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應用非平衡生產量模式評估太平洋黑鮪系群

Stock assessment of Pacific bluefin tuna (*Thunnus orientalis*) by non-equilibrium global production model analysis

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摘要

太平洋黑鮪(*Thunnus orientalis*)為一種高經濟價值的溫帶鮪類。從 1950 年代起，即開始對於該資源進行開發利用，而每年的漁獲量也逐漸增加。在北太平洋主要的作業國家有日本、韓國、台灣、美國及墨西哥；而捕撈的漁法有圍網、延繩釣、曳繩釣、一支釣、定置網及拖網。本研究蒐集 1952 至 2006 年北太平洋主要漁業的漁獲量(catch)及單位努力漁獲量(CPUE)，利用非平衡生產量模式(non-equilibrium production model)對太平洋黑鮪進行資源評估。

估計所得 *T.orientalis* 的最大持續生產量(MSY)介於 19,000 至 26,000 噸之間。利用估計所得的 MSY 進行 15 年的模擬，發現若將每年的漁撈水準(catch level)設定大於 18,000 噸時，15 年後的資源量會接近或小於達到 MSY 所需的資源量(B_{MSY})，並且將會大於達到最大持續生產量(MSY)的漁獲死亡率(F_{MSY})。因此，建議將 *T.orientalis* 的最大容許漁獲量(TAC)設定在小於 18,000 噸。

關鍵字：太平洋黑鮪、非平衡生產量模式、最大持續生產量、最大容許漁獲量

Abstract

Pacific bluefin tuna (*Thunnus orientalis*) is a temperate tuna with highly economic value. The exploitation of Pacific bluefin tuna began in 1950s and was mainly utilized by Japan, Korea, Taiwan, United States of America and Mexico in the North Pacific Ocean and the fishing methods are mainly purse seine, longline, troll, pole and line, set net and trawl. In this study, I gathered catch and CPUE data of these fisheries from 1952 to 2006 and used the non-equilibrium production model for stock assessment of *T. orientalis*.

The estimated maximum sustainable yield (MSY) by non-equilibrium production model is between 19,000 ~ 26,000 metric tons. From projection results, the biomass of *T.orientalis* would be closer or lower than biomass at MSY (B_{MSY}) and fishing mortality would exceed fishing mortality at MSY (F_{MSY}) if catch level greater than 18,000 MT. So suggest setting total allowance catch (TAC) of Pacific bluefin tuna smaller than 18,000 metric tons.

Key words：Pacific bluefin tuna(*Thunnus orientalis*)、non-equilibrium production model、maximum sustainable yield (MSY)、total allowance catch (TAC)

Contents

1. Introduction

1.1 Description of bluefin tuna

Bluefin tuna *Thunnus* sp is a highly economic species widely distributed in Pacific Ocean, Atlantic Ocean and Mediterranean Sea. The bluefin tuna include *T. thynnus* that distributes in the Atlantic Ocean and Mediterranean Sea, *T. orientalis* that distribute mainly in Northern Pacific, and *T. maccoyii* that almost occurs in high latitude oceans of the southern hemisphere including Indian, Atlantic and South Pacific Oceans.

The *T. orientalis* is an eurythermal and epipelagic species that inhabits within the thermal ranges between 5℃ - 29 ℃ and between 1 to 200 m in depth, it is widely distributed in the North Pacific Ocean between 50°N - 5°S and 110°E -117°W. The maximum captured fish size of Pacific bluefin tuna was 300 cm in fork length and 550 kg in weight.

1.2 Description of fisheries

The fishery of Pacific bluefin tuna has been recorded since early 1950s, and the annual catches reported from 1952 to 2006 ranged between 8,600 metric tons in 1990 to 40,500 metric tons in 1956 (Table 1 and Fig.1) (Anon. 2007). Historical catches increased from 1952 to 1956, reached a maximum, and then declined to about 11,000 mt. In 1970, the catches increased again up to 34,641 mt in 1981, fluctuated and declined afterward to about 8,600 mt in 1990, then increased to a recent maximum level of about 32,000 mt in 2000. It maintained between 19,000 mt and 27,000 mt in recent five years.

T. orientalis in Northern Pacific are mainly caught by purse seine, longline, troll, pole and line, set net and gillnet (Collette and Nauen, 1983), and Fig. 2 is approximate distribution of these fisheries. According to fishing areas, these fisheries could be divided into three groups, i.e., the eastern Pacific Ocean, the western Pacific Ocean and the high seas fisheries (IATTC 2001). In the eastern Pacific Ocean, catches are mainly taken by American and Mexican purse seiners; in the western Pacific Ocean, those are taken by Japanese, Taiwanese and Korean fishers, using purse seiners, longliners, troll, pole and line, set netters and gillnetters (Park et al., 1994; Tomlinson, 1996; Ito and Machado, 1997; Uosaki and Bayliff, 1999). More details on the fisheries and catches are described as following nations:

1.2.1 The western Pacific Ocean

1.2.1.1 Japan

(1) Coastal longline fishery

The catch of Japanese coastal longline fishey occupied approximately 3% of the annual total catch in Japan and the annual total catch was between 67 mt to 3183 mt from 1970 to 2006. The fishing area of coastal longline fishery is mainly in the coastal waters of Japan in Miyako, Ishigaki and Irimote and mainly targets for young/mature adult Pacific bluefin tuna.

(2) Offshore & distant-water longline

The catch of Japanese offshore and distant-water longline fishery occupied roughly 6% of the annual total catch in Japan and the annual total catch of Japanese offshore & distant-water longline fishery was between 44 mt to 6791 mt from 1952 to 2006. The fishing area of this fishery is mainly in the North Pacific Ocean, and the targeted size of Pacific bluefin tuna mainly ranges between 100 and 200 kg.

(3) Purse seine

The catch of purse seine fishery occupied approximately 56% of the annual total catch in Japan, and the annual total catch of Japanese purse seine fishery was between 4,457 mt to 30,204 mt from 1952 to 2006. The fishing area of Japanese purse seine fishery could be divided into two parts: Pacific Ocean of eastern Japan and Sea of Japan, and East China Sea. In the former area, the target is mature individuals in summer (Jul-Aug) and immature ones in spring (Apr-Jun). In the East China Sea, it is mainly caught by small purse seine and targets immature individuals smaller than 5 kg.

(4) Pole and line

The Japanese pole and line fishery mainly targeted to catch skipjack and albacore, and occasionally caught Pacific bluefin tuna. The catch of Japanese pole and line fishery occupied approximately 3% of the annual total catch in Japan, and the annual total catch of Japanese pole and line fishery was between 34 mt to 4,060 mt from 1952 to 2006. The Japanese Pole and line fishery mainly targets for fish size less than 100 cm in fork length and mainly concentrats in the range 30-80 cm in fork length.

(5) Troll

The catch of Japanese troll fishery occupied approximately 12% of the annual total catch in Japan, and the annual total catch of Japanese troll fishery was between 546 mt to 5,121 mt from 1952 to 2006. Japanese Troll fishery mainly operated in coastal area of Japan. The size of fish caught by this fishery is less than 100 cm in fork length and mainly concentrated in the 20-60 cm FL range with the weight less than 3 – 4 kg.

(6) Set net

The catch of Japanese set net fishery occupied around 12% of the annual total catch in Japan, and the annual total catch of Japanese set net fishery ranged between 716 mt to 6,019 mt from 1952 to 2006. Japanese set net fishery mainly operates in coastal area of Japan. It targets to catch a wide fish size of Pacific bluefin tuna , but mainly juveniles in recent years.

1.2.1.2 Taiwan

Pacific bluefin tuna are traditionally exploited by Taiwan's small scale tuna longline vessels (<100 GRT) annually from late April to June due to the behavior that they aggregate for spawning in the waters off eastern Luzon and Taiwan during this period. The catch of this fishery mainly unloaded at three domestic ports, Tungkang (>70%), Suao and Hsinkang. The annual total catch of Taiwanese longline fishery ranged from 1 mt to 3809 mt from 1965 to 2006, and mainly targets for large adults.

1.2.1.3 Korea

The Korean purse seine fishery mainly targets to catch mackerel, and Pacific bluefin tuna is caught by accident. The fishing area of Korean purse seine fishery is major in Cheju and Tsushima Island. The annual total catch of Korean purse seine fishery ranged between 1 mt and 1,054 mt from 1982 to 2006, and captured fish size mainly ranged from 30 to 80 cm.

1.2.2 The eastern Pacific Ocean

1.2.2.1 USA

Purse seine is the major fishery for Pacific bluefin tuna in USA and the annual total catch ranged between 22 mt and 13,934 mt from 1952 to 2006. About 75% of the annual catch was caught by small purse seine fishery in Southern California and costal area of Mexico , and the fish size mainly ranged between 80 and 120 cm.

1.2.2.2 Mexico

The major fishery for Pacific bluefin tuna in Mexico is purse seine and the annual total catch was between 1 mt and 9,816 mt from 1959 to 2006. The Mexican purse seine fishery is also targeted for yellowfin tuna (*Thunnus albacares*), and the fish size of Pacific bluefin tuna caught by Mexican purse seine fishery is mainly ranged between 80 and 120 cm.

1.3 Motivation of the present study

Numerous studies have been conducted for pacific bluefin tuna, such as distribution and migration, swimming patterns (Itoh et al. 2003a; 2003b), age and growth (Bayliff et al. 1991; Bayliff 1993; Foreman 1996; Hsu et al. 2000), reproductive biology, mortality estimation (Bayliff et al. 1991), catch-at-age estimation, population dynamics by yield per recruit analysis (Huang 2003) and virtual population analysis.

The models used for stock assessment could be divided them into three groups： Production models, Dynamic pool models and Age-structured models. Each model has its own advantage and disadvantages. For the dynamic pool models and age-structured models, such as the stock-recruitment model (Ricker, 1954), the Beverton-Holt model (Beverton and Holt ,1957), A-SCALA model (Maunder and

Watters, 2000) and MULTIFAN-CL (Fournier et al. 1998; Hampton and Fournier, 2001; Kleiber et al. 2003), they discriminate fish stock into several age groups or age classes, and seem to be more truthfulness and factual in natural world. These models need to classify the Pacific bluefin tuna stock into several age groups for parameters estimation. Due to lots of parameters demand, there are with some difficulties in data preparation and computation. On the other hand, for the production models, the parameters needed to be estimated are relatively reduced and the demand of age slicing from catch at size into catch at age is not required. Based on the results of the Pacific Bluefin Tuna Working Group sessions (a Working Group of the International Scientific Commission for the Stock Assessment on Tuna and Tuna-like Species in the North Pacific Ocean, ISC), the virtual population analyses and stock synthesis II are always used to evaluate the stock status, and the production-related models have never been used in previous assessments. However, they said age-structured models and length based methods analyses are used only with the standardized abundance indices limited to some Japanese fisheries, and the most important spawner index developed from Taiwanese small-scaled longline fishery was never found. For this reason, the production models are the candidates since they only need catch, effort and standardized catch per unit effort (CPUE) as abundance indices to estimate parameters.

1.4 Objectives of study

The aim of this study is to use production model with non-equilibrium assumption and all abundance indices available to assess the *T. orientalis* stock, to assess the stock status, and to address a reasonable and reliable biological reference point for accommodating the management of the North Pacific bluefin tuna stock.

2. Materials and Methods

2.1 Catch and CPUE indices

Datasets used in this study include catch, effort and standardized CPUE of fisheries employed by Japanese (purse seine, longline, troll, pole and line, set net), Korean (purse seine, trawl), Taiwanese (longline, purse seine, drift net), USA (purse seine, sport), and Mexican (purse seine) fishers, and the information is summarized in the workshop reports of 2006 and 2007 Pacific Bluefin Tuna Group of the International Scientific Committee for tuna and tuna-like species in the North Pacific ocean (ISC) (Anon., 2006; 2007). These information are described as follow and the detailed annual catches by nation and by fishery are shown in Table 1:

2.1.1 Catch data structures

The time series of catch indices is from 1952 to 2006 but some fishery mentioned above banned in some year.

2.1.1.1 Japan

(1) Purse seine

There are two types of Japanese purse seine fishery, tuna PS and small PS, operated in the coastal and offshore waters off Japan in the North Pacific Ocean, catching Pacific bluefin tuna. The compiled time series data of tuna PS is from 1952 to 2006 and annual catches were between 945 mt to 25,422 mt, and for small PS, the annual catch ranged from 22 mt to 13,575 mt.

(2) Longline

Two datasets of Japanese longline fisheries in the Northern Pacific, compiled from distant waters and offshore longline, and Coastal Longline. The distant waters and offshore longline fishery is operated both in the Northern and Southern Pacific Ocean nearby Japan, the annual catch ranged between 30 mt to 6,364 mt from 1952 to 2006 in north pacific surrounding Japan, and was minor ranged between 5 mt and 565 mt from 1952 to 2006 in south pacific surrounding Japan. The annual catch of coastal longline fishery ranged between 67 mt and 3,183 mt from 1969 to 2006.

(3) Troll

The catch of Japanese troll fishery ranged between 546 mt and 5,121 mt, and operated in the eastern North Pacific Ocean off Japan from 1952 to 2006.

(4) Pole and line

The catch data compiled from Japanese pole and line fishery was between 35 mt to 4,060 mt for the years from 1952 to 2006.

(5) Set net

The time series data compiled from Japanese set net ranged between 716 mt and 6,019 mt from 1952 to 2006.

2.1.1.2 Korea

(1) Purse seine

The annual catch taken by Korean purse seine fishery ranged between 1 mt and 1,054 mt from 1982 to 2006.

(2) Trawl

The Korean trawl fishery caught Pacific bluefin tuna incidentally since 2000 with an annual catch ranged between 1 mt and 10 mt.

2.1.1.3 Taiwan

(1) Longline

The Pacific bluefin taun taken by Taiwanese fishers is mainly made by small-scale longliners (<100 GRT) with an accurate catch statistical records from 1993. The annual catch datasets from 1960s to early 1990s mainly obtained from the Taiwanese Fishery Yearbooks, and these datasets had lower accuracy and precision. The annual catch ranged from 1 mt to 3,089 mt, and from about 1,148 mt (2006) to 1,863 mt (2003) in recent five years.

(2) Purse seine

The Taiwanese purse seine fishery accounted for a very small proportion of annual total catch, approximated 3% for Taiwanese Pacific bluefin tuna production, and the annual catch ranged between 1 mt and 259 mt with doubted estimation for some very few amounts taken by purse seiners.

(3) Distant-water driftnet

The distant-water driftnet fishery of Taiwan was mainly operated from 1982 to 1992 in the North Pacific Ocean and Indian Ocean, the annual catch from 2 mt to 299 mt was extracted from Taiwanese Fishery Yearbooks. Those statistics may have high uncertainty in fishing regions (North Pacific Ocean or Indian Ocean?) and species (Northern bluefin tuna or southern bluefin tuna?).

2.1.1.4 USA

The catch data in USA is mainly purse seine fishery and sport fishing with 97% and 2%, respectively. The annual catch of purse seine fishery in 1952-2006 ranged between 22 mt and 15,450 mt. The annual catch of sport fishing in 1952-2006 ranged between 1 mt and 654 mt.

2.1.1.5 Mexico

Purse seiner is the only fishing gear used to take Pacific bluefin tuna in Mexico. The annual catch of Mexican purse seiner in 1959-2006 ranged from 1 mt to 9,816 mt. There was no catch recorded from 1952 to 1958, and this was due to catches in these years were being included in USA catches.

2.2 Abundance indices

The CPUE datasets were from 2006 ISC report, and CPUE indices of six fisheries (Japan Troll, EPO Purse Seine, CPFV Recreational, Japan Purse Seine, Taiwan Longline, Japan Longline Offshore, Japan Longline Coastal) were applied in the report (Fig. 3).

2.2.1 Eastern Pacific Ocean Purse Seine (EPOPS)

The CPUE index of Eastern Pacific Ocean purse seine combined USA and Mexico, and the time series was from 1960 to 2005. The CPUE indices of EPOPSranged between 0.00171 and 0.1899 and the unit is weight.

2.2.2 Japanese Troll (JPTL)

The CPUE indices of Japanese troll fishery was from 1981 to 2004, and ranged between 0.3223 and 3.6435. The unit of index is weight in kg.

2.2.3 Japanese Purse Seine (JPPS)

The CPUE indices of Japanese purse seine fishery was from 1981 to 2004, and ranged between 19.175 and 605.582. The unit of index is unknown.

2.2.4 Taiwan Coastal Longline (TWCOLL)

The CPUE indices of Taiwan coastal longline fishery was from 1999 to 2005, and ranged between 0.0926 and 0.4092. The unit of index is number / 1000 hooks.

2.2.5 Japanese Offshore Longline (JPOFFLL)

The CPUE indices of Japanese offshore longline fishery was from 1952 to 2005 except 1958, 1959, and ranged between 0.0009 and 1.5841. The unit of index is number / 1000 hooks.

2.2.6 Japanese Coastal Longline (JPCOLL)

The CPUE indices of Japanese coastal longline was from 1994 to 2005, and ranged between 0.173 and 0.443. The unit of index is number.

2.3 ASPIC (Analysis of surplus production models incorporated covariates)

ASPIC (Prager, 1994) is originally developed by using the Graham-Schaefer surplus production model (Graham, 1935; Schaefer, 1954, 1957), and the primary equation could be represented by the differential equation:

$$\frac{dB_t}{dt} = (r - F_t)B_t - \frac{r}{K}B_t^2. \quad (1)$$

where B_t is the biomass in year t, r is the intrinsic growth rate of the population, K is the carrying capacity, and F_t is the instantaneous fishing mortality in year t. Moreover, let $\alpha_t = r - F_t$, $\beta = r/K$, $t = h$, and ending at time $t = h + \delta$, during which the instantaneous fishing mortality rate is F_h, the time-dependent solution of biomass is

$$B_{h+\delta} = \frac{\alpha_h B_h e^{\alpha_h \delta}}{\alpha_h + \beta\delta\left(e^{\alpha_h \delta} - 1\right)} \text{ when } \alpha_h \neq 0, \text{ or} \quad (2)$$

$$B_{h+\delta} = \frac{B_h}{1 + \beta\delta B_h} \text{ when } \alpha_h = 0. \quad (3)$$

The yield in the same period could be expressed by the following equation

$$Y_h = \int_{t=h}^{h+\delta} F_t B_t \, dt \tag{4}$$

Substitute Eqs.2 and 3 into Eqs.4 and the yield in time h can be solved as

$$Y_h = \frac{F_h}{\beta} ln \left[1 - \frac{\beta B_h (1 - e^{\alpha_h \delta})}{\alpha_h}\right] \text{ when } \alpha_h \neq 0, \text{ or} \tag{5}$$

$$Y_h = \frac{F_h}{\beta} ln(1 + \delta \beta B_h) \text{ when } \alpha_h = 0. \tag{6}$$

The logistic growth used in the Graham-Schaefer surplus production model has been criticized that the model is inflexible as the maximum productivity always occurred as the stock biomass is equal to half of the carrying capacity (the maximum stock biomass), although the inflexible logistic growth provides a parsimonious parameter for the surplus production models. Pella and Tomlinson (1969) suggested a rate equation of productivity which was more flexible for maximum change of productivity while a superfluous parameter was used. The rate equation for stock productivity is:

$$\dot{P}(B) = \pm a B^n \mp bB \qquad a, b > 0 \tag{8}$$

Positive case was used when $0 < n < 1$ and negative case was used when $n > 1$. Thus the Pella-Tomlison generalized production model was reconstructed by Fletcher (1978) and formulated as:

$$\frac{dB_t}{dx} = \gamma m \left(\frac{B_t}{K}\right) - \gamma m \left(\frac{B_t}{K}\right)^n - F_t B_t \tag{9}$$

where m is the maximum sustainable yield for the study stock (MSY) with a biomass per time units; n is an undetermined power in order to govern the shape of production curve flexibly; and γ is the Fletcher's gamma and is an function of n,

$$\gamma = \frac{n^{n/(n-1)}}{n-1} \tag{10}$$

When n is equal to 2, the generalized production model is equal to Graham-Schaefer surplus production model; and when n is approaching to 1, the Fox type surplus production model is obtained.

As the governing equation of Pella-Tomlinson generalized production model, the time-dependent solution of stock biomass at time t is B_t,

$$B_t = \left[B^{*(1-n)} + \left(B_0^{1-n} - B^{*(1-n)}\right) \cdot e^{\left(\frac{\gamma m}{B_0} - F\right)(1-n)t} \right] \tag{11}$$

where B^* is the stock biomass at equilibrium state, $B^* = \left[\frac{\gamma m}{\gamma m - FB_\infty}\right]^{\frac{1}{1-n}} \cdot B_\infty$; and B_0 is the initial stock biomass that could be the stock virgin biomass or the stock biomass at reference time equal to 0 ($t = 0$) of the time series catch and effort data observed.

The Pella-Tomlinson generalized production model was applied for assessing the Pacific bluefin tuna stock and its EFT algorithm of ASPIC Version 5.15 (ICCAT, International Commission for the Conservation of Atlantic Tunas, 2005; http://www.iccat.int/) was used in the this study.

2.3.1 Fitting model

Given catch and effort for many time series, Prager (2004) proposed two algorithms (YLD mode and EFT mode) to estimate the relative parameters of the production models under multiple gear contexts. If annual yield is used, the YLD mode is applied. The penalty function of YLD model is assumed that

$$Y_{ij} = \hat{Y}_{ij} + \varepsilon_{ij} \tag{12}$$

where Y_{ij} and $\hat{Y}_{ij}$ denotes the observed catch and expected catch for fishery j in year t, and ε_{ij} is the observation error with a log-normal distribution.

As assumed, catches are as in equations (5) and (6), the penalty function for YLD mode can be applied with a weighting factor, w_{ij} for fishery j in year t, as:

$$\varepsilon^2 = \sum_{i=1}^{I} \sum_{j=1}^{j} w_{ij} \left(ln \frac{c_{ij}}{\widehat{c_{ij}}} \right)^2 \tag{13}$$

Then to minimize ε^2, the parameters of production odel can be obtained. Further, the EFT mode is used as the catch rate (or standardized abundance index) is applied. The EFT mode was used as the similar notations as YLD mode, the penalty function is:

$$\varepsilon^2 = \sum_{i=1}^{I} \sum_{j=1}^{j} w_i \left(ln \frac{f_{ij}}{\widehat{f_{ij}}} \right)^2 = \sum_{i=1}^{I} \sum_{j=1}^{j} w_i \left(ln \frac{c_{ij}/f_{ij}}{c_{ij}/\widehat{f_{ij}}} \right)^2 \tag{14}$$

where f_{ij} is the observed fishing effort and $\widehat{f_{ij}}$ is the expected fishing effort for the fishery j in year i. When ε^2 is minimized using observed time series catch and effort data of different fisheries, the parameters can be obtained for the shape parameter, n, B_{MSY}/K, MSY (maximum sustainable yield), K (carrying capacity) and q_i (catchability of fishery). During the study runs, ASPIC version 5.15 (ICCAT, 2005) was applied.

2.3.2 Starting guess parameters

Because there are many unknown parameters to be estimated than the observed datasets, an educated starting guess to simulate iteratively the production models to obtain parameters was initiated during the study runs. When ASPIC version 5.15 was applied, the starting guess of input parameters for B_1/K, *MSY*, *K*, and q_i(catchability of fishery i) were given. When the search was converged, an Akaike Information Criterion (AIC) used for model selection was also estimated for each scenario. The smallest AIC was judged as the model with the goodness-of-fit, while the *MSY*, B_{msy}(biomass at MSY) and F_{msy}(fishing mortality at MSY) were adopted as the biological reference points. 1,000 bootstraps (BOT mode in ASPIC) were run to evaluate the variation of estimates.

2.3.3 Baseline case

During 2000 and 2004 stock assessment on *T. orientalis* using VPA, the abundance indices of JPLL, JPPS and JPTL fishery were used. For the simplicity, The standardized CPUE of JPLL, JPPS and JPTL were also selected as baseline run in this study, and further some newly developed standardized CPUE, such as from Taiwanese longline and eastern purse seine were additionally used as sensitivity analyses.

2.4 Sensitive analysis

There are 6 standardized abundance indices available for five different fisheries, i.e. Japanese coastal longline index (JPCOLL), Japan offshore longline (JPOFFLL), eastern Pacific purse seine index (EPOPS), Japanese purse seine index (JPPS), Japanese troll index (JPTL) and Taiwanese longline index (TWCOLL). Those indices were with different lengths of time frame and data quality. The annual catch for each fishery is also different, thus a weighting by using catch as factors was also applied during each run.

As for those criteria, using several base case and sensitive runs to check sensitivity. The fisheries EPOPS and TWCOLL were used to run as sensitivity analyses by combination of adding one fishery for each run. In order to grasp the sensitivity of CPUE indices in each fishery, using separated and combined CPUE indices examine sensitivity. Table 2 shows all combinations of the base case and sensitivity runs.

2.4.1 Catch data aggregated for CPUE indices

Fig. 4. illustrates the catch aggregation for indices used in base case and sensitivity runs, in which the criterion of aggregated catch was depending on the fishery as similar attributes as the one used to develop abundance index.

2.4.2 Weight of abundance indices

There are unknown the uncertainty of standardized abundance indices (Fig. 3), some weighting on each index may be necessary during parameter estimation. Within the 20 base case and sensitive runs, 11 runs used equal weight and other 9 used the proportion of annual catch of each fishery individually as weight.

2.4.3 Separated or combined CPUE indices

Because there are six abundance indices, some characteristics of these indices are similar such as: JPCOLL, JPOFFLL and TWCOLL fishery are same fishing methods and all operated in mesopelagic area; EPOPS and JPPS fishery are same fishing methods and all operated in epipelagic area. So in run 16 and 17 combined JPCOLL, JPOFFLL and TWCOLL CPUE indices; run 10 and 11 combined JPPS and EPOPS CPUE indices.

2.5 Projection

To understand the effect of different catch levels on the stock status under the current fishing capacity, the best goodness-of-fit of base case run was selected to project $\frac{B_i}{B_{MSY}}$ and $\frac{F_i}{F_{MSY}}$ for the year i, $i=$2008, 2009, ….2021. And finally, a optimal catch level to sustain the stock will be recommended as the total allowable catch (TAC). The projection is manipulated by ASPICP, which a subroutine of ASPIC Version 5.15 (Pranger, 1994).

3. Results

3.1 Catches and abundance indices

Fig. 1 illustrates the total catch by fisheries annually. Those catches were mainly taken by 5 fisheries, i.e., Japanese purse seine fisheries (JPPS), eastern Pacific purse seine fisheries (EPOPS), Japanese longline fisheries (offshore and coastal longline before 1994; and pelagic longline afterward) (JPLL), Japanese troll fisheries (JPTL) and Taiwanese small scale longline fisheries (TWCOLL). The annual total catch of Pacific bluefin tuna fisheries recorded from 1952 to 2006 ranged between 8,653 (1990) and 40,383 metric tons (1956). The entire fishery declined greatly from 1952 to the historical low level in 1990, and then increased with great fluctuations to 2006.

Among the fisheries, most of the catches were made by Japanese (JPPS) and eastern Pacific purse seine (EPOPS) fisheries, Japanese longline fishery (JPLL) and Japanese troll fishery (JPTL), in which those fisheries show likely equivalent total catch for all the years, and in particular, a significant catch made by Taiwanese small scale coastal longline fishery (TWCOLL) incepted in 1993, which its catch level was maintained around 1,500 mt onward except 1998 (over 3,000 mt).

The standardized abundance indices of 5 main fisheries mentioned above were adopted from the most report of Pacific Bluefin Tuna Workshop, International Scientific Commission for the Stock Assessment on Tuna and Tuna-like Species in the

North Pacific Ocean (ISC) (Anon., 2007). Those abundance indices are redrawn as Fig. 3.

3.2 Generalized production model

EFT optimization algorithm of ASPIC version 5.05 (ICCAT, 2004) was applied to estimate parameters of generalized production models, in which the 5 abundance indices used in combination for baseline case and sensitivity analyses. During ASPIC running, 1,000 times bootstrapping were iterated to obtain results. Table 3 is summarized all parameters estimated for all base case and sensitive runs.

The fitting results of base case run, MSY is 17,990 mt, and F_{MSY} is 0.12 $year^{-1}$. During all sensitive runs, the results of MSY range between 19,800 mt and 853,000 mt, and the results of F_{MSY} range between 0.13 $year^{-1}$ and 0.49 $year^{-1}$. During all base case and sensitive runs, there is the lowest AIC in run 7 and detailed fitting results of run 7 show in Table 4.

3.3 B/B_{MSY} and F/F_{MSY} ratio

The annual biomass ratio (B/B_{MSY}) and fishing mortality ratio (F/F_{MSY}) of run 7 from 1952 - 2006 show in Fig. 4, and the explicit ratio of B_{2006}/B_{MSY} and F_{2006}/F_{MSY} in all base case and sensitive runs also show in Table 3.

In using equal weighting of all base case and sensitive runs, the estimated B_{2006}/B_{MSY} ratio range between 0.61 and 0.90, and the estimated F_{2006}/F_{MSY} ratio range between 1.51 and 1.71. In using non-equal weighting of all base case and sensitive runs, the estimated B_{2007}/B_{MSY} *ratio* range between 0.25 and 2.05, and the estimated F_{2006}/F_{MSY} *ratio* range between 0.015 and 23.71.

3.4 Sensitive analysis

The results of sensitive analysis show in Table 3. When using equal weighting, the results of MSY, K and F_{MSY} are very similar; in non-equal weighting, the fitting results quite different when using less fishery as CPUE indices such as using JPPS and JPLL as baseline case run. Compared the fitting results of equal or non-equal weighting, using non-equal weighting would obtain a lower MSY value in some base case and sensitive runs. When using non-equal weighting, it could have lower AIC value in the goodness of fit. When combining more CPUE indices into single index, could not get better fitting results and there would be no solved in using single CPUE index, such as: TWCOLL and JPPS CPUE only fitting model.

3.5 Projection

Run 7 is chosen to run the projection under different catch levels, due to run 7 converged with the smallest AIC value, and much more concentrated on B/B_{msy} ratio and F/F_{msy} ratio in bootstrap analysis. Further, the different catch levels were designed within the MSY ranges between 18,000 and 26,000 mt, those are 18,000 mt, 19,000 mt, 20,000 mt and 26,000 mt. The projected results of B/B_{msy} ratio show in Fig. 7, and the results of F/F_{msy} ratio show in Fig. 8.

4. Discussion

The production model, also called surplus production model, have been used widely in managing fisheries, largely because they are based only on catch and effort data, which are relatively simple to collect. According to the techniques for model fitting, it could be divided into equilibrium or non-equilibrium production models. The equilibrium method depends on the assumption that catch rates are in equilibrium with the natural production, this does not conform to relative situation, and is quiet dangerous. On the contrary, the non-equilibrium production depends on the assumption of process-error or observation-error methods (Hilborn & Walters, 1992; Quinn & Deriso, 1999) in model fitting, and seems to be more reasonable than equilibrium method. The generalized production model has a parameter, *n*, added to the Schaefer logistic model, and could offer more flexibility in the shape of productivity curves. This is the reason why this study just uses non-equilibrium method and generalized production model for stock assessment of *T. orientalis*.

4.1 Generalized production model

This study is first application of generalized production modeling approach to model the dynamics of Pacific bluefin tuna, assess the stock condition in relation to biological reference point and project stock conditions in the future. MSY estimated in this study range between 17,990 mt and 25,750 mt, was a little higher than Huang in 2003 (5,676-24,563 mt). Multiple fishing methods in an area would estimate higher MSY especially in purse seine and longline (Maunder, 2002), longline and purse seine occupied great proportion of annual catch in Pacific bluefin tuna, and this might be the reason why MSY estimated in this study is greater than Huang.

From fitting results in Table 3, using different CPUE index of fisheries as base case and sensitive runs to fit generalized production model could get different trends in *MSY*, *K*, F_{MSY}, B_{msy} n and *phi*. It is especially significant in using equal or non-equal statistical weights of fisheries fit model. When using equal weighting, the fitting results of fishing mortality rate at *MSY* (F_{MSY}) and MSY are similar in all base case runs but are much more variable in non-equal weighting. This may be due to the influence or the effect of statistical weight. In the annual catch of PBF in North Pacific Ocean, purse seine fishery occupied more than 50% and using non-equal statistical weight may enhance the property of fishing gears (high or low catchability), tendency of CPUE or errors (bias) of datasets (years of datasets). The phi estimated from all base case runs are smaller than 1 and according to Fletcher 1978, γ is negative when n smaller than 1 and γ has a maximum value around 1. So γ is negative in all base case runs.

4.2 B/B_{MSY} and F/F_{MSY} ratio

In the historical trend of B/B_{MSY} and F/F_{MSY} ratio from 1952 to 2005, major lay in fourth quadrant before 1980s, second quadrant after 1980s, first or fourth quadrant after 1990s, and recent year was all in second quadrant. This present the situation of the pacific bluefin tuna stock was overfished and overfishing after 1980s, stock biomass restored in 1990s, overfishing and overfished in recent years.

B_{2006}/B_{MSY} ratio is lower than 1 or closer to 1, this shows that stock biomass of *T.orientalis* was risky, and had tendency of overfished in 2006. The F_{2006}/F_{MSY} ratio was greater than 1, and this shows that fishing pressure for *T.orientalis* in North Pacific Ocean was too high and had tendency of overfishing in 2006.

Comparing estimated biomass of Pacific bluefin tuna in this study (Fig. 9) with VPA, which was made by Yamada in 2004, the tendency was similar in 1960s, 1980s, 1990s, and 2000s. There was a great difference in 1970s, the biomass had increased trend in VPA, but in this study had decreased trend. This difference caused different biomass level in recent years, the biomass was in good condition in VPA, but was in a quite lower level in this study.

4.3 Sensitive analysis

In the application of production model, CPUE index is taken as abundance index of stock biomass, and apply in model fitting. Hence, the accuracy and precision of

CPUE index is quite important. In this study, the unit of JPPS CPUE index is unknown, and this might raise the uncertainty in model fitting. From the results of sensitive analysis, using more CPUE index of fisheries as datasets would increase the variation of fitting results, and using equal or non-equal statistical weight of fisheries in model fitting also have influence in fitting results. Comparing the results of sensitive analysis in using equal or non-equal weighting, using equal weighting are much more stable than using non-equal weighting, but seems to be less sensitive. This may be due to statistic weights are in good measurement of characteristics in different fishery. In using non-equal weighting, adding Taiwan data into base case change the fitting results a lot in some base case runs, and this may be due to Taiwan longline fishery mainly target largest fish of PBF or Taiwan CPUE data only had 9 year CPUE indices hence influencing the fitting results.

In combining CPUE indices, combined CPUE index of longline fishery could have better fitting results (lower AIC) than combined CPUE index of purse seine fishery. This might be due to estimating or standardizing CPUE index of purse seine fishery is very difficult and fairly complicated. So combining different CPUE index of purse seine fishery might cause much more errors or bias in model fitting. The unit of Japanese purse seine CPUE index is unknown and this might increase uncertainty in combining purse seine indices.

When using single CPUE index such as JPPS, JPTL and TWCOLL fit model, there would be no fitting results. This might be due to the time series of these CPUE index is too short and could not offer enough abundance index information in model fitting.

4.4 Projection

Industrialized fisheries typically reduced community biomass by 80% within 15 years of exploitation (Myers, 2003), and Pacific bluefin tuna has already been exploited over 50 years in North Pacific Ocean. It is quite important to understand stock status and manage the fishery in North Pacific Ocean.

When using a higher quota (greater than 18,000 MT) as TAC for projection, the B/B_{msy} ratio will be less than 1 in 2022 and almost closer to zero. The F/F_{msy} ratio will be larger than 1 and almost greater more than F_{msy} four to six times. On the contrary, when using a lower quota (smaller than 18,000 MT), the B/B_{msy} ratio will be greater than 1 and biomass would be almost twice of B_{msy}. The F/F_{msy} ratio will be less than 1 and almost to half. From the results of projection, on purpose of making sustainable exploitation of *T. orientalis* in North Pacific Ocean advice setting the annual catch of *T. orientalis* in North Pacific Ocean to a lower than 18,000 mt.

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Table 1. Catches for Pacific bluefin tuna from 1952 to 2006.

Unit: Metric ton

Year	Western Pacific															
	Japan									Korea		Taiwan				
	Purse Seine		Dist&Off LL		Coastal Longline	Troll	Pole and Line	Set Net	Others	Purse Seine	Trawl	Longline	Purse Seine	Distant Driftnet	Others	Sub total
	tuna PS	small PS	north pacific	south pacific												
1952	7680		2694	9		667	2198	2145	1700							17094
1953	5570		3040	8		1472	3052	2335	160							15636
1954	5366		3088	28		1656	3044	5579	266							19027
1955	14016		2951	17		1507	2841	3256	1151							25739
1956	20979		2672	238		1763	4060	4170	385							34268
1957	18147		1685	48		2392	1795	2822	414							27302
1958	8586		818	25		1497	2337	1187	215							14666
1959	9996		3136	565		736	586	1575	167							16760
1960	10541		5910	193		1885	600	2032	369							21531
1961	9124		6364	427		3193	662	2710	599							23078
1962	10657		5769	413		1683	747	2545	293							22107
1963	9786		6077	449		2542	1256	2797	294							23201
1964	8973		3140	114		2784	1037	1475	1884							19406
1965	11496		2569	194		1963	831	2121	1106			54				20334
1966	10082		1370	174		1614	613	1261	129							15243
1967	6462		878	44		3273	1210	2603	302			53				14825
1968	9268		500	7		1568	983	3058	217			33				15634
1969	3236		313	20	565	2219	721	2187	195			23				9479
1970	2907		181	11	426	1198	723	1779	224							7448
1971	3721		280	51	417	1492	938	1555	317			1				8773
1972	4212		107	27	405	842	944	1107	197			14				7854
1973	2266		110	63	728	2108	526	2351	636			33				8821
1974	4106		108	43	3183	1656	1192	6019	754			47			15	17124
1975	4491		215	41	846	1031	1401	2433	808			61			5	11332
1976	2148		87	83	233	830	1082	2996	1237			17			2	8716
1977	5110		155	23	183	2166	2256	2257	1052			131			2	13335
1978	10424		444	7	204	4517	1154	2546	2276			66			2	21642
1979	13881		220	35	509	2655	1250	4558	2429			58				25595
1980	11327		140	40	671	1531	1392	2521	1953			114			5	19693
1981	25422		313	29	277	1777	754	2129	2653			179				33532
1982	19234		206	20	512	864	1777	1667	1709	31		207		2		26228
1983	14774		87	8	130	2028	356	972	1117	13		175	9	2		19670

Table 1. (Continued)

Unit: Metric ton

Year	Western Pacific															
	Japan									Korea		Taiwan				
	Purse Seine		Dist&Off LL		Coastal Longline	Troll	Pole and Line	Set Net	Others	Purse Seine	Trawl	Longline	Purse Seine	Distant Driftnet	Others	Sub total
	tuna PS	small PS	north pacific	south pacific												
1984	4433		57	22	85	1874	587	2234	868	4		477	5	0	8	10655
1985	4154		38	9	67	1850	1817	2562	1175	1		210	80	11		11975
1986	7412		30	14	72	1467	1086	2914	719	344		70	16	13		14157
1987	8653		30	33	181	880	1565	2198	445	89		365	21	14		14474
1988	3583	22	51	30	106	1124	907	843	498	32		108	197	37	25	7562
1989	6077	113	37	32	172	903	754	748	283	71		205	259	51	3	9707
1990	2834	155	42	27	267	1250	536	716	455	132		189	149	299	16	7067
1991	4336	5472	48	20	170	2069	286	1485	650	265		342	0	107	12	15262
1992	4255	2907	85	16	428	915	166	1208	1081	288		464	73	3	5	11896
1993	5156	1444	145	10	667	546	129	848	365	40		471	1		3	9825
1994	7345	786	238	20	968	4111	162	1158	398	50		559				15795
1995	5334	13575	107	10	571	4778	270	1859	586	821		335			2	28248
1996	5540	2104	123	9	778	3640	94	1149	570	102		956				15066
1997	6137	7015	142	12	1158	2740	34	803	811	1054		1814				21720
1998	2715	2676	169	10	1086	2865	85	874	700	188		1910				13277
1999	11619	4554	127	17	1030	3387	35	1097	709	256		3089				25919
2000	8193	8293	121	7	832	5121	102	1125	689	794		2780			2	28058
2001	3139	4481	63	6	728	3329	180	1366	782	995	10	1839			4	16922
2002	4171	5102	47	5	794	2427	99	1100	631	674	1	1523			4	16579
2003	945	5399	85	12	1152	1839	44	839	446	591		1863			21	13236
2004	4792	2577	231	9	1616	2182	132	896	514	636		1714			3	15301
2005	3871	7389	117	14	1818	3406	606	2182	548	594		1368				21914
2006	3889	3272	77	16	1058	1544	108	1421	777	949		1148				14259

Table 1. (Continued)

Unit: Metric ton

Year	Eastern Pacific					Sub total	Out of ISC members		Grand Total
	USA			Mexico					
	Purse Seine	other	Sport	Purse Seine	other		NZ	Others	
1952	2076		2			2078			19172
1953	4433		48			4481			20117
1954	9537		11			9548			28575
1955	6173		93			6266			32005
1956	5727		388			6115			40383
1957	9215		73			9288			36590
1958	13934		10			13944			28610
1959	3506	56	13	171	32	3779			20539
1960	4547	0	1			4548			26079
1961	7989	16	23	130		8158			31236
1962	10769	0	25	294		11088			33195
1963	11832	28	7	412		12280			35481
1964	9047	39	7	131		9224			28631
1965	6523	77	1	289		6890			27224
1966	15450	12	20	435		15918			31161
1967	5517	0	32	371		5920			20745
1968	5773	8	12	195		5989			21623
1969	6657	9	15	260		6940			16419
1970	3873	0	19	92		3983			11432
1971	7804	0	8	555		8367			17140
1972	11656	45	15	1646		13362			21216
1973	9639	21	54	1084		10798			19619
1974	5243	30	58	344		5675			22799
1975	7353	84	34	2145		9616			20948
1976	8652	25	21	1968		10666			19381
1977	3259	13	19	2186		5477			18811
1978	4663	6	5	545		5218			26860
1979	5889	6	11	213		6119			31715
1980	2327	24	7	582		2940			22634
1981	867	14	9	218		1109			34641
1982	2639	2	11	506		3159			29387
1983	629	11	33	214		887			20557
1984	673	29	49	166		917			11573
1985	3320	28	89	676		4113			16089
1986	4851	57	12	189		5109			19266
1987	861	20	34	119		1033			15507
1988	923	50	6	447	1	1427			8989
1989	1046	21	112	57		1236			10943
1990	1380	92	65	50		1587			8653
1991	410	6	92	9		517	2		15781
1992	1928	61	110	0		2099	0		13995
1993	580					981	6		10811
1994	906	59	89	63	2	1118	2		16916
1995	657	49	258	11		975	2		29225
1996	4639	70	40	3700		8449	4		23519
1997	2240	133	156	367		2897	14		24632
1998	1771	281	413	1	0	2466	20		15764
1999	184	184	441	2369	35	3213	21		29153
2000	693	61	342	3019	99	4214	21		32293
2001	292	48	356	863		1559	50		18531
2002	50	12	654	1708	2	2427	55	10	19071
2003	22	18	394	3211	43	3689	41	19	16984
2004	0	11	49	8880	14	8954	67	10	24333
2005	201	6	79	4542		4828	20	7	26770
2006	0	1	96	9816		9913	21	3	24196

Table 2. Input parameters and CPUE indices for all base case and sensitive runs in ASPIC.

Model, parameter	Base case	Sensitive analysis	Sensitive analysis	Sensitive analysis
Run number	Run 1	Run 2	Run 3	Run4
run data name	a1	b1	b2	b3
Model of operation	Fit	Fit	Fit	Fit
Comment	'Pella and Tomlinson'	'Pella and Tomlinson'	'Pella and Tomlinson'	'Pella and Tomlinson'
Error type	GENGRID YLD SSE 25 80 3 8.0	GENGRID YLD SSE 25 80 3 8.0	GENGRID YLD SSE 25 80 3 8.0	GENGRID YLD SSE 25 80 3 8.0
Verbosity	2 12	2 12	2 12	2 12
Number of bootstrap trials	0	0	0	0
Monte Carlo searching	1 50000	1 50000	1 50000	1 50000
Convergence criterion for optimizer	1.0d-8	1.0d-8	1.0d-8	1.0d-8
Restart control	3d-8 6	3d-8 6	3d-8 6	3d-8 6
Control of iterative computations	1d-6 16	1d-6 16	1d-6 16	1d-6 16
Maximum estimated F	8d0	8d0	8d0	8d0
Statistical weight for B_1 penalty in objective function	0d0	0d0	0d0	0d0
Number of data series	3	3	4	4
Series-specific statistical weights	1 1 1	7.8d-1 1.3d-1 9d-2	1 1 1 1	7.6d-1 1.3d-1 0.9d-1 0.2d-1
Starting guess for B_1/K	0.85d0	0.85d0	0.85d0	0.85d0
Starting guess for MSY	2d4	2d4	2d4	2d4
Starting guess for K	1d5	1d5	1d5	1d5
Starting guess for q	5d-5 5d-5 5d-5	5d-5 5d-5 5d-5	5d-5 5d-5 5d-5 5d-5	5d-5 5d-5 5d-5 5d-5
Flags to estimate (or fix) individual parameters	1 1 1 1 1 1	1 1 1 1 1 1	1 1 1 1 1 1 1	1 1 1 1 1 1 1
Bounds on MSY	1.0d2 1.0d7	1.0d2 1.0d7	1.0d2 1.0d7	1.0d2 1.0d7
Bounds on K	2.0d4 2.0d7	2.0d4 2.0d7	2.0d4 2.0d7	2.0d4 2.0d7
Random number seed	1963285	1963285	1963285	1963285
Number of years in data set	55	55	55	55
Title	CC	CC	CC	CC
Data series	PBF CPUE, Yield	PBF CPUE, Yield	PBF CPUE, Yield	PBF CPUE, Yield
CPUE(s) used	JPPS+JPLL+JPTL	JPPS+JPLL+JPTL	JPPS+JPLL+JPTL+TWCOLL	JPPS+JPLL+JPTL+TWCOLL

Table 2. (continued).

Model, parameter	Sensitive analysis g	Sensitive analysis	Sensitive analysis	Sensitive analysis
Run number	Run 5	Run 6	Run 7	Run 8
run data name	b4	b5	b6	b7
Model of operation	Fit	Fit	Fit	Fit
Comment	'Pella and Tomlinson'	'Pella and Tomlinson'	'Pella and Tomlinson'	'Pella and Tomlinson'
Error type	GENGRID YLD SSE 25 80 3 8.0	GENGRID YLD SSE 25 80 3 8.0	GENGRID YLD SSE 25 80 3 8.0	GENGRID YLD SSE 25 80 3 8.0
Verbosity	2 12	2 12	2 12	2 12
Number of bootstrap trials	0	0	0	0
Monte Carlo searching	1 50000	1 50000	1 50000	1 50000
Convergence criterion for optimizer	1.0d-8	1.0d-8	1.0d-8	1.0d-8
Restart control	3d-8 6	3d-8 6	3d-8 6	3d-8 6
Control of iterative computations	1d-6 16	1d-6 16	1d-6 16	1d-6 16
Maximum estimated F	8d0	8d0	8d0	8d0
Statistical weight for B_1 penalty in objective function	0d0	0d0	0d0	0d0
Number of data series	5	3	3	4
Series-specific statistical weights	1 1 1 1 1 1 1 1	1 1 1	7.8d-1 1.3d-1 9d-2	1 1 1 1
Starting guess for B_1/K	0.85d0	0.85d0	0.85d0	0.85d0
Starting guess for MSY	2d4	2d4	2d4	2d4
Starting guess for K	1d5	1d5	1d5	1d5
Starting guess for q	5d-5 5d-5 5d-5 5d-5 5d-5	5d-5 5d-5 5d-5	5d-5 5d-5 5d-5	5d-5 5d-5 5d-5 5d-5
Flags to estimate (or fix) individual parameters	1 1 1 1 1 1 1 1 1	1 1 1 1 1 1	1 1 1 1 1 1	1 1 1 1 1 1 1
Bounds on MSY	1.0d2 1.0d7	1.0d2 1.0d7	1.0d2 1.0d7	1.0d2 1.0d7
Bounds on K	2.0d4 2.0d7	2.0d4 2.0d7	2.0d4 2.0d7	2.0d4 2.0d7
Random number seed	1963285	1963285	1963285	1963285
Number of years in data set	55	55	55	55
Title	CC	CC	CC	CC
Data series	PBF CPUE, Yield	PBF CPUE, Yield	PBF CPUE, Yield	PBF CPUE, Yield
CPUE(s) used	JPPS+JPLL+JPTL+TWCOLL+EPOPS	EPOPS+JPLL+JPTL	EPOPS+JPLL+JPTL	EPOPS+JPLL+JPTL+TWCOLL

Table 2. (continued).

Model, parameter	Sensitive analysis	Sensitive analysis	Sensitive analysis	Sensitive analysis
Run number	Run 9	Run 10	Run 11	Run 12
run data name	b8	b9	b10	b11
Model of operation	Fit	Fit	Fit	Fit
Comment	'Pella and Tomlinson'	'Pella and Tomlinson'	'Pella and Tomlinson'	'Pella and Tomlinson'
Error type	GENGRID YLD SSE 25 80 3 8.0	GENGRID YLD SSE 25 80 3 8.0	GENGRID YLD SSE 25 80 3 8.0	GENGRID YLD SSE 25 80 3 8.0
Verbosity	2 12	2 12	2 12	2 12
Number of bootstrap trials	0	0	0	0
Monte Carlo searching	1 50000	1 50000	1 50000	1 50000
Convergence criterion for optimizer	1.0d-8	1.0d-8	1.0d-8	1.0d-8
Restart control	3d-8 6	3d-8 6	3d-8 6	3d-8 6
Control of iterative computations	1d-6 16	1d-6 16	1d-6 16	1d-6 16
Maximum estimated F	8d0	8d0	8d0	8d0
Statistical weight for B_1 penalty in objective function	0d0	0d0	0d0	0d0
Number of data series	4	3	3	6
Series-specific statistical weights	7.8d-1 1.1d-1 0.9d-1 0.2d-1	1 1 1	7.8d-1 1.3d-1 0.9d-1	1 1 1 1 1 1
Starting guess for B_1/K	0.85d0	0.85d0	0.85d0	0.85d0
Starting guess for MSY	2d4	2d4	2d4	2d4
Starting guess for K	1d5	1d5	1d5	1d5
Starting guess for q	5d-5 5d-5 5d-5 5d-5	5d-5 5d-5 5d-5	5d-5 5d-5 5d-5	5d-5 5d-5 5d-5 5d-5 5d-5 5d-5
Flags to estimate (or fix) individual parameters	1 1 1 1 1 1 1	1 1 1 1 1 1	1 1 1 1 1 1	1 1 1 1 1 1 1 1 1
Bounds on MSY	1.0d2 1.0d7	1.0d2 1.0d7	1.0d2 1.0d7	1.0d2 1.0d7
Bounds on K	2.0d4 2.0d7	2.0d4 2.0d7	2.0d4 2.0d7	2.0d4 2.0d7
Random number seed	1963285	1963285	1963285	1963285
Number of years in data set	55	55	55	55
Title	CC	CC	CC	CC
Data series	PBF CPUE, Yield	PBF CPUE, Yield	PBF CPUE, Yield	PBF CPUE, Yield
CPUE(s) used	EPOPS+JPLL+JPTL+TWCOLL	PCOPS, WESTLL, JPTL	PCOPS, WESTLL, JPTL	JPOFFLL, JPCOLL, EPOPS, JPTL, TWCOLL, JPPS

Table 2. (continued).

Model, parameter	Sensitive analysis	Sensitive analysis	Sensitive analysis	Sensitive analysis
Run number	Run 13	Run 14	Run 15	Run 16
run data name	b12	b13	b14	b15
Model of operation	Fit	FIT	FIT	Fit
Comment	'Pella and Tomlinson'	Pella and Tomlinson	Pella and Tomlinson	'Pella and Tomlinson'
Error type	GENGRID YLD SSE 25 80 3 8.0	GENGRID YLD SSE 25 80 3 8.0	GENGRID YLD SSE 25 80 3 8.0	GENGRID YLD SSE 25 80 3 8.0
Verbosity	2 12	2 12	2 12	2 12
Number of bootstrap trials	0	0	0	0
Monte Carlo searching	1 50000	1 50000	1 50000	1 50000
Convergence criterion for optimizer	1.0d-8	1.0d-8	1.0d-8	1.0d-8
Restart control	3d-8 6	3d-8 6	3d-8 6	3d-8 6
Control of iterative computations	1d-6 16	1d-6 16	1d-6 16	1d-6 16
Maximum estimated F	8d0	8d0	8d0	8d0
Statistical weight for B_1 penalty in objective function	0d0	1d0	1d0	0d0
Number of data series	6	1	1	4
Series-specific statistical weights	2.4d-1 0.5d-1 0.6d-1 0.9d-1 0.2d-1 5.4d-1	1	1	1 1 1 1
Starting guess for B_1/K	0.85d0	0.85d0	0.85d0	0.85d0
Starting guess for MSY	2d4	2d4	2d4	2d4
Starting guess for K	1d5	1d5	1d5	1d5
Starting guess for q	5d-5 5d-5 5d-5 5d-5 5d-5 5d-5	5d-5	5d-5	5d-5 5d-5 5d-5 5d-5
Flags to estimate (or fix) individual parameters	1 1 1 1 1 1 1 1 1	1 1 1 1	1 1 1 1	1 1 1 1 1 1
Bounds on MSY	1.0d2 1.0d7	1.0d2 1.0d7	1.0d2 1.0d7	1.0d2 1.0d7
Bounds on K	2.0d4 2.0d7	2.0d4 2.0d7	2.0d4 2.0d7	2.0d4 2.0d7
Random number seed	1963285	1963285	1963285	1963285
Number of years in data set	55	55	55	55
Title	CC	CC	CC	CC
Data series	PBF CPUE, Yield	PBF CPUE, Yield	PBF CPUE, Yield	PBF CPUE, Yield
CPUE(s) used	JPOFFLL, JPCOLL, EPOPS, JPTL, TWCOLL, JPPS	TWCOLL CPUE only	JPPS CPUE only	WESTLL, EPOPS, JPTL, JPPS

Table 2. (continued).

Model, parameter	Sensitive analysis	Sensitive analysis	Sensitive analysis	Sensitive analysis
Run number	Run 17	Run 18	Run 19	Run 20
run data name	b16	b17	b18	b19
Model of operation	Fit	FIT	FIT	Fit
Comment	'Pella and Tomlinson'	Pella and Tomlinson	Pella and Tomlinson	'Pella and Tomlinson'
Error type	GENGRID YLD SSE 25 80 3 8.0	GENGRID YLD SSE 25 80 3 8.0	GENGRID YLD SSE 25 80 3 8.0	GENGRID YLD SSE 25 80 3 8.0
Verbosity	2 12	2 12	2 12	2 12
Number of bootstrap trials	0	0	0	0
Monte Carlo searching	1 50000	1 50000	1 50000	1 50000
Convergence criterion for optimizer	1.0d-8	1.0d-8	1.0d-8	1.0d-8
Restart control	3d-8 6	3d-8 6	3d-8 6	3d-8 6
Control of iterative computations	1d-6 16	1d-6 16	1d-6 16	1d-6 16
Maximum estimated F	8d0	8d0	8d0	8d0
Statistical weight for B_1 penalty in objective function	0d0	0d0	0d0	0d0
Number of data series	4	2	2	5
Series-specific statistical weights	2.4d-1 1.3d-1 0.9d-1 5.4d-1	1 1	0.86d0 0.14d0	1 1 1 1 1 1 1 1
Starting guess for B_1/K	0.85d0	0.85d0	0.85d0	0.85d0
Starting guess for MSY	2d4	2d4	2d4	2d4
Starting guess for K	1d5	1d5	1d5	1d5
Starting guess for q	5d-5 5d-5 5d-5 5d-5	5d-5 5d-5	5d-5 5d-5	5d-5 5d-5 5d-5 5d-5 5d-5
Flags to estimate (or fix) individual parameters	1 1 1 1 1 1	1 1 1 1 1	1 1 1 1 1	1 1 1 1 1 1 1 1 1
Bounds on MSY	1.0d2 1.0d7	1.0d2 1.0d7	1.0d2 1.0d7	1.0d2 1.0d7
Bounds on K	2.0d4 2.0d7	2.0d4 2.0d7	2.0d4 2.0d7	2.0d4 2.0d7
Random number seed	1963285	1963285	1963285	1963285
Number of years in data set	55	55	55	55
Title	CC	CC	CC	CC
Data series	PBF CPUE, Yield	PBF CPUE, Yield	PBF CPUE, Yield	PBF CPUE, Yield
CPUE(s) used	WESTLL, EPOPS, JPTL, JPPS	JPLL, EPOPS	JPLL, EPOPS	JPPS+JPLL+JPTL+TWCOLL+EPOPS

Table 3. Results of the ASPIC potential base case and sensitive runs. *MSY*: maximum sustainable yield; F_{MSY}: fishing mortality give MSY; f_{MSY}: fishing effort of each fishery in MSY; B_{MSY}: biomass giving MSY; γ: Fletcher's gamma; K: maximum population size; q: catchability of each fishery; n: exponent in production function.

Model, parameter	Base case	Sensitive analysis	Sensitive analysis	Sensitive analysis	Sensitive analysis	Sensitive analysis	Sensitive analysis	Sensitive analysis
Run number	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8
run data name	a1	b1	b2	b3	b4	b5	b6	b7
Model	GENGRID	GENGRID	GENGRID	GENGRID	GENGRID	GENGRID	GENGRID	GENGRID
Year of data	1952-2006	1952-2006	1952-2006	1952-2006	1952-2006	1952-2006	1952-2006	1952-2006
CPUE(s) used	JPPS+JPLL+JPTL	JPPS+JPLL+JPTL	JPPS+JPLL+JPTL+TWCOLL	JPPS+JPLL+JPTL+TWCOLL	JPPS+JPLL+JPTL+TWCOLL+EPOPS	EPOPS+JPLL+JPTL	EPOPS+JPLL+JPTL	EPOPS+JPLL+JPTL+TWCOLL
Weighting of fishery	equal	non-equal	equal	non-equal	equal	equal	non-equal	equal
MSY (MT)	17990	24240	25750	Converged No significant	No converged	23700	19800	No converged
K (MT)	611300	157300	146000			188400	208200	
B_{MSY} (MT)	152800	71970	53230			51020	52060	
F_{MSY}	0.12	0.34	0.48			0.47	0.38	
B_{2006}/B_{MSY}	0.91	0.25	0.62			0.61	0.54	
F_{2006}/F_{MSY}	1.51	23.71	1.63			1.71	2.63	
phi	0.25	0.46	0.37			0.28	0.25	
AIC	76.18	24.15	53.78			54.39	19.38	

Table 3. (continued).

Model, parameter	Sensitive analysis	Sensitive analysis	Sensitive analysis	Sensitive analysis	Sensitive analysis	Sensitive analysis	Sensitive analysis
Run number	Run 9	Run 10	Run 11	Run 12	Run 13	Run 14	Run 15
run data name	b8	b9	b10	b11	b12	b13	b14
Model	GENGRID	GENGRID	GENGRID	GENGRID	GENGRID	GENGRID	GENGRID
Year of data	1952-2006	1952-2006	1952-2006	1952-2006	1952-2006	1952-2006	1952-2006
CPUE(s) used	EPOPS+JPLL+JPTL+TWCOLL	PCOPS, WESTLL, JPTL	PCOPS, WESTLL, JPTL	JPOFFLL, JPCOLL, EPOPS, JPTL, TWCOLL, JPPS	JPOFFLL, JPCOLL, EPOPS, JPTL, TWCOLL, JPPS	TWCOLL CPUE only	JPPS CPUE only
Weighting of fishery	non-equal	equal	non-equal	equal	non-equal	1	1
MSY (MT)	21560	Converged No significant	853000	No converged	No converged	No converged	No converged
K (MT)	256600		15530000				
B_{MSY} (MT)	71710		6677000				
F_{MSY}	0.30		0.13				
B_{2006}/B_{MSY}	0.30		2.05				
F_{2006}/F_{MSY}	5.47		0.015				
phi	0.28		0.43				
AIC	31.79		296.6				

Table 3. (continued).

Model, parameter	Sensitive analysis	Sensitive analysis	Sensitive analysis	Sensitive analysis	Sensitive analysis
Run number	Run 16	Run 17	Run 18	Run 19	Run 20
run data name	b15	b16	b17	b18	B19
Model	GENGRID	GENGRID	GENGRID	GENGRID	GENGRID
Year of data	1952-2006	1952-2006	1952-2006	1952-2006	1952-2006
CPUE(s) used	WESTLL, EPOPS, JPTL, JPPS	WESTLL, EPOPS, JPTL, JPPS	JPLL, EPOPS	JPLL, EPOPS	JPPS+JPLL+JPTL+TWCOLL+EPOPS
Weighting of fishery	equal	non-equal	equal	non-equal	non-equal
MSY (MT)	No converged	20910	22470	No converged	No converged
K (MT)		178800	183000		
B_{MSY} (MT)		44710	45750		
F_{MSY}		0.47	0.49		
B_{2006}/B_{MSY}		0.31	0.70		
F_{2006}/F_{MSY}		1.71	1.60		
phi		0.25	0.25		
AIC		203.1	53.57		

Table 4. Detailed fitting results and estimated model parameters in sensitive run 7.

MODEL PARAMETER ESTIMATES (NON-BOOTSTRAPPED)

Parameter		Estimate	User/pgm guess	2nd guess	Estimated	User guess
B1/K	Starting relative biomass (in 1952)	3.370E+00	8.500E-01	3.197E-01	1	1
MSY	Maximum sustainable yield	1.980E+04	2.000E+04	1.928E+04	1	1
K	Maximum population size	2.082E+05	1.000E+05	1.157E+05	1	1
phi	Shape of production curve (Bmsy/K)	0.2500	0.000E+00	0.000E+00	1	1
--------- Catchability Coefficients by Data Series ---------------						
q(1)	EPOPS	4.440E-07	5.000E-07	4.750E-05	1	1
q(2)	JPLL	1.612E-06	2.000E-06	1.900E-04	1	1
q(3)	JPTL	1.938E-05	3.000E-05	2.850E-03	1	1

MANAGEMENT and DERIVED PARAMETER ESTIMATES (NON-BOOTSTRAPPED)

Parameter		Estimate	Logistic formula	General formula
MSY	Maximum sustainable yield	1.980E+04	----	----
Bmsy	Stock biomass giving MSY	5.206E+04	K/2	K*n**(1/(1-n))
Fmsy	Fishing mortality rate at MSY	3.802E-01	MSY/Bmsy	MSY/Bmsy
n	Exponent in production function	0.5000	----	----
g	Fletcher's gamma	-4.000E+00	----	[n**(n/(n-1))]/[n-1]
B./Bmsy	Ratio: B(2007)/Bmsy	4.128E-01	----	----
F./Fmsy	Ratio: F(2006)/Fmsy	2.624E+00	----	----
Fmsy/F.	Ratio: Fmsy/F(2006)	3.810E-01	----	----
Y.(Fmsy)	Approx. yield available at Fmsy in 2007	8.172E+03	MSY*B./Bmsy	MSY*B./Bmsy
	...as proportion of MSY	4.128E-01	----	----
Ye.	Equilibrium yield available in 2007	1.727E+04	4*MSY*(B/K-(B/K)**2)	g*MSY*(B/K-(B/K)**n)
	...as proportion of MSY	8.722E-01	----	----
--------- Fishing effort rate at MSY in units of each CE or CC series ---------				
fmsy(1)	EPOPS	8.565E+05	Fmsy/q(1)	Fmsy/q(1)
fmsy(2)	JPLL	2.359E+05	Fmsy/q(2)	Fmsy/q(2)
fmsy(3)	JPTL	1.962E+04	Fmsy/q(3)	Fmsy/q(3)

Table 4. (continued).

ESTIMATES FROM BOOTSTRAPPED ANALYSIS

Param name	Point estimate	Estimated bias in pt estimate	Estimated relative bias	Bias-corrected approximate confidence limits: 80% lower	80% upper	50% lower	50% upper	Inter-quartile range	Relative IQ range
B1/K	2.589E+00	-1.100E+00	-42.47%	4.561E+00	4.561E+00	4.561E+00	4.561E+00	0.000E+00	0.000
K	2.235E+05	3.741E+04	16.74%	1.535E+05	2.314E+05	1.535E+05	2.092E+05	5.571E+04	0.249
q(1)	4.914E-07	7.063E-08	14.37%	3.416E-07	5.445E-07	3.987E-07	4.968E-07	9.808E-08	0.200
q(2)	1.771E-06	3.570E-07	20.16%	1.054E-06	2.245E-06	1.222E-06	1.888E-06	6.657E-07	0.376
q(3)	2.231E-05	5.470E-06	24.52%	1.242E-05	4.513E-05	1.594E-05	3.163E-05	1.569E-05	0.703
MSY	1.976E+04	2.479E+02	1.25%	1.887E+04	2.021E+04	1.907E+04	1.993E+04	8.626E+02	0.044
Ye(2007)	1.914E+04	-7.925E+03	-41.40%	1.878E+04	2.102E+04	1.991E+04	2.102E+04	1.111E+03	0.058
Y.@Fmsy	1.107E+04	-6.102E+03	-55.14%	1.142E+04	1.861E+04	1.410E+04	1.861E+04	4.513E+03	0.408
Bmsy	3.352E+04	1.555E+04	46.39%	3.259E+04	3.259E+04	3.259E+04	3.259E+04	0.000E+00	0.000
Fmsy	5.894E-01	-1.694E-01	-28.74%	6.463E-01	6.463E-01	6.463E-01	6.463E-01	0.000E+00	0.000
fmsy(1)	1.199E+06	-4.350E+05	-36.27%	1.148E+06	1.148E+06	1.148E+06	1.148E+06	0.000E+00	0.000
fmsy(2)	3.329E+05	-1.208E+05	-36.28%	3.578E+05	4.258E+05	3.996E+05	4.258E+05	2.625E+04	0.079
fmsy(3)	2.642E+04	-7.039E+03	-26.64%	2.036E+04	7.025E+04	2.866E+04	4.352E+04	1.486E+04	0.563
B./Bmsy	5.600E-01	-3.133E-01	-55.94%	6.085E-01	8.861E-01	8.329E-01	8.861E-01	5.322E-02	0.095
F./Fmsy	1.976E+00	7.397E+00	374.31%	1.241E+00	1.863E+00	1.241E+00	1.356E+00	1.151E-01	0.058
Ye./MSY	9.688E-01	-4.096E-01	-42.28%	9.810E-01	9.982E-01	9.967E-01	9.982E-01	1.503E-03	0.002
n	2.337E-01	9.907E-02	42.39%	2.413E-01	2.413E-01	2.413E-01	2.413E-01	0.000E+00	0.000
phi	1.500E-01	3.983E-02	26.55%	1.535E-01	1.535E-01	1.535E-01	1.535E-01	0.000E+00	0.000
q2/q1	3.603E+00	2.303E-01	6.39%	2.293E+00	4.653E+00	2.834E+00	4.070E+00	1.236E+00	0.343
q3/q1	4.539E+01	4.365E+00	9.62%	2.548E+01	9.477E+01	3.348E+01	6.566E+01	3.218E+01	0.709

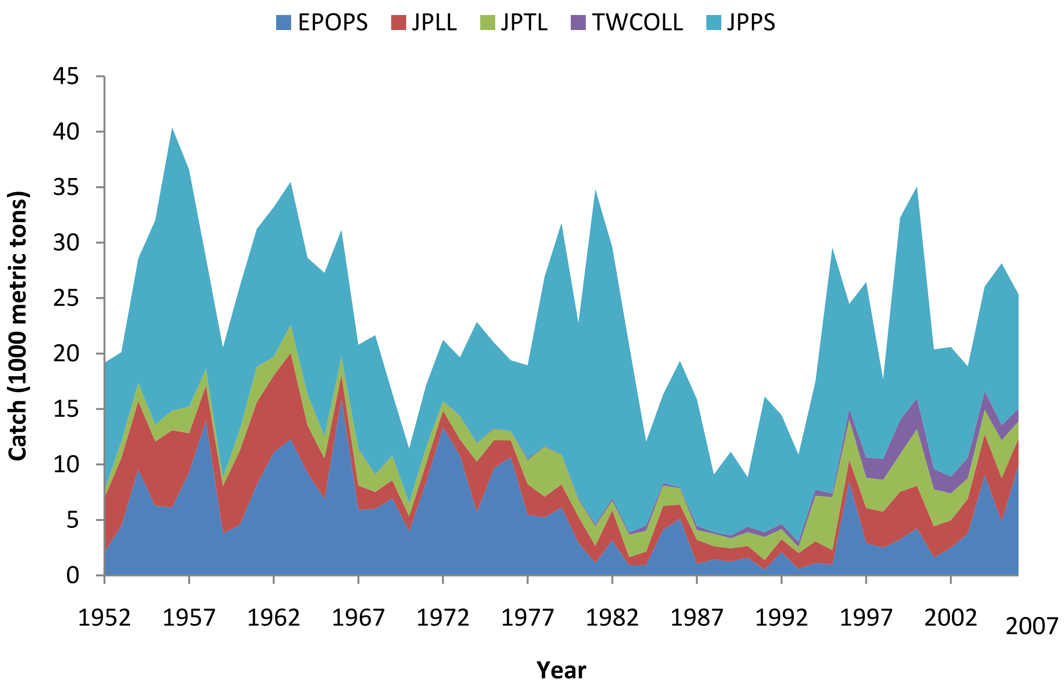


Fig.1. The annual catches of pacific bluefin tuna from 1950 to 2005 (Data sources: Anon,, 2007).

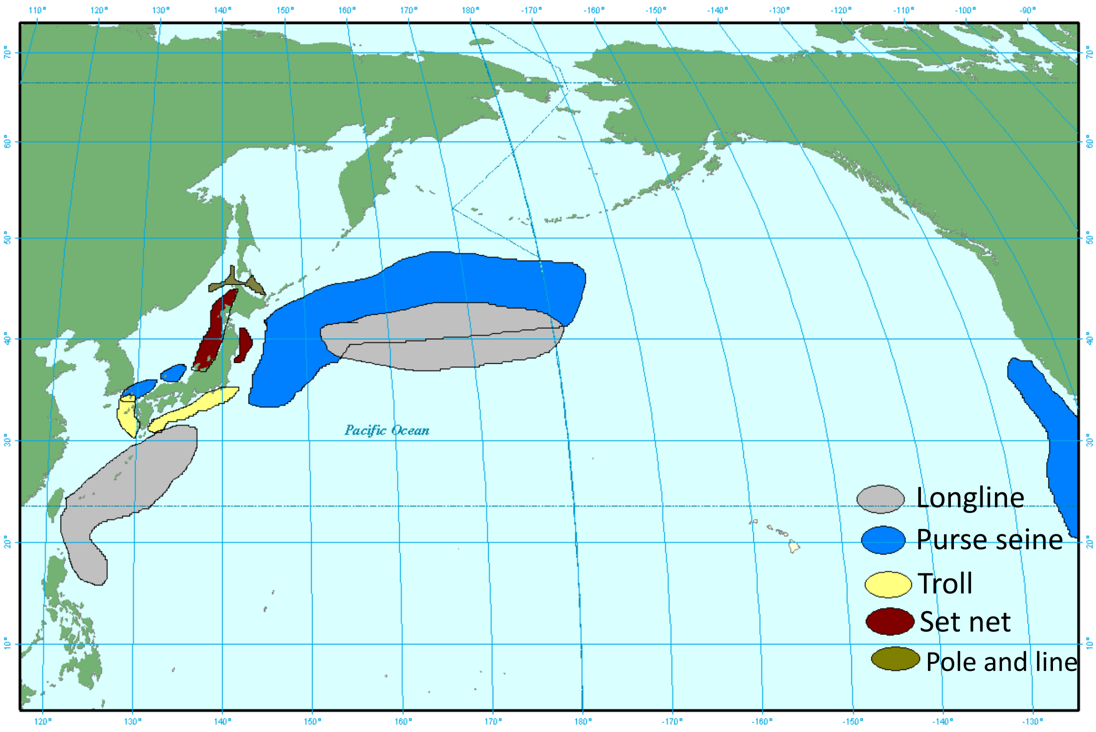
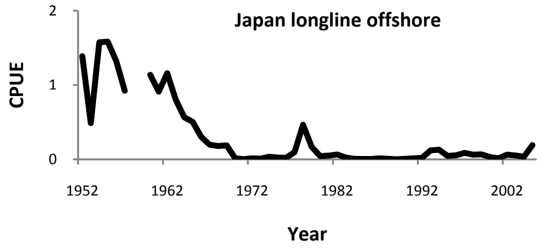
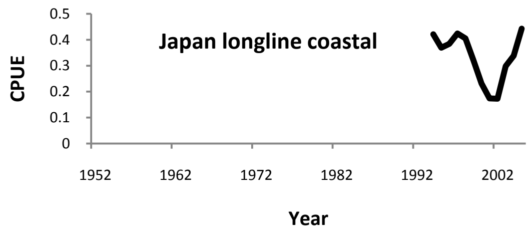


Fig. 2. Main fishery targets for Pacific bluefin tuna in Northern Pacific.

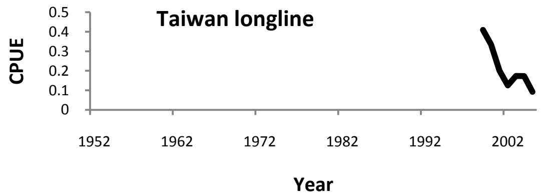
(a)



(b)



(c)



(d)

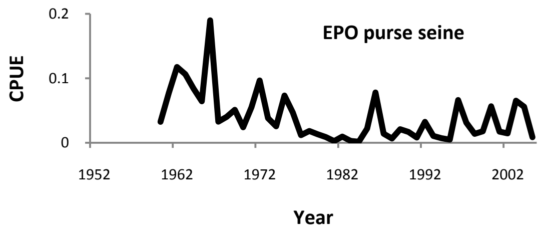
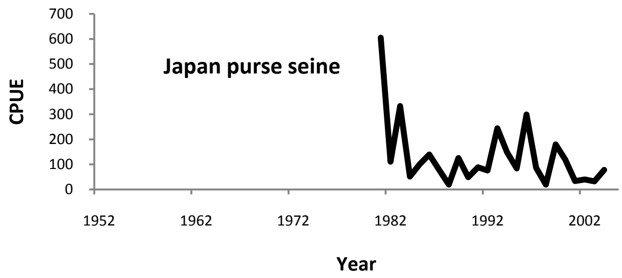


Fig. 3. The estimated time series of CPUE from each data source.(a) Japan longline offshore (b) Japan longline coastal (c) Taiwan longline (d) Eastern Pacific Ocean purse seine (e) Japan purse seine (f) Japan troll.

(e)



(f)

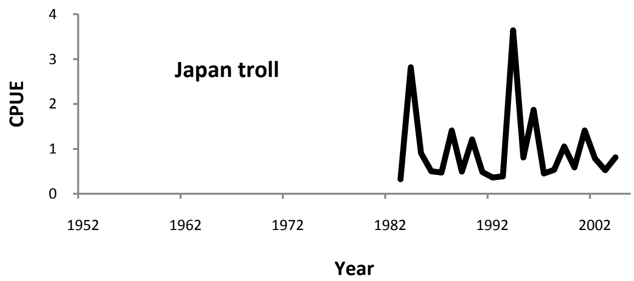
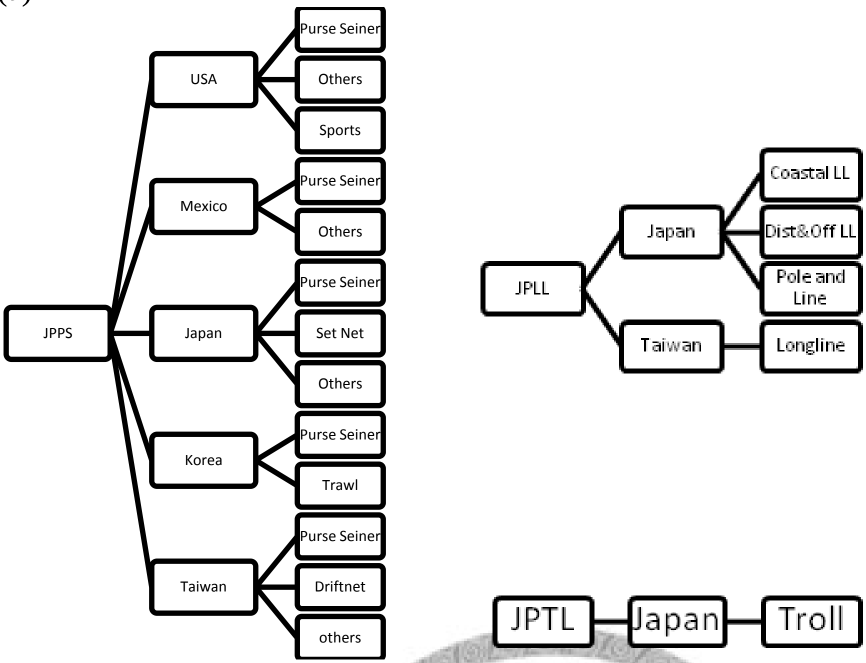


Fig. 3. (continued).

(a)



(b)

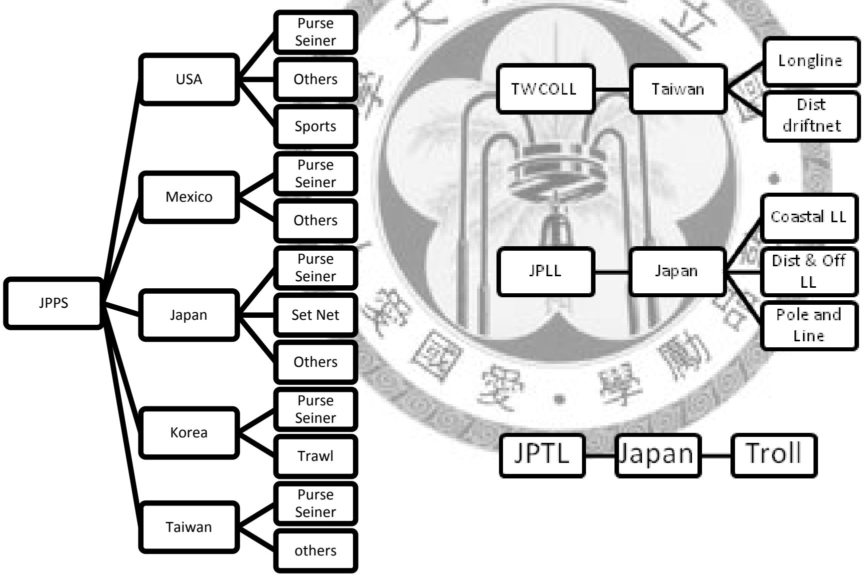
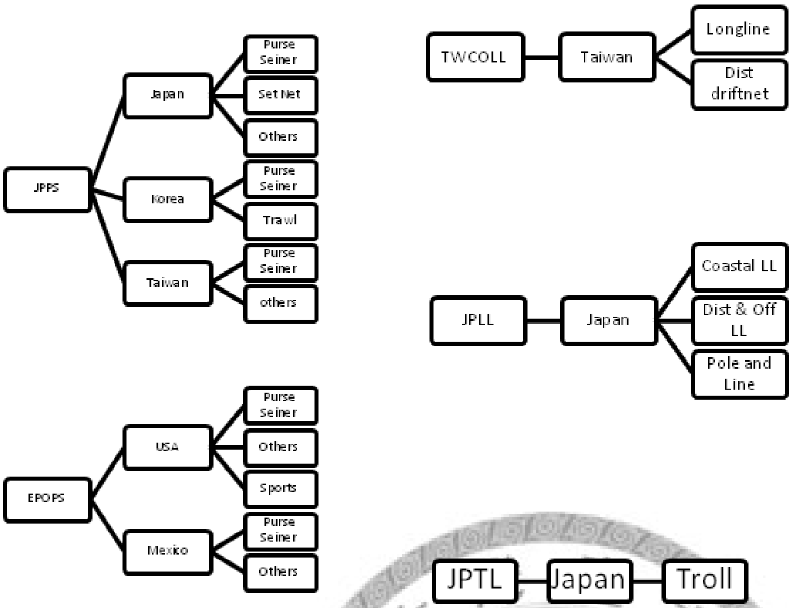


Fig. 4. Detailed descriptions of re-arrangement fishery catch data in run 1 ~ run20 (a) run1 & run2 (b) run3 & run4 (c) run5 & run20 (d) run6 & run7 (e) run8 & run9 (f) run10 & run11 (g) run12 & run13 (h) run16 & run17 (i) run18 & run19.

(c)



(d)

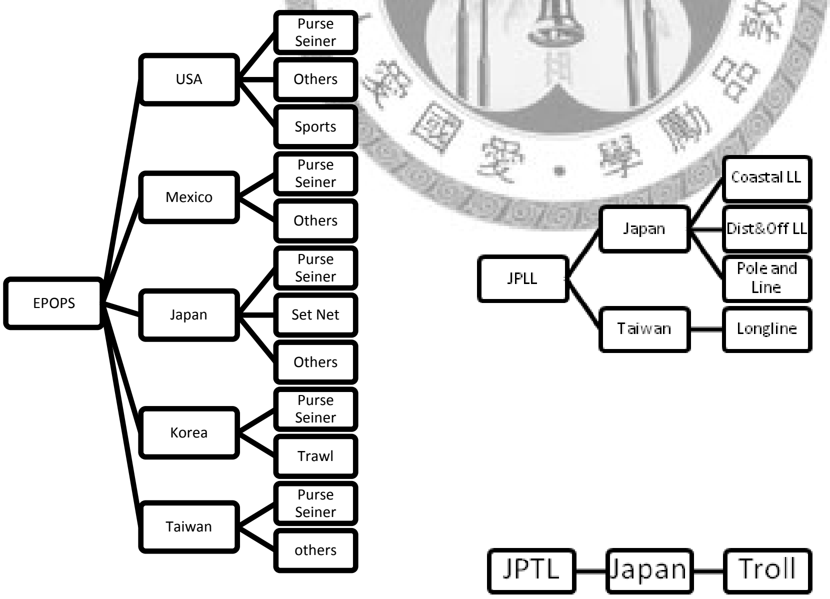
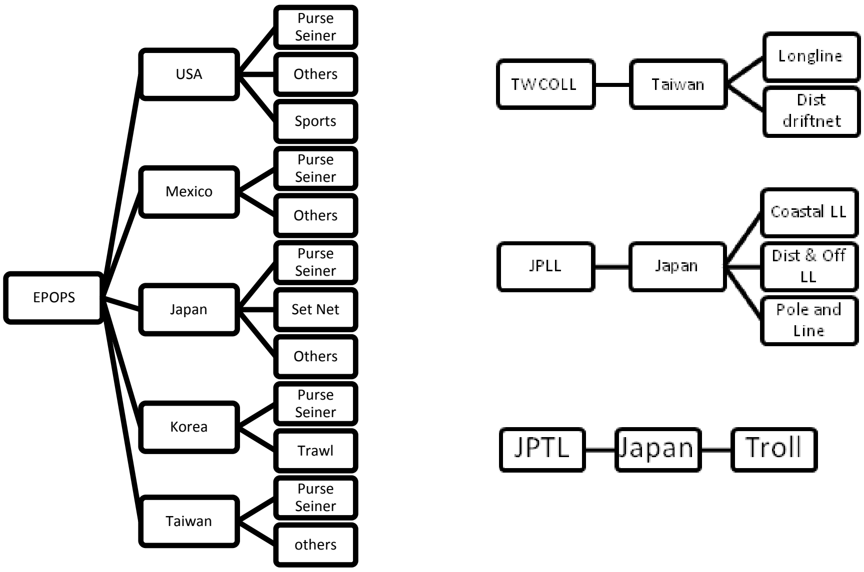


Fig. 4. (continued).

(e)



(f)

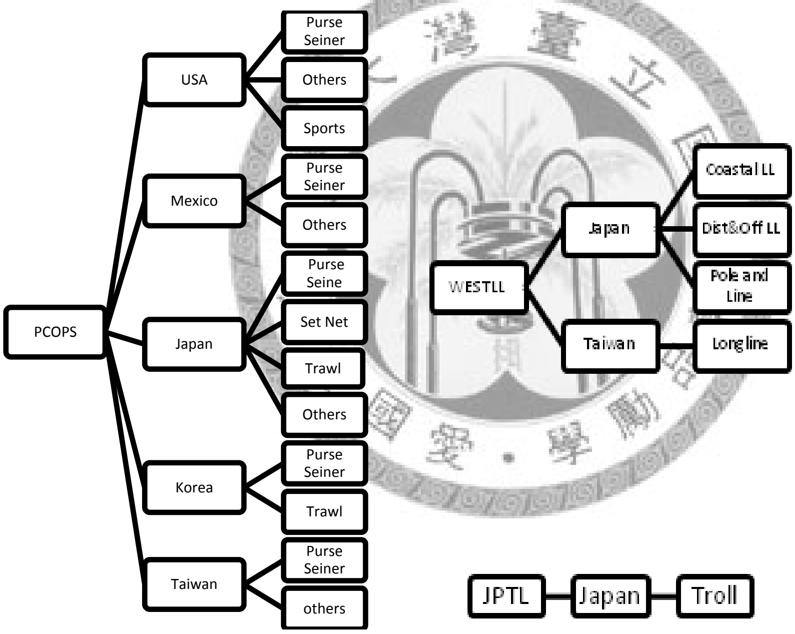


Fig. 4. (continued).

(g)

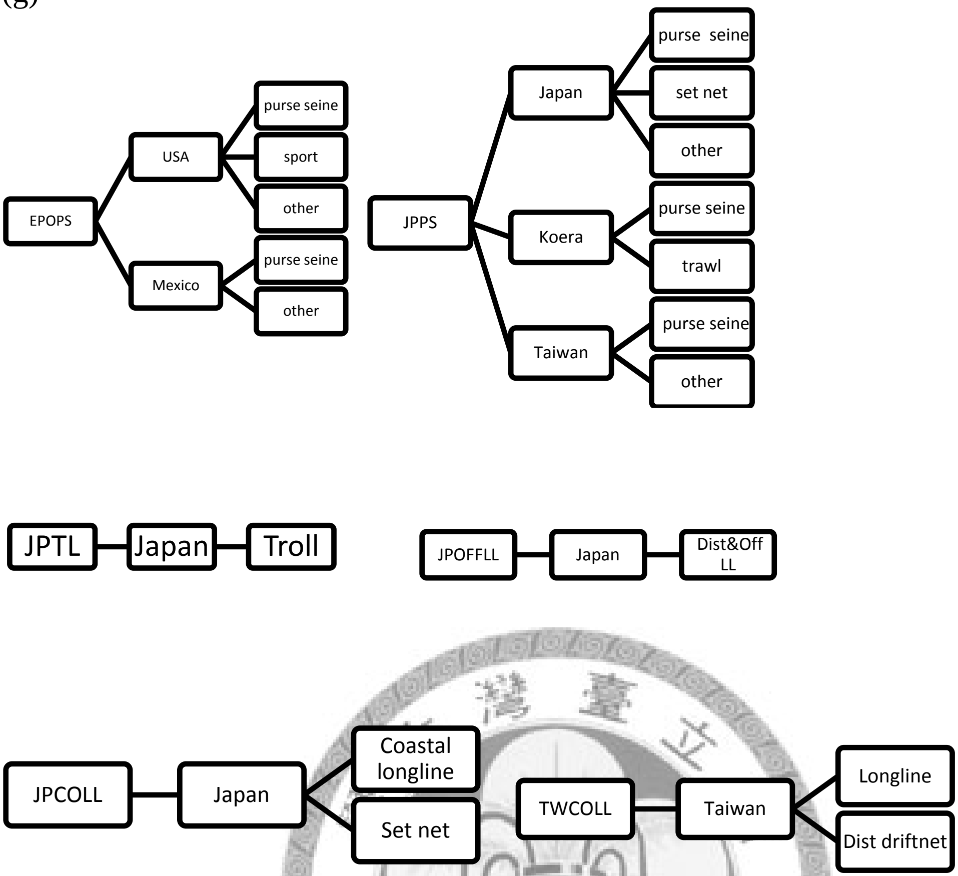
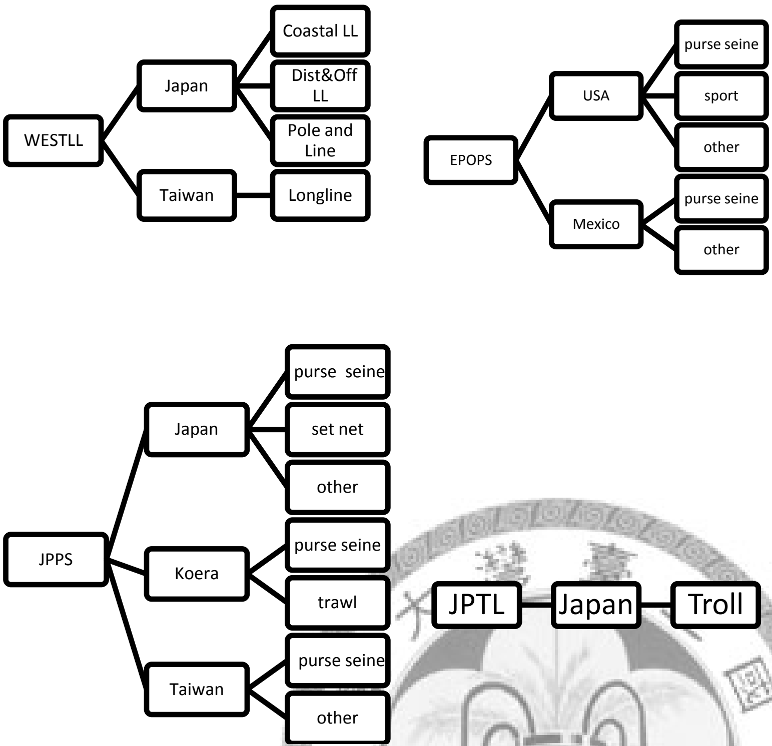


Fig. 4. (continued).

(h)



(i)

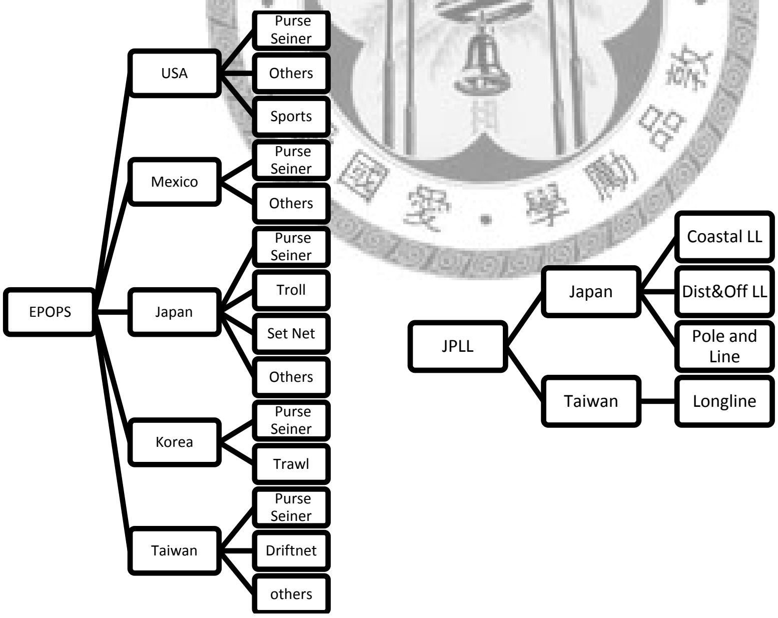


Fig. 4. (continued).

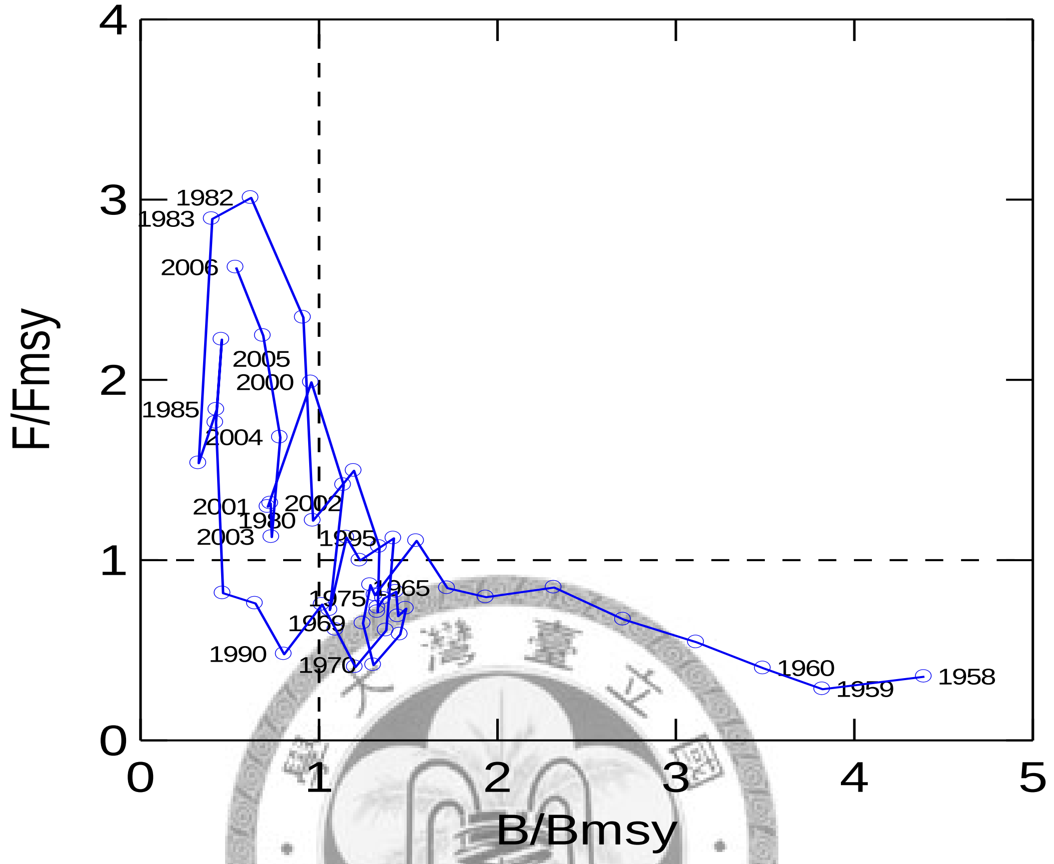


Fig. 5. Annual biomass ratio (B/B_{MSY}) and fishing mortality ratio (F/F_{MSY}) ratio for Pacific bluefin tuna (1952-2006) using generalized production model in run 7.

(a)

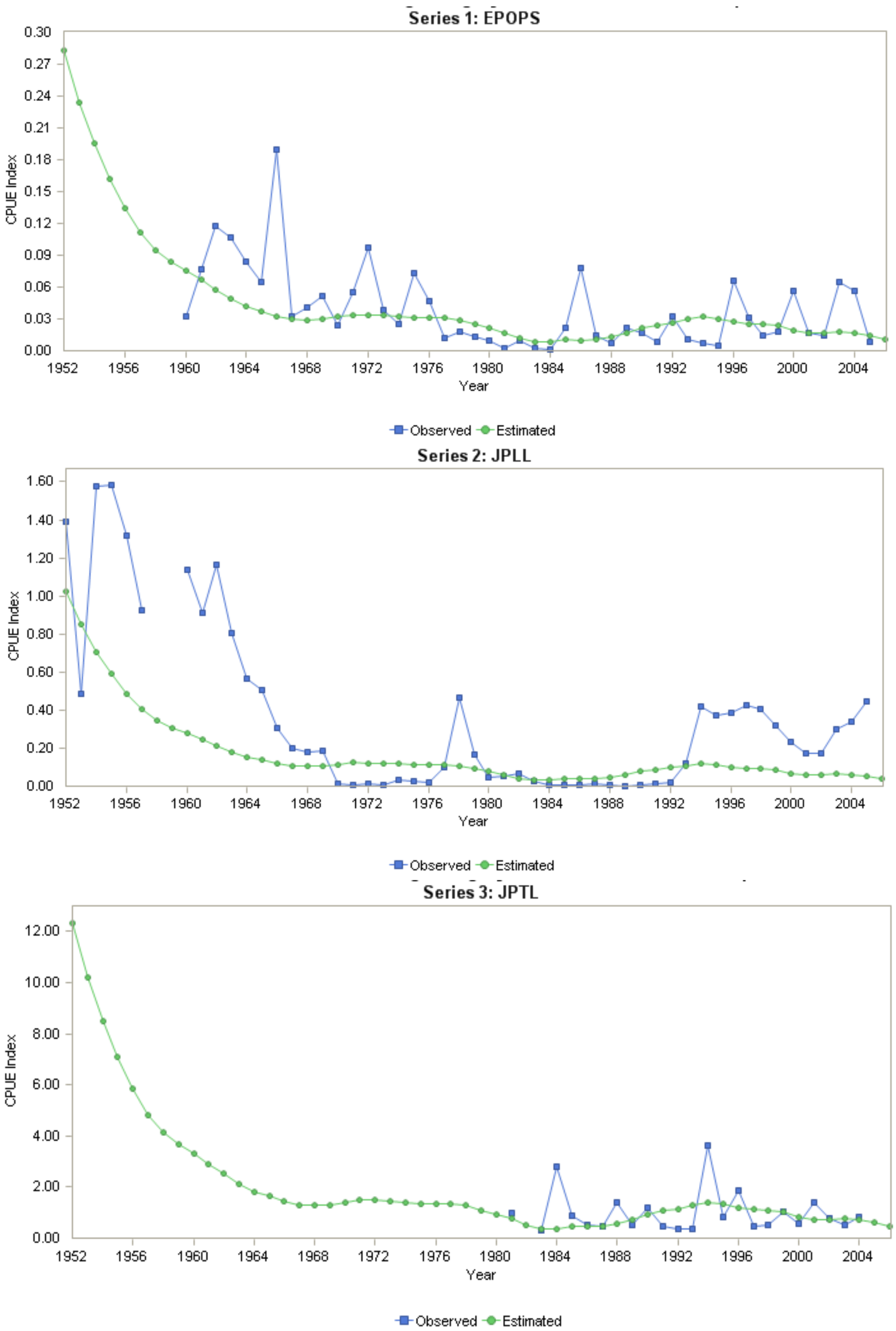
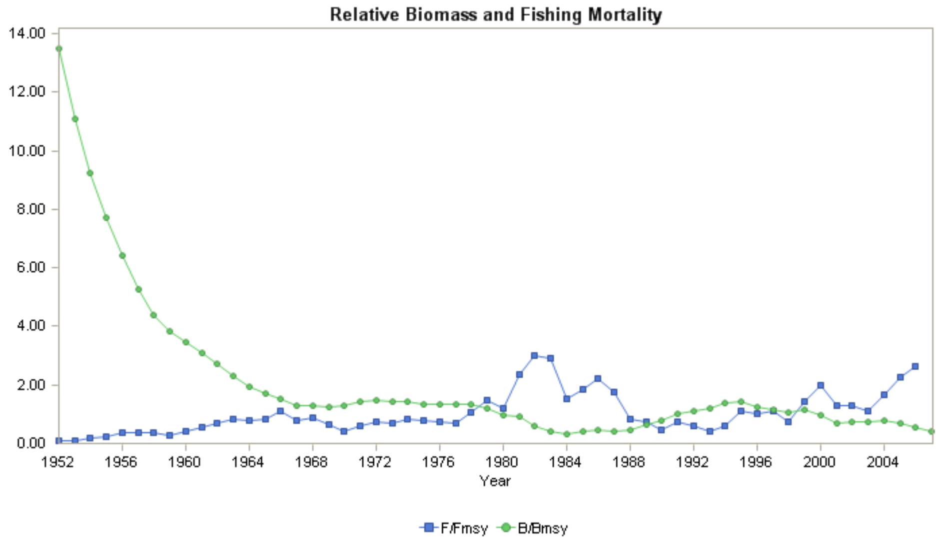


Fig. 6. The fitting results of run 7 (EPOPS, JPLL, and JPTL)(non-equal).
(a) CPUE trajectory of each fishery (b) B-ratio and F-ratio (c) B-ratio and F-ratio of model and bootstrap (d) distribution of relationship between B-ratio and F-ratio in 2006.

(b)



(c)

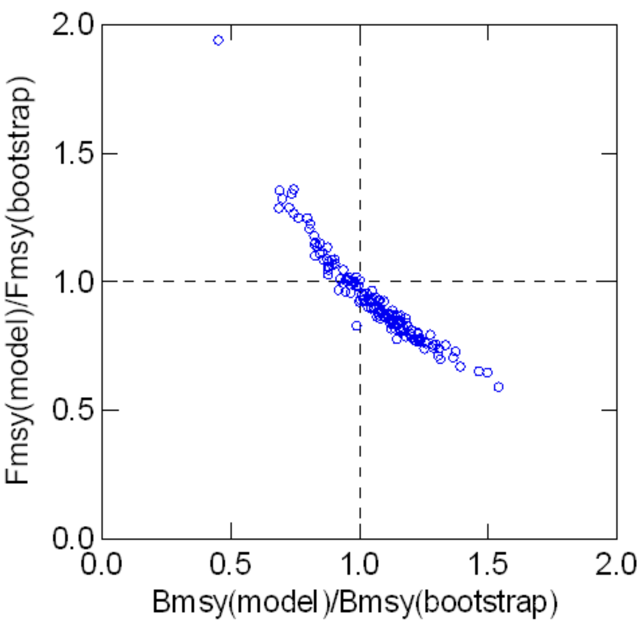


Fig. 6. (continued).

(d)

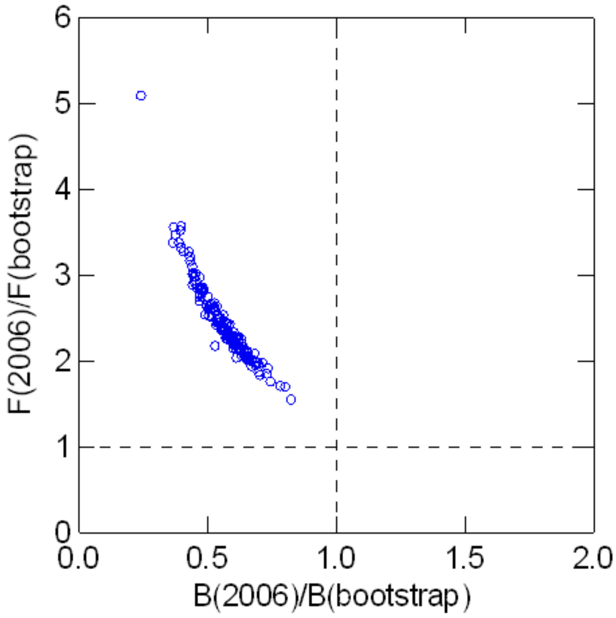
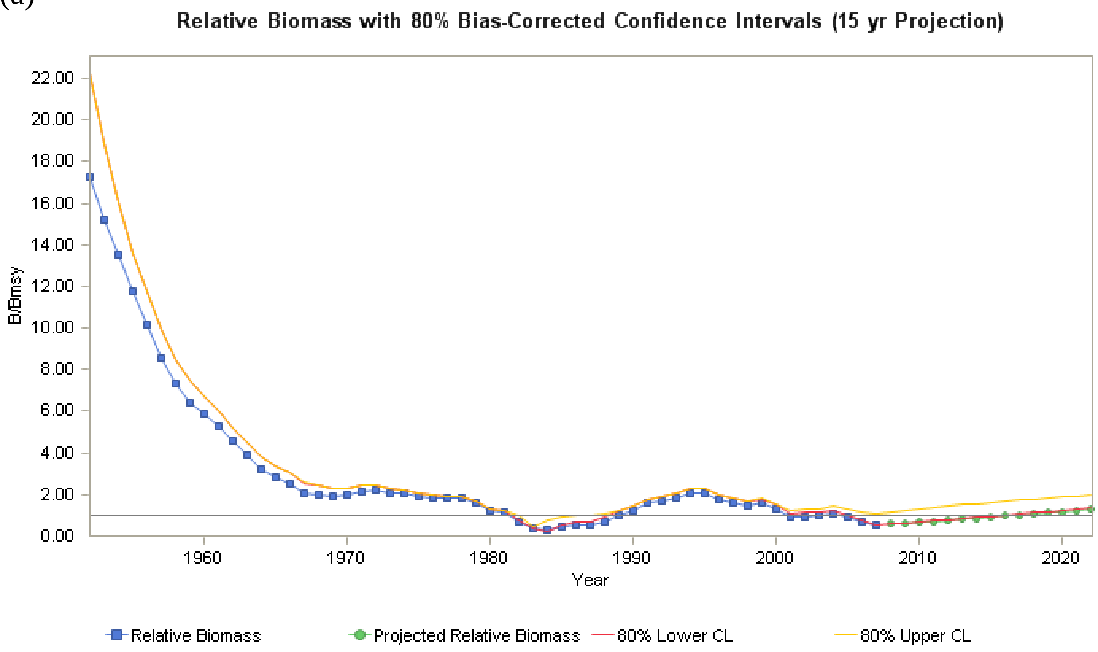


Fig. 6. (continued).

(a)



(b)

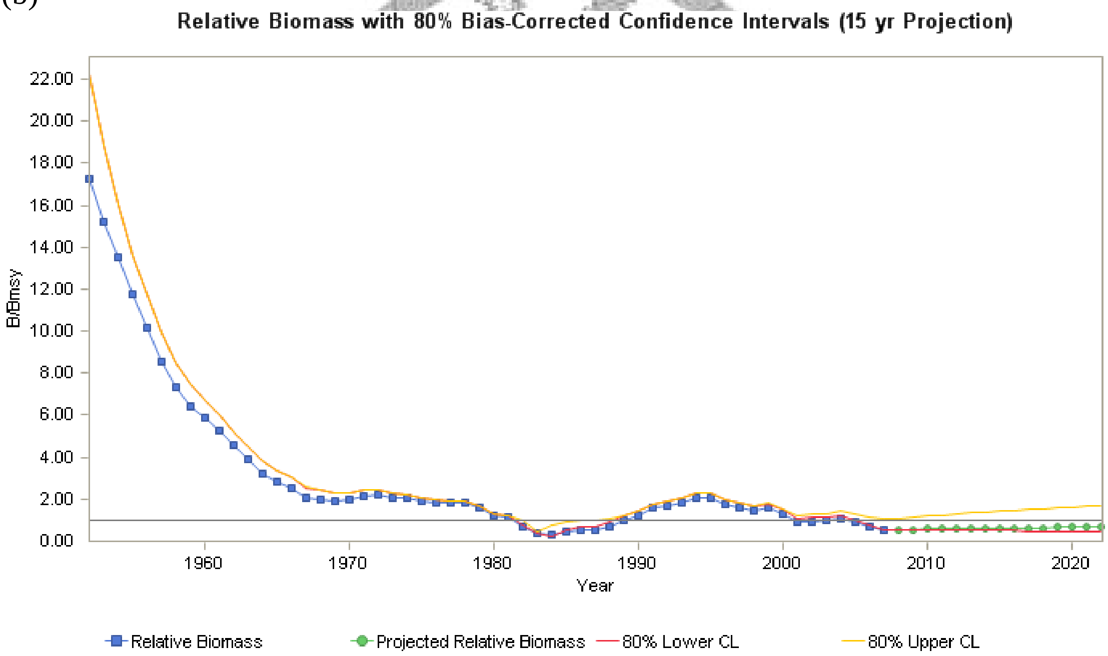
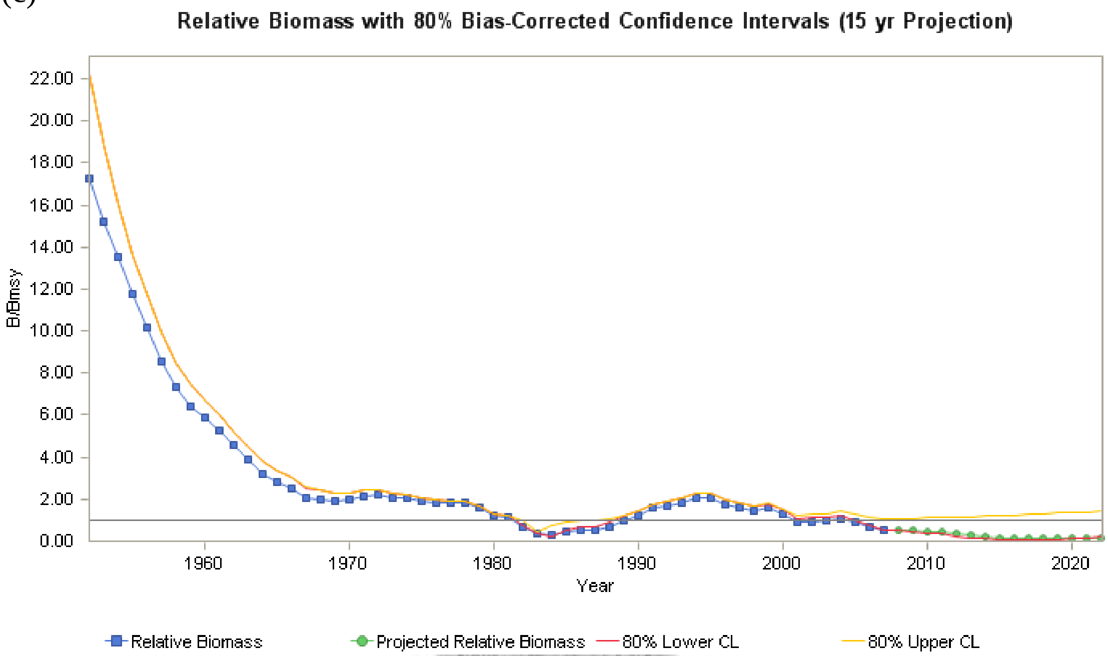


Fig. 7. The results of using run 7 for projection in B/B_{msy} ratio after 15 year. (a)catch level : 18,000 mt (b)catch level : 19,000 mt (c)catch level : 20,000 mt (d) catch level : 26,000 mt

(c)



(d)

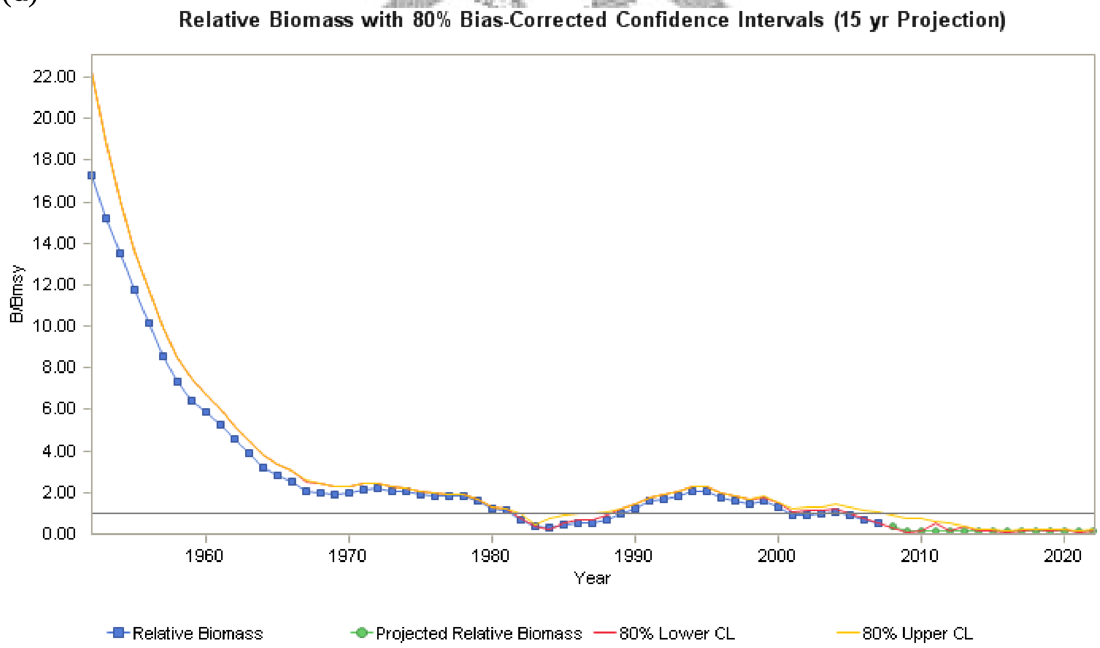
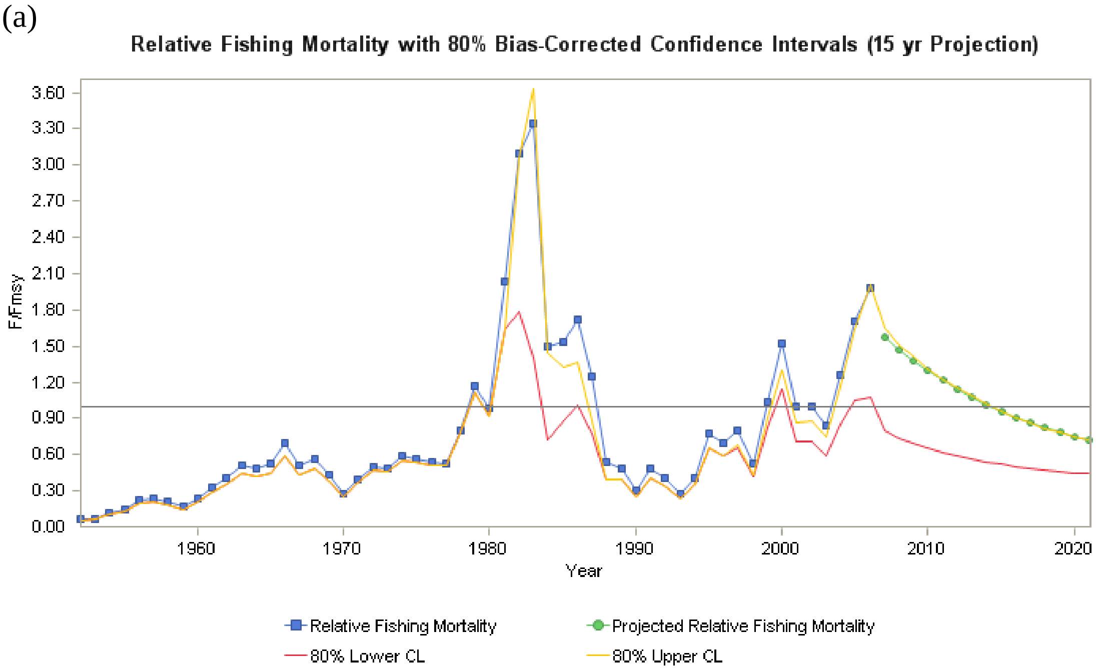


Fig. 7. (continued).

(a)



(b)

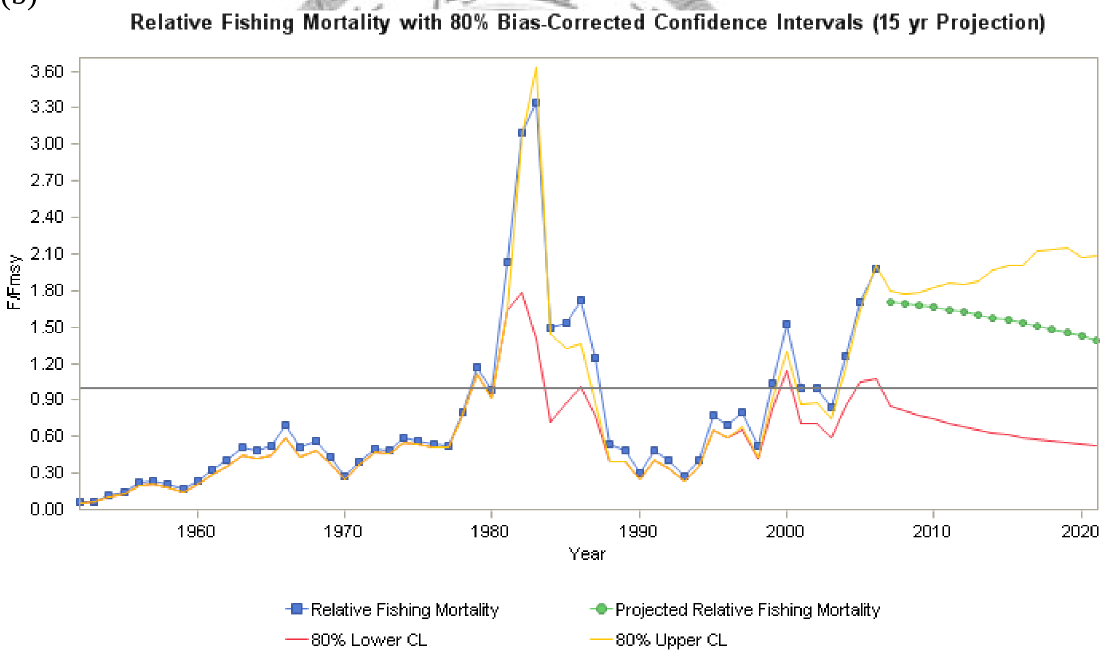
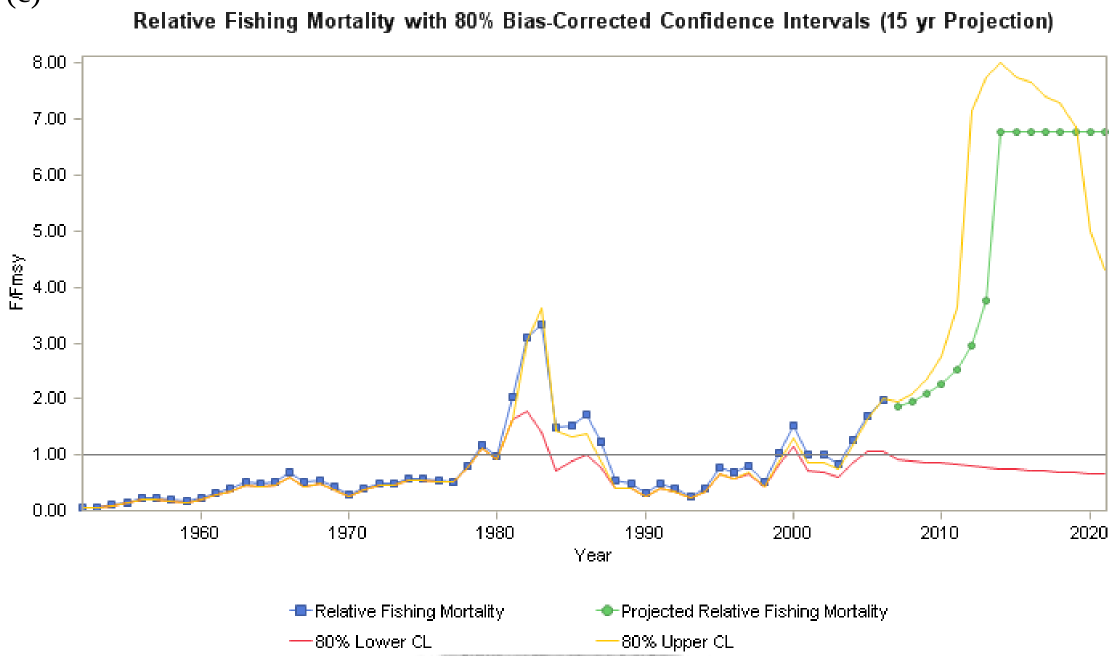


Fig. 8. The results of using base case run 7 for projection in F/F_{msy} ratio after 15 year. (a)catch level : 18,000 mt (b)catch level : 19,000 mt (c)catch level : 20,000 mt(d) catch level : 26,000 mt

(c)



(d)

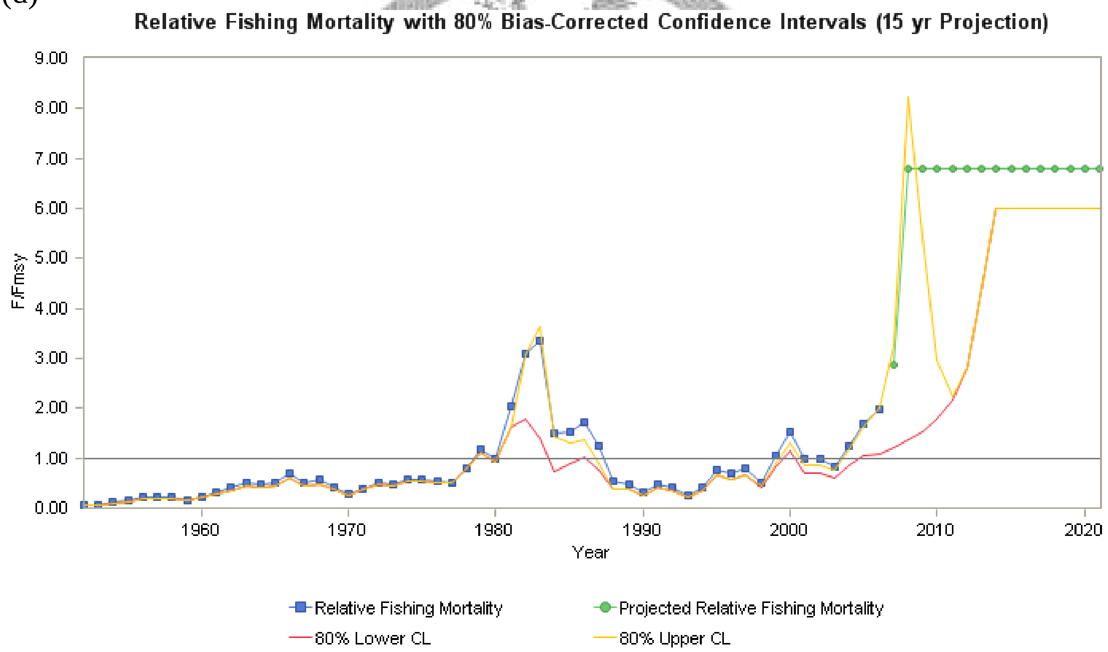


Fig. 8. (continued).

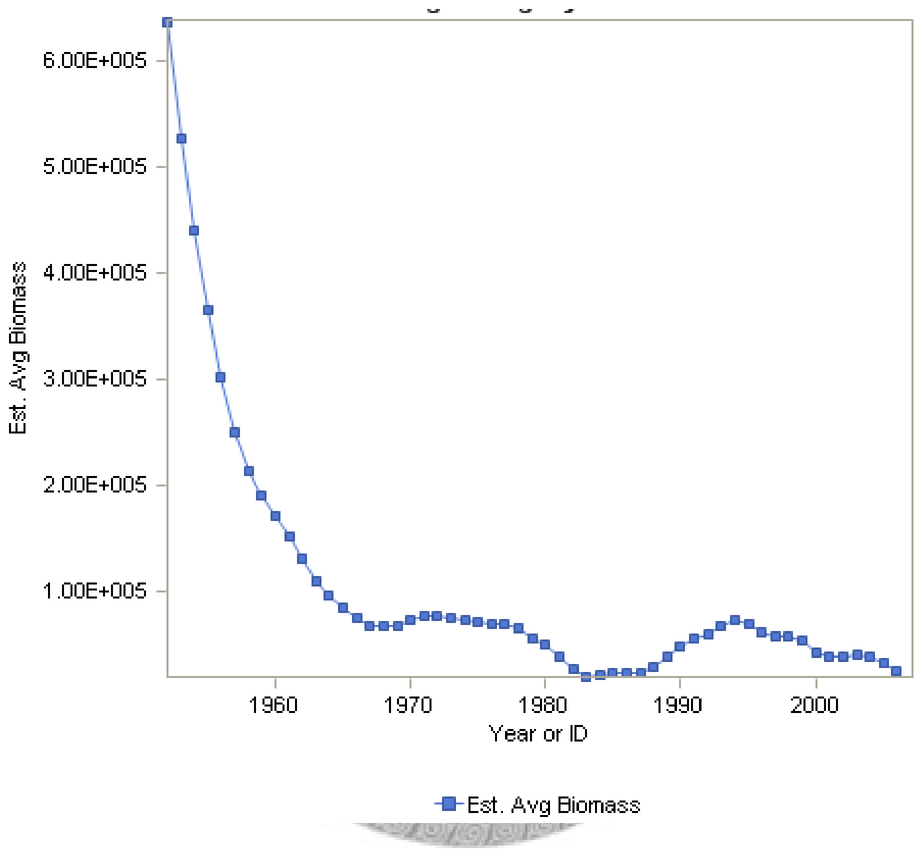


Fig. 9. The estimated average biomass of Pacific bluefin tuna in this study from 1952 to 2006.