, and P. M. Grewe. 2000. Genetic stock structure of bigeye tuna in the Indian Ocean using mitochondrial DNA and microsatellites. Journal of Fish Biology 60, 767 – 770. • • •

Arrizabalaga, H. 2008. Methods to estimate fishing capacity, using stock assessment information: sensitivity tests and application to Pacific, Atlantic and Indian Ocean tuna stocks. IOTC Science Committee. IOTC-2008-SC-INF03

Booth, A. J. 1999. Development of a multispecies-multigear per recruit model that incorporates parameter variability. Report of the third workshop on the assessment of shrimp and groundfish fisheries on the Brazil-Guianas Shelf. Belém, Brazil, 24 May - 10 June 1999. FAO Fisheries Report No. 628, 33 – 36. FAO, Rome.

Chiang, H. C., **C. C. Hsu**, G. C. C. Wu, S. K. Chang and H. Y. Yang. 2008. Population structure of bigeye tuna (*Thunnus obesus*) in the Indian Ocean inferred from mitochondrial DNA. Fisheries Research, 90:305-312.

Collette, B.B. and C. E. Nauen. 1983. FAO species catalogue. Scombrid of the world. FAO, Rome.

Dorizo, J., C. Assan, and A. Fonteneau. 2008. Analysis of tuna catches and CPUEs by Purse Seiners fishing in the Western Indian Ocean over the period January to July 2008. Doc. IOTC 2008-WPTT-20.

Eveson, J. P. and J. Million. 2008. Estimation of growth parameters for yellowfin, bigeye and skipjack tuna using tag-recapture data. IOTC Working Party on Tagging Data Analysis. IOTC-2008-WPTT-09.

Formacion, S.P., J. M. Rongo and V. C. Sambilay. 1991. Extreme value theory applied to the statistical distribution of the largest lengths of fish. Asian Fisheries Science, 123 – 135.

Froese, R. and C. Binohlan. 2000. Empirical relationships to estimate asymptotic length, length at first maturity and length at maximum yield per recruit in fishes, with a simple method to evaluate length frequency data. Journal of Fish Biology 56, 758 – 753.

Hovgård, H. and H. Lassen. 2000. Manual on estimation of selectivity for gillnet and longline gears in abundance surveys. FAO Fisheries Technical Paper 397. FAO, Rome.

Hillary, R. M. 2008. Surplus production analyses for Indian Ocean yellowfin and bigeye tuna. A document presented to the Indian Ocean Tuna Commission Working Party on Tropical Tunas in 2008. IOTC-2008-WPTT-12.

Hsu, C.C. 2006. Standardized catch per unit effort of bigeye tuna (*Thunnus obesus*) caught by Taiwanese longline fleets in the Indian Ocean by general linear mixed model. IOTC working party on tropical tunas. IOTC-2006-WPTT-20.

IOTC. 2008. Estimation of catch-at-size, catch-at-age and total catch per area. IOTC working party on tropical tunas. IOTC-WPTT-2008-08.

King, M. 2007. Fisheries Biology, Assessment and Management. 2nd edition. Blackwell Publishing. Oxford, UK. 382 pp.

Nishida , T. and H. Shono. 2006. Updated stock assessment of bigeye tuna (*Thunnus obesus*) resource in the Indian Ocean by the age structured production model (ASPM) analyses (1960-2004). IOTC working party on tropical tunas. IOTC--2006-WPTT-22.

Pauly, D. 1979. Gill size and temperature as governing factors in fish growth: a generalization of von Bertalanffy's growth formula. Berichte des Institus für Meereskunde and der Universität Kiel 63, 156 pp.

Pauly, D. 1980. On the interrelationships between natural mortality, growth parameters and mean environmental temperatures in 175 fish stocks. Journal du Conseil international pour l'Exploration de la Mer 39, 175 – 192.

Pianet, R., P. Bretaudeau, and A. Hervé. 2008. French purse-seine tuna fisheries statistics in the Indian Ocean, 1981-2007. IOTC working party on tropical tunas. IOTC-2008-WPTT-06.

Quinn, J.T.II and R. B. Deriso. 1999. Quantitative Fish Dynamics. Oxford University Press, New York. 542 p.

Shono, H., H. Okamoto, and Y. Senba. 2006. Preliminary stock assessment for bigeye tuna in the Indian Ocean using Stock Synthesis II (SS2). IOTC working party on tropical tunas. IOTC-2006-WPTT-18.

Soto M., E. Chassot and F. Marsac. 2008. Sandardized catch rates for yellowfin (*Thunnus albacares*) and skipjack (*Katsuwonus pelamis*) for the European purse seine fleet of the Indian Ocean, 1984-2007. A document presented to the Indian Ocean Tuna Commission Working Party on Tropical Tuna s in 2008. IOTC-2008-WPTT-26

Sparre, P. and S. C. Venema. 1992 Introduction to tropical fish stock assessment. FAO Fisheries Technical Paper 306/1. FAO, Rome.

Stéquert, B. and Conand (2004). Age and growth of Bigeye tuna (*Thunnus obesus*) in the Western Indian Ocean. Cybium 28, 163 – 170.

Tankevich, P.B. 1982. Age and growth of bigeye tuna in the Indian Ocean. Journal of Ichthyology 22, 26 – 31.

Whitelaw, A.W. and V. K. Unnithan. 1997. Synopsis of the Distribution, Biology and Fisheries of the Bigeye Tuna (*Thunnus obesus*, Lowe) with a Bibliography. CSIRO Marine Lavatories Report 228. 62 pp.

Table 1. Estimated values of current fishing mortality rate for longline ($F_{cur,LL}$) and purse seine ($F_{cur,PS}$), natural morality rate (M_P) from Pauly's empirical formulae, von Bertalanffy growth parameters (L_∞, K and t_0) and maximum age used in multi-gear YPR and SPR model.

Parameters	Value
$F_{cur,LL}$ (year^{-1})	0.38
$F_{cur,PS}$ (year^{-1})	1.48
M_P (year^{-1})	0.25
L_∞ (cm)	211
K (year^{-1})	0.15
t_0 (year)	-0.67
Maximum age (year)	9

Table 2. Age-specific selectivity of longline ($S_{a,LL}$) and purse seine ($S_{a,PS}$), Lorenzen's natural mortality ($M_{L,a}$) and maturity fraction (Mat_a) used in pooled and multi-gears YPR and SPR models.

Ages	$S_{a,LL}$	$S_{a,PS}$	$M_{L,a}$	Mat_a
0+	0.000	0.763	1.355	0
1+	0.000	1.000	0.812	0
2+	0.001	0.221	0.532	0
3+	0.010	0.069	0.409	0.5
4+	0.116	0.032	0.342	1
5+	0.620	0.064	0.302	1
6+	0.953	0.081	0.274	1
7+	0.996	0.034	0.254	1
8+	1.000	0.015	0.240	1
9+	1.000	0.009	0.229	1

Table 3. Percent change in YPR_M (%YPR_M) of bigeye tuna with various multipliers on the fishing mortality of longline (M_{LL}) and purse seine (M_{PS}). The current level of fishing mortality is indicated by the circle.

%YPR_M	M_{PS}																				
M_{LL}	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2
0	-100%	-47%	-17%	-2%	4%	4%	0%	-6%	-13%	-20%	-27%	-33%	-39%	-44%	-49%	-53%	-57%	-60%	-63%	-65%	-68%
0.1	58%	68%	67%	59%	48%	35%	23%	11%	-1%	-11%	-20%	-28%	-35%	-42%	-47%	-52%	-56%	-59%	-62%	-65%	-67%
0.2	185%	160%	133%	107%	83%	61%	41%	24%	9%	-4%	-15%	-25%	-33%	-40%	-46%	-51%	-55%	-59%	-62%	-65%	-67%
0.3	285%	233%	186%	145%	111%	81%	56%	34%	17%	2%	-11%	-22%	-31%	-38%	-44%	-50%	-54%	-58%	-62%	-65%	-67%
0.4	365%	290%	228%	176%	133%	97%	67%	43%	23%	6%	-8%	-19%	-29%	-37%	-44%	-49%	-54%	-58%	-61%	-64%	-67%
0.5	428%	336%	261%	200%	150%	109%	76%	49%	27%	9%	-6%	-18%	-28%	-36%	-43%	-49%	-54%	-58%	-61%	-64%	-67%
0.6	477%	371%	286%	218%	163%	119%	83%	54%	31%	12%	-4%	-16%	-27%	-35%	-42%	-48%	-53%	-58%	-61%	-64%	-67%
0.7	516%	399%	306%	232%	173%	126%	88%	58%	34%	14%	-2%	-15%	-26%	-35%	-42%	-48%	-53%	-57%	-61%	-64%	-67%
0.8	545%	420%	321%	243%	181%	132%	92%	61%	36%	15%	-1%	-15%	-26%	-34%	-42%	-48%	-53%	-57%	-61%	-64%	-67%
0.9	567%	436%	333%	251%	187%	136%	95%	63%	37%	16%	-1%	-14%	-25%	-34%	-42%	-48%	-53%	-57%	-61%	-64%	-67%
1	583%	447%	341%	257%	191%	139%	97%	64%	38%	17%	0%	-14%	-25%	-34%	-42%	-48%	-53%	-57%	-61%	-64%	-67%
1.1	595%	456%	347%	261%	194%	141%	99%	65%	39%	17%	0%	-14%	-25%	-34%	-41%	-48%	-53%	-57%	-61%	-64%	-67%
1.2	603%	461%	351%	264%	196%	142%	100%	66%	39%	18%	0%	-13%	-25%	-34%	-41%	-48%	-53%	-57%	-61%	-64%	-67%
1.3	608%	465%	353%	265%	197%	143%	100%	66%	39%	18%	1%	-13%	-25%	-34%	-41%	-48%	-53%	-57%	-61%	-64%	-67%
1.4	611%	466%	354%	266%	197%	143%	100%	66%	39%	18%	0%	-13%	-25%	-34%	-42%	-48%	-53%	-57%	-61%	-64%	-67%
1.5	611%	467%	354%	266%	197%	143%	100%	66%	39%	18%	0%	-14%	-25%	-34%	-42%	-48%	-53%	-57%	-61%	-64%	-67%
1.6	611%	466%	353%	265%	196%	142%	100%	66%	39%	17%	0%	-14%	-25%	-34%	-42%	-48%	-53%	-57%	-61%	-64%	-67%
1.7	609%	465%	352%	264%	196%	142%	99%	65%	39%	17%	0%	-14%	-25%	-34%	-42%	-48%	-53%	-57%	-61%	-64%	-67%
1.8	606%	463%	350%	263%	195%	141%	98%	65%	38%	17%	0%	-14%	-25%	-34%	-42%	-48%	-53%	-57%	-61%	-64%	-67%
1.9	603%	460%	348%	261%	193%	140%	98%	64%	38%	16%	-1%	-14%	-25%	-34%	-42%	-48%	-53%	-57%	-61%	-64%	-67%
2	599%	457%	346%	260%	192%	139%	97%	64%	37%	16%	-1%	-14%	-26%	-35%	-42%	-48%	-53%	-58%	-61%	-64%	-67%

Table 4. SPR_M relative to unexploited status (%SPR_M) of bigeye tuna with various multipliers on the fishing mortality of longline (M_{LL}) and purse seine (M_{PS}). The current level of fishing mortality is indicated by the circle.

% SPR_M	M_{PS}																				
M_{LL}	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2
0	100%	74%	55%	41%	30%	22%	17%	12%	9%	7%	5%	4%	3%	2%	2%	1%	1%	1%	0%	0%	0%
0.1	89%	66%	49%	36%	27%	20%	15%	11%	8%	6%	4%	3%	2%	2%	1%	1%	1%	1%	0%	0%	0%
0.2	79%	59%	43%	32%	24%	18%	13%	10%	7%	5%	4%	3%	2%	2%	1%	1%	1%	1%	0%	0%	0%
0.3	70%	52%	39%	29%	21%	16%	12%	9%	7%	5%	4%	3%	2%	1%	1%	1%	1%	0%	0%	0%	0%
0.4	63%	47%	35%	26%	19%	14%	11%	8%	6%	4%	3%	2%	2%	1%	1%	1%	1%	0%	0%	0%	0%
0.5	57%	42%	31%	23%	17%	13%	10%	7%	5%	4%	3%	2%	2%	1%	1%	1%	1%	0%	0%	0%	0%
0.6	51%	38%	29%	21%	16%	12%	9%	7%	5%	4%	3%	2%	2%	1%	1%	1%	0%	0%	0%	0%	0%
0.7	47%	35%	26%	19%	14%	11%	8%	6%	4%	3%	2%	2%	1%	1%	1%	1%	0%	0%	0%	0%	0%
0.8	43%	32%	24%	18%	13%	10%	7%	5%	4%	3%	2%	2%	1%	1%	1%	1%	0%	0%	0%	0%	0%
0.9	39%	29%	22%	16%	12%	9%	7%	5%	4%	3%	2%	2%	1%	1%	1%	0%	0%	0%	0%	0%	0%
1	36%	27%	20%	15%	11%	8%	6%	5%	3%	3%	2%	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%
1.1	33%	25%	18%	14%	10%	8%	6%	4%	3%	2%	2%	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%
1.2	31%	23%	17%	13%	10%	7%	5%	4%	3%	2%	2%	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%
1.3	28%	21%	16%	12%	9%	7%	5%	4%	3%	2%	2%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%
1.4	26%	20%	15%	11%	8%	6%	5%	4%	3%	2%	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%
1.5	25%	19%	14%	10%	8%	6%	4%	3%	2%	2%	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%
1.6	23%	17%	13%	10%	7%	5%	4%	3%	2%	2%	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%
1.7	22%	16%	12%	9%	7%	5%	4%	3%	2%	2%	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%
1.8	21%	15%	12%	9%	7%	5%	4%	3%	2%	2%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%
1.9	19%	15%	11%	8%	6%	5%	3%	3%	2%	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%
2	18%	14%	10%	8%	6%	4%	3%	2%	2%	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%

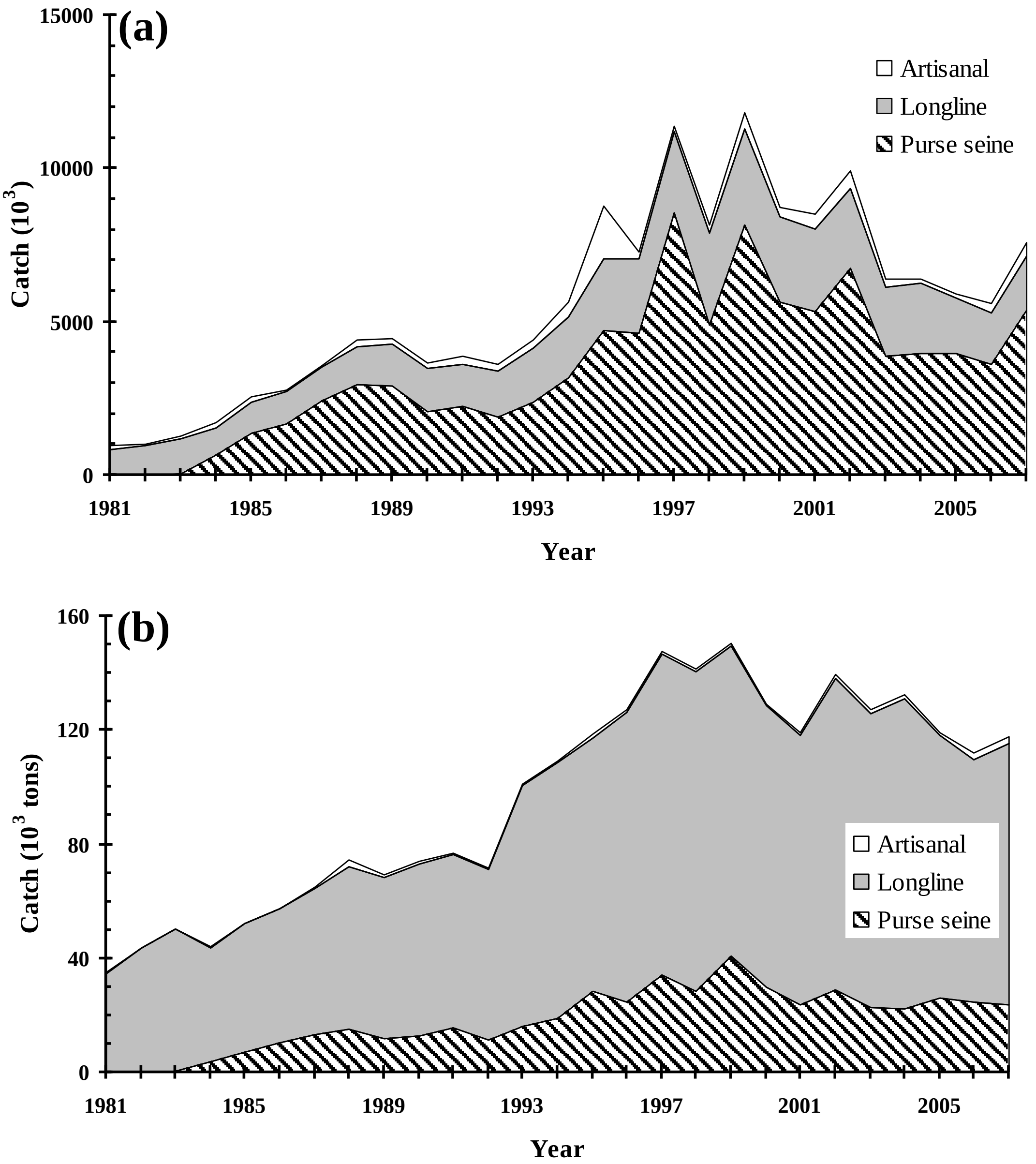

Fig.1. Total catches in (a) numbers (10^3 inds) and (b) weights (10^3 tons) of bigeye tuna by longline (grey), purse seine (shaded) and artisanal fisheries (white) from 1981 to 2007 according to IOTC (2008).

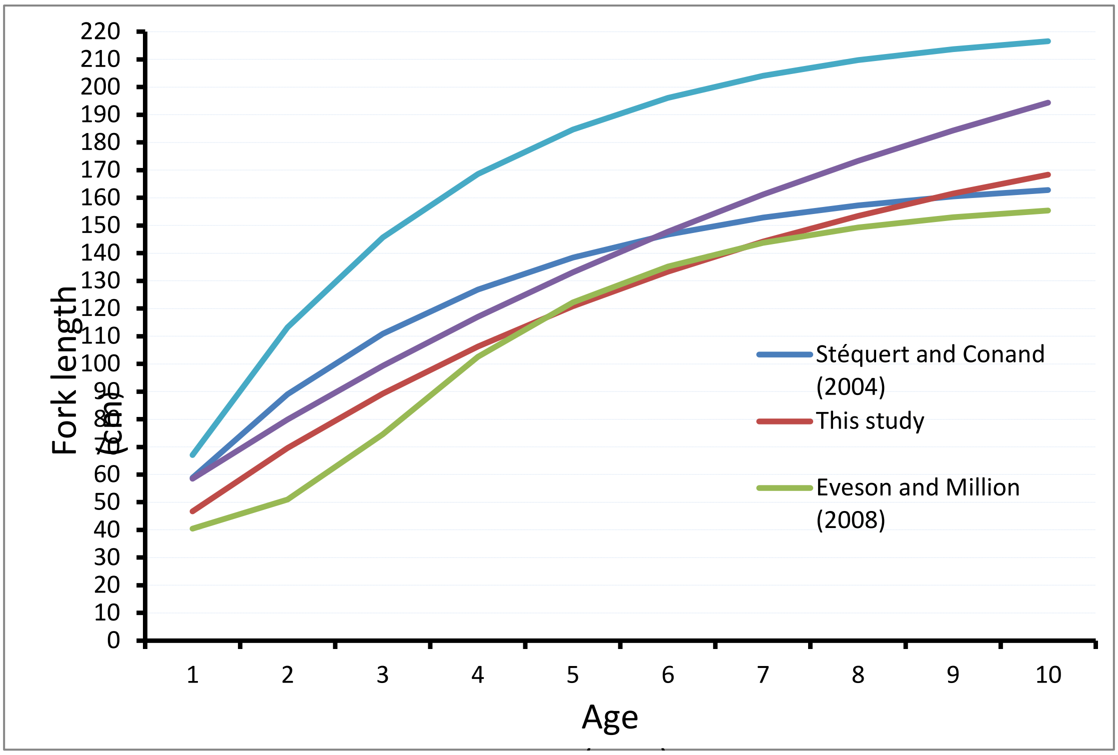

Fig. 2. Von Bertalanffy growth curves obtained from the present study and compared with reported previously by different hard parts and tag-recapture study.

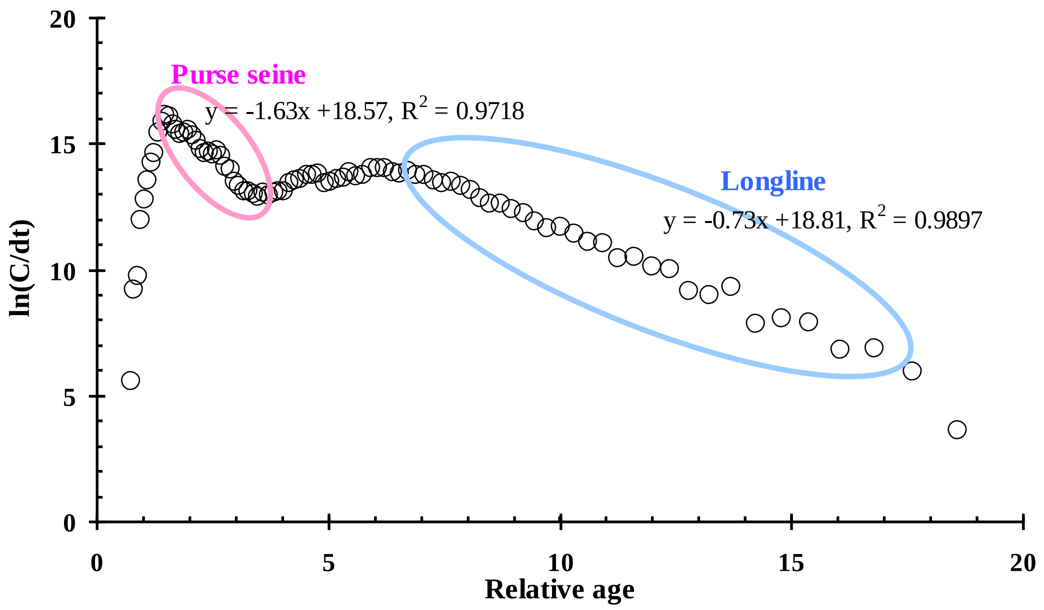

Fig. 3. Length-converted catch curve for bigeye tunas, in which gears and months were pooled. Two regions of different slopes were found and used to estimate the instantaneous total mortality rate for purse seine (purple region) and longline (blue region).

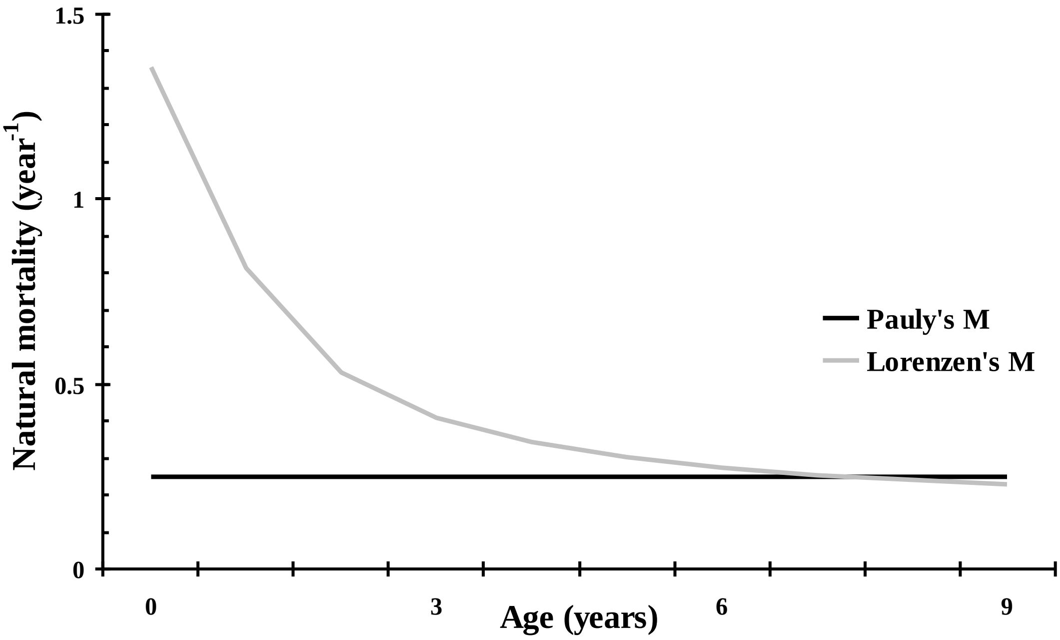

Fig. 4. Diagram showing Pauly's M (Pauly, 1980), which was assumed constant for all age classes and Lorenzen's M (Lorenzen, 1996), which was assumed to decreased with increasing body mass and age.

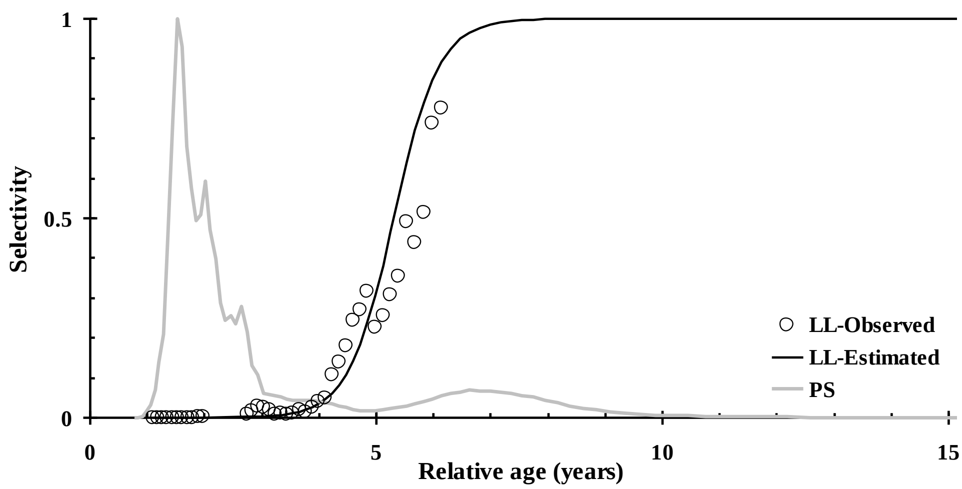

Fig. 5. Observed (open circles) and estimated selectivity (black line) of longline (LL) using logistic curve, and estimated selectivity of purse seine (PS) using observed catch at size data.

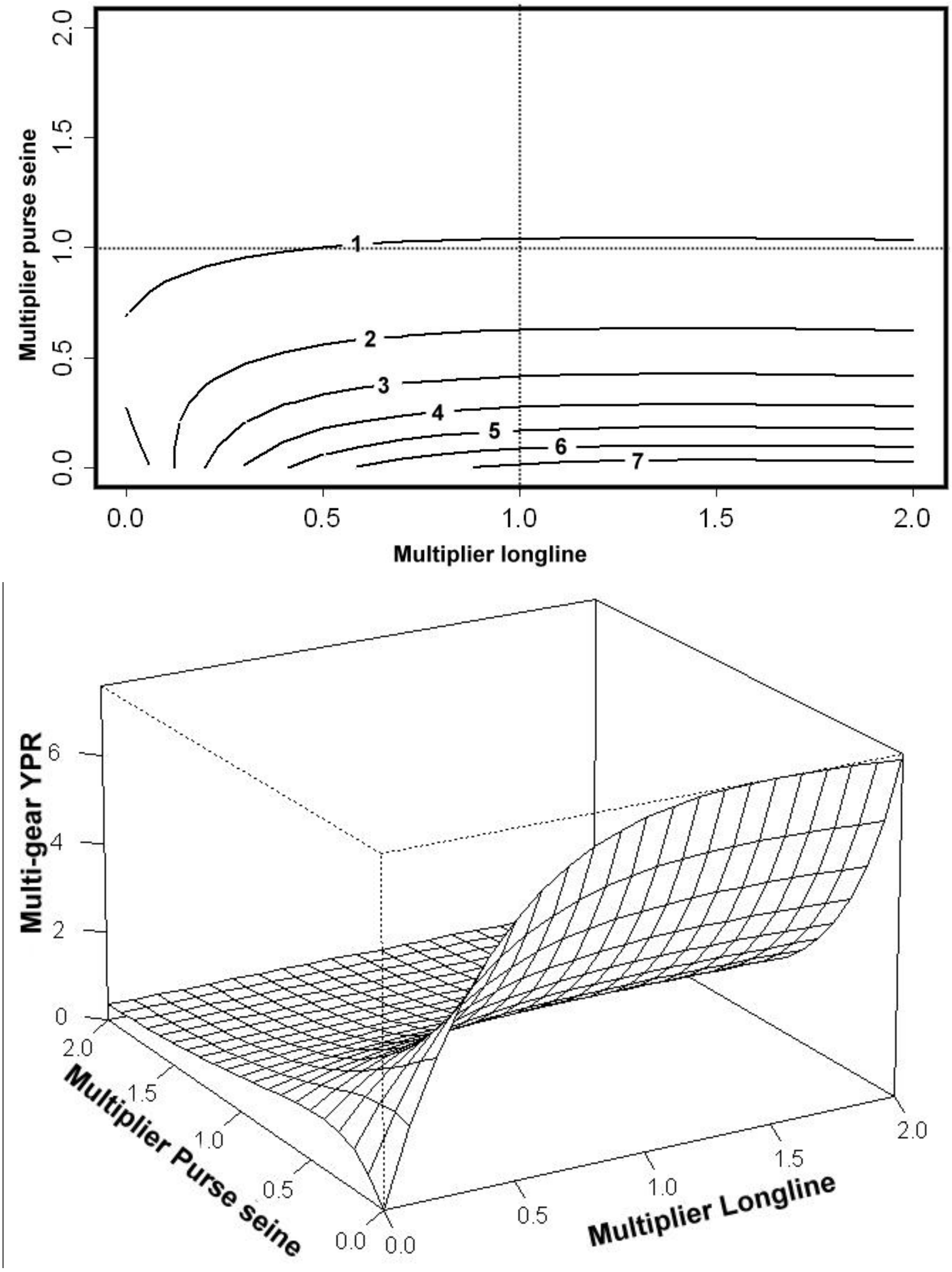

Fig. 6. Isopleth (upper panel) and response surface (lower panel) of multi-gear YPR with various values of multiplier on fishing mortality in longline and purse seine. Broken lone indicated current fishing mortality (multiplier = 1).

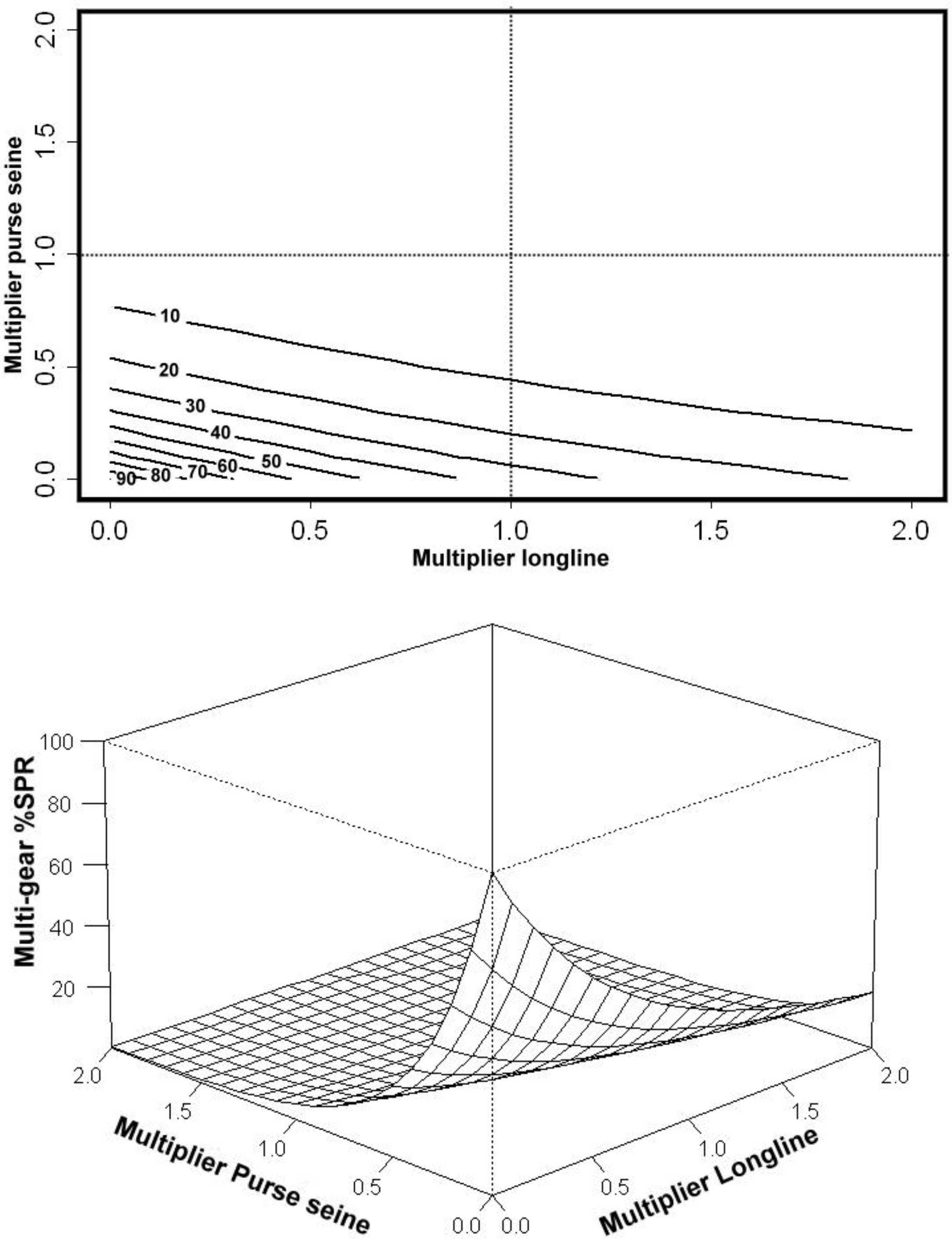

Fig. 7. Isopleth (upper panel) and response surface (lower panel) of multi-gear relative SPR (%SPR) with various values of multiplier on fishing mortality in longline and purse seine.