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北太平洋黑鮪漁獲策略的貝氏統計模式建構與參數估計研究(3/3)

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行政院國家科學委員會補助專題研究計畫 ■成果報告
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執行單位：國立臺灣大學海洋研究所

中　華　民　國　96　年　10　月　22　日

Abstract

Bluefin tuna is the largest and the highest economic species among tunas. Traditionally, Pacific bluefin tuna were exploited by Japan, Taiwan, U.S.A. Mexico and South Korea. About 90% of annual catch was caught by Japanese, and 5% for Taiwanese. Japan used longline, troll, purse seine, handline and driftnet to catch adult and juvenile fish smaller than 215 cm; Taiwan used longline to catch fish over 185 cm; U.S.A. used purse seine incidentally to catch smaller fish; Mexico used purse seine to catch juveniles for farming; and South Korea used purse seine and trawl to fish seasonally. Recently, the production was lower than 15,000 t after the highest harvest was made in 1980 (33,494 t). The recent two decades, declined productions may result from decreasing standing crops. And the accuracy of reported catches and selectivity are the issues of analyzed the stock accurately. The study used abundance indices from different fisheries to build the production models by Bayesian approach and to analyze the uncertainty of the observed data. Then the study used age-structured models to investigate the population dynamics, and finally the study estimated the population reproductive potential in order to understand when a strong year-class occurred. Results indicated that Taiwanese longline index declined from the peaked in 1999 to the lowest in 2002, then increased slight then after. Bayesian model was built with uncertainty shows that total biomass was the lowest in 2002 about 80,000 t, and recovered to 130,000 t in 2004. The exploitation rate was declined from 2002 to 2004 about lower than 40% annually. The estimated MSY ranged from 24,400 t to 25,000 t. The standing crop was at moderate to full exploitation status. The adaptive VPA indicated that the spawning stock biomass (over 5-year-old) was in fluctuated increasing, about 30,000 t to total biomass about 60,000 t in 2003. This result was more conservative than from Bayesian approach, but the abundance is the second high since 1970s. The recruit shows a great fluctuation recent decade from 1 to 9 million fish. Population reproductive potential analysis shows the tendency of recruitment coincidently. However, the great fluctuation of recruits needs to be investigated in future.

Keywords: Pacific bluefin tuna; abundance index; Bayesian approach; production analysis; virtual population analysis; reproductive value; population reproductive potential; recruit; spawning stock biomass; exploitation rate; maximum sustainable yield

摘要

黑鮪是鮪類中體型最大，經濟價值最高，因此，被過度捕撈的機率也最大。傳統的太平洋黑鮪系群漁業國主要爲日本、臺灣、美國、墨西哥和南韓。日本漁獲量佔有總漁獲量的90%以上，臺灣約佔有5%。日本以鮪延繩釣、曳繩釣、圍網、手釣和刺網漁業爲主，捕撈215公分以下的成魚和幼魚；臺灣以鮪延繩釣爲主，捕撈185公分以上的成魚；美國主要爲圍網的意外兼捕；墨西哥以圍網捕撈幼魚，作爲黑鮪養殖之種苗；南韓則是季節性的在濟州島外海，爲圍網和拖網漁業的意外捕獲。近年，自1980年達歷年最高產量(33,493公噸)以後，總捕獲量趨於穩定在15,000公噸或以下。20年來，漁獲量下降是資源存量的問題，抑或是努力量降低的問題，是管理此一資源所應探討的重點。且漁獲量的準確度和各漁業所捕獲不同的年級群，故本研究採用不同漁業的資源指標，進行貝氏統計建構及漁獲量不準確度的分析，再則採用年齡群構造的年級群分析模式做年級群動態分析，以及估計該族群的生殖潛能，以了解該族群有否強度年級群的加入。

分析結果顯示，臺灣鮪延繩釣漁業捕獲的產卵群資源量指標，自1999年的最高點以來，持續下降至2002年，後呈兩年的略微上升。這一現象是否實質表現出該資源已自低點回升，貝氏統計建構及漁獲量不準確度的分析指出總資源存量在2002年呈現近年來的最低點(約80,000公噸)，已回升到約130,000公噸。開發率也由2000年的最高點，下降到2003年又再度回升，該現象表現出其中量尙維持在40%的資源存量之下。又，估計平均最大持續生產量約24,400-25,000公噸。故，北太平黑鮪資源上在中度到完全充分開發之間。經用年級分析法分析，更表現出產卵群(5歲以上成魚)雖呈波動上升，2003年以後呈增加趨勢，有約30,000公噸以上；而總資源生物量也已超過60,000公噸。結果雖較貝氏分析結果保守，資源量已是1970年以後，達次高點。分析加入群數量顯示，近10年來年度波動很大，自1百萬尾至9百萬尾之間，結果正確與否，值得在研究。由生殖潛能分析發現，加入群量的趨勢和族群生殖潛能是相一至的。但加入群量的高度波動原因如何，值得繼續探討。

關鍵詞：太平洋黑鮪，資源量指標，貝氏途徑，生產量分析，年級群分析，生殖價，族群生殖潛能，加入群量，產卵群生物量，開發率，最大持續生產量。

INTRODUCTION

Bluefin tuna is a common name for three species, those are northern bluefin tuna which includes *Thunnus thynnus* distributing in the Atlantic Ocean where is mainly the Carrabean Sea in the western Atlantic, Mid-northern Atlantic and Eastern Atlantic and the Mediterranean Sea; and *Thunnus orientalis* in the North Pacific Ocean; *Thunnus maccoyii* in the waters circum-southern hemisphere (Gibbs and Collette 1967). Usually, *T. thynnus* is called as Atlantic bluefin tuna, *T. orientalis* is Pacific bluefin tuna and *T. maccoyii* is southern bluefin tuna. Fig. 1-1 indicates the distribution of PBF in the Pacific Ocean (Collete and Nauen 1983) for the species.

Bluefin tuna is a highly migratory species, it can migrate trans-ocean (Mather, 1960；Orange and Fink, 1963；Clemens, 1969；Mather, 1980；Cort and Rey, 1985；Clay, 1991；Bayliff, 1993; Anonymous 2007). It can be found mainly in temperate and tropical waters of northern hemisphere, including the Pacific ocean; Atlantic Ocean and Mediterranean Sea (Nakamura, 1938；Blackburn, 1965；Nakamura and Warashina, 1965；Shingu *et al.*, 1974；Collette and Nauen, 1983). The bluefin tuna can tolerate a very wide range of water temperature that is from about 5°C to 29°C, as long as the archival tags for western Atlantic bluefin tuna indicated the water temperature at their habitat ranged from 4°C to 24°C during the late winter and early spring (Block et al. 1998). The distribution of Pacific bluefin tuna (PBF) was investigated by biological studies (Deriso and Bayliff 1991), fishery (Bayliff 1994) and tagging (Takahashi et al. 2002). The PBF adults migrate to northeastern waters off Luzon, eastern and northeasternTaiwan, Ryukyu Islands, southern Kyushiu prefecture and the Sea of Japan (Deriso and Bayliff 1991) in the western North Pacific; The juveniles and sub-adults distribute in the waters northward off southern Japan and the eastern North Pacific where are the waters off California and Mexico in the western North America, and they return to the western North Pacific waters when they grow to about 4 and 5-year-old as becoming sexual maturity (Bayliff 1994; Takahashi et al. 2002).

Many studies and reports were issued to describe the stock status of the Pacific bluefin tuna during the past two decades, however, other than biological studies, the stock assessment was very few with the abundance index derived from Japanese fleets and purse seiners in the eastern Pacific Ocean.[2] For this species are exposed to multi-fisheries over most of a wide fishery space extent, historical statistics from different fishing parties should be very essential to indicate its different population patterns. To assess and propose a management measures for the Pacific bluefin tuna, thus, catch and effort data collection as well as developing a reliable abundance index to represent the spawning stock are urged for Taiwanese fishery. Biomass dynamic models are one of the simplest analytical methods available that focuses on the dynamics of the population as a whole. The original method of assuming equilibrium conditions has been criticized for providing overly optimistic estimates of optimum effort and maximum sustainable yield and suggestions were made to abandon the use of the models (Hilborn and Walters, 1992; Haddon, 2001; Williams and Prager, 2002). The major concerns about fitting these models to time-series data are that uncertainties and variability are not taken into consideration. Parameters are point estimates or assumed values are used and uncertainties of parameters are often ignored or additional analyses are conducted to assess uncertainties using sensitivity analysis (e.g. Goodyear, 1995), confidence intervals (e.g. Mohn, 1993) or sampling distributions using re-sampling methods (e.g. Smith et al., 1993). However, none of these provide integrated analyses to describe unknowns and parameters in the form of probability for complex model (McAllister and Kirkwood, 1998). Further uncertainties are associated with how the model handles observation and process errors.

To resolve both the observation error and the process error structures for Pacific bluefin tuna, the state-space modeling with a Bayesian approach was used. The model incorporates uncertainties about reported catch data in and abundance indices from the six major fisheries, which Taiwanese small longline fisheries seasonally was included and those fisheries were weighted equally within the model in order to capture the true uncertainties about quantities of interest such as maximum sustainable yield. Therefore, the following 5 topics were pursued in this three-year term project, in which a synopsis of PBF fishery and 4 complete papers that have and will be submitted to SCI journals was presented and attached as a final report of this project.

1. Pacific bluefin tuna fishery;
2. Abundance index for the longline fishery targeting spawning Pacific bluefin tuna in the southwestern North Pacific Ocean;
3. Incorporating uncertainty into the estimation of biomass for the Pacific bluefin tuna;
4. Stock assessment of bluefin tuna in the North Pacific Ocean by virtual population analysis with adaptive framework;
5. Reproductive potential analysis of bluefin tuna in the North Pacific Ocean;

1. PBF fishery

PBF provides important fishery for Japan, Mexico, Taiwan, U.S.A. and South Korea (Anon. 2007). Table 1-1 shows the historical catches by those nations. The PBF catch is mainly from western North Pacific Ocean, which occupies about 84% by Japan, Taiwan and South Korea; from eastern North Pacific by U.S.A. and Mexico. The catches by nations were summarized as followed:

1.1 Japan

Fig. 1-2 shows catch of PBF by Japanese fisheries (Yamada 2007). Japan has used PBF before 1952, including several gears, such as purse seine, longline, troll, pole and line and set net etc. The annual catch varied from 8,000 tons to 30,000 tons. Since 1990s, annual catches ranged from 8,000 tons to 22,000 tons with a 80% age composition about 0-2 years old juveniles, and in particular, 95% in 1991 (Takahashi and Yamada 2002). Yamada and Yamazaki (2002) reported that 70% of Japanese catch (about 5,000 tons to 8,000 tons year to year) were from the coastal purse seine fishery, in which two places were operated, those were the Pacific waters off eastern Japan for juveniles and adults from June to August each year, and off the Sea of Japan for adults from July to August and for juveniles from April to June. Japanese longline was operated at coastal waters off Japan and distant waters in the North Pacific Ocean from late April to early June, including southwestern waters of Miyako Island, southeastern waters of Ishigaki Island and northern waters of Nishimote Island. The annual production varied between 300 and 1,400 tons. Troll fishery was mainly operated in sides of the Sea of Japan from July to March. Catches were almost the juveniles about 20-30 cm. The pole and line fishery fish juvenile PBF incidentally from June to December, with a great variation catches from 100 to 400 tons annually. The Japanese set net fishery exploited size variety PBF in different seasons, the catches were less than 500 tons with main 0 and 1-year-old PBF. And the driffnet fished PBF at coastal waters for juveniles; the catches were less than 100 tons.

1.2 Taiwan

Fig. 1-3 shows the historical catches of PBF (Hsu 2007). Taiwan exploited PBF by using small-scaled longline during late April and late June only in the waters off eastern Luzon and eastern Taiwan; and only for the giant mature adults. The PBF catches by Taiwanese longliners were less than 189 tons before; and increased since then to the peak of 3,089 tons in 1999, then declined year to year, about 1,400 tons in 2006.

1.3 South Korea

PBF by South Korean fishermen was caught using mackerel purse seiners incidentally from January to August off Cheju and Tsushima. The sizes of caught PBF were about 30-80 cm, equivalent to about o year-old and one-year-old. And the total annual catch was about 1,000 tons with more than 30 purse seiners and 4 trawlers (Anon.2007).

1.4 U.S.A.

The PBF fishery in the eastern Pacific Ocean was exploited from 23^{o}N to 34^{o}30'N, northward to Alaska waters using mainly the purse seiners from May to October. Besides, the recreational fishery was taken by U.S.A. and drift net by Mexico. The annual catches were from 250 tons to 4,900 tons, in which were about 75% were taken from south California and the coastal waters off Mexico (Dreyfus 2007). Also the swordfish and bigeye tuna fisheries can take PBF incidentally by longline gear in the California and Hawaii waters.

1.5 Mexico

Mexicans took PBF from the coast waters during June and October with a PBF mean weight about 20 kg (5 – 60 kg)。 The catches were from 100 tons to 700 tons annually before 1989 and from 0 to about 9,900 tons then after.

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Table 1-1 shows the historical catches by those nations. (From Report of the 2007 Pacific Bluefin Tuna Workshop, Shimizu, Japan)

Year	Western Pacific States													Sub Total	Eastern Pacific States					Sub Total	***** Other countries	Grand Total
	Japan							Korean**		Chinese Taipei					United States			Mexico				
	Purse Seine		Longline	Troll***	Pole and Line	Set Net	Others	Purse Seine	Trawl	Longline ****	Purse Seine	Distant Driftnet	Others		Purse Seine	Others	Sport	Purse Seine	Others			
	Tuna PS	Small PS																				
1952	7,680		2,581	439	2,198	2,145	357							15,400	2,076		2			2,078		17,478
1953	5,570		1,998	1,465	3,052	2,335	133							14,553	4,433		48			4,481		19,034
1954	5,366		1,588	1,656	3,044	5,579	266							17,499	9,537		11			9,548		27,047
1955	14,016		2,099	1,507	2,841	3,256	264							23,983	6,173		93			6,266		30,249
1956	20,979		1,242	1,765	4,060	4,170	703							32,919	5,727		388			6,115		39,034
1957	18,147		1,490	2,395	1,795	2,822	208							26,857	9,215		73			9,288		36,145
1958	8,586		1,429	1,509	2,337	1,187	190							15,238	13,934		10			13,944		29,182
1959	9,996		3,667	1,011	586	1,575	154							16,988	6,914		15			6,929		23,917
1960	10,541		5,784	1,846	600	2,032	363							21,166	5,422		1	0		5,423		26,589
1961	9,124		6,175	3,116	662	2,710	598							22,385	8,136		26	130		8,292		30,677
1962	10,657		2,238	978	747	2,545	289							17,454	11,268		28	294		11,590		29,044
1963	9,786		2,104	2,403	1,256	2,797	279							18,626	12,271		8	412		12,691		31,317
1964	8,973		2,379	2,739	1,037	1,475	365							16,968	9,218		8	131		9,357		26,325
1965	11,496		2,062	1,429	831	2,121	356			54				18,348	6,887		1	289		7,177		25,525
1966	10,082		3,388	1,502	613	1,261	114			-				16,960	15,897		23	435		16,355		33,315
1967	6,462		2,099	3,115	1,210	2,603	282			53				15,824	5,889		36	371		6,296		22,120
1968	9,268		2,278	1,407	983	3,058	203			33				17,231	5,976		1	195		6,172		23,403
1969	3,236		1,366	1,836	721	2,187	184			23				9,553	6,926		17	260		7,203		16,756
1970	2,907		1,123	1,181	723	1,779	215			-				7,929	3,966		21	92		4,079		12,008
1971	3,721		757	2,189	938	1,555	226			1				9,386	8,360		8	555		8,923		18,309
1972	4,212		724	2,385	944	1,107	154			14				9,539	13,348		17	1,646		15,011		24,550
1973	2,266		1,158	3,519	526	2,351	576			33				10,430	10,746		61	1,084		11,891		22,321
1974	4,106		1,220	2,994	1,192	6,019	679			47				16,258	5,617		65	344		6,026		22,284
1975	4,491		1,558	941	1,401	2,433	781			61				11,667	9,583		38	2,145		11,766		23,433
1976	2,148		520	920	1,082	2,996	1,226			17				8,910	10,646		23	1,968		12,637		21,547
1977	5,110		712	2,230	2,256	2,257	1,031			131				13,727	5,473		21	2,186		7,680		21,407
1978	10,427		1,049	4,757	1,154	2,546	2,183			66				22,183	5,396		5	545		5,946		28,129
1979	13,881		1,223	2,659	1,250	4,558	2,200			58				25,830	6,118		12	213		6,343		32,173
1980	11,327		1,170	1,494	1,392	2,521	1,931			114				19,948	2,938		8	582		3,528		23,476
1981	25,422	8	796	1,758	754	2,129	2,540			179				33,587	867	15	6	218		1,106		34,693
1982	19,234		880	872	1,777	1,667	1,622	31		207	-	11		26,302	2,639	4	7	506		3,156		29,458
1983	14,774	10	707	2,020	356	972	892	13		175	9	12		19,939	629	134	21	214		998		20,937
1984	4,433		360	1,905	587	2,234	658	4		477	5			10,664	673	34	31	166		904		11,568
1985	4,154	8	496	1,920	1,817	2,562	992	1		210	80	67		12,308	3,320	155	55	676		4,206		16,514
1986	7,412		249	1,562	1,086	2,914	468	344		70	16	81		14,202	4,851	339	7	189		5,386		19,588
1987	8,653	19	346	1,030	1,565	2,198	308	89		365	21	87		14,681	861	114	21	119		1,115		15,796
1988	3,583	18	241	1,190	907	843	403	32		108	197	234	197	7,953	923	81	4	447	1	1,456		9,409
1989	6,077	89	440	1,025	754	748	204	71		205	259	319	259	10,450	1,046	65	70	57	0	1,238		11,688
1990	2,834	125	396	1,291	536	716	351	132		189	149	305	149	7,174	1,380	165	40	50	0	1,635		8,809
1991	4,336	4,421	285	2,168	286	1,485	340	265		342	-	107	-	14,035	410	11	57	9	0	487		14,522
1992	4,255	2,387	573	908	166	1,208	986	288		464	73	3	73	11,385	1,928	128	93	0	0	2,149		13,534
1993	5,156	1,102	857	534	129	848	263	40		471	1		4	9,404	580	103	114	0	0	797		10,201
1994	7,345	564	1,138	3,427	162	1,158	301	50		559			-	14,705	906	160	24	63	2	1,155		15,860
1995	5,334	12,009	769	4,618	270	1,859	225	821		335			2	26,242	689	49	166	10	0	914		27,156
1996	5,540	1,798	978	3,203	94	1,149	276	102		956			-	14,097	4,523	70	30	3,700	0	8,323		22,420
1997	6,137	5,862	1,383	2,634	34	803	379	1,054		1,814			-	20,101	2,240	85	90	367	0	2,782		22,883
1998	2,715	2,269	1,260	2,550	85	874	238	188		1,910			-	12,089	1,771	271	213	1	0	2,256		14,345
1999	11,619	3,863	1,155	3,164	35	1,097	150	256		3,089			-	24,428	184	85	397	2,369	35	3,070		27,498
2000	8,193	6,802	1,005	4,367	102	1,125	271	794	0	2,780			2	25,440	693	61	220	3,025	103	4,102		29,542
2001	3,139	3,912	1,004	3,124	180	1,366	457	995	10	1,839			104	16,130	149	47	226	863	0	1,285		17,415
2002	4,171	4,359	889	2,422	99	1,011	590	674	1	1,523			4	15,743	50	12	348	1,708	6	2,124		17,867
2003	945	4,850	1,230	1,695	44	841	710	1,591	0	1,863			21	13,790	22	17	229	3,211	46	3,525	28	17,342
2004	4,792	2,218	1,311	2,067	132	896	1,091	636	0	1,714				14,857	0	11	34	8,880	11	8,936	27	23,820
2005	3,927	6,249	1,824	3,382	549	4,595	725	1,476		1,368				24,094	201	5	79	4,488		4,773	14	28,881
2006*	3,780	3,317	1,037	1,445	108	2,907	697	1,007		1,148				15,447	0	1	96	9,706		9,803	57	25,306

* Preliminary for 2006
** Catch statistics of Korea derived from Japanese Import statistics for 1982-1999, and 2005-2006 as minimum estimates.
*** The troll catch for farming estimating 10 - 20 mt since 2000, is excluded.
**** Catches of Chainese Taipei's longline for 2005 and 2006 are preliminary.
***** Other countries include NZ, AUS, Cooks, and so on. Catches derived from Japanese Imort Statistics as minimum estimates.

太平洋黑鮪的分佈

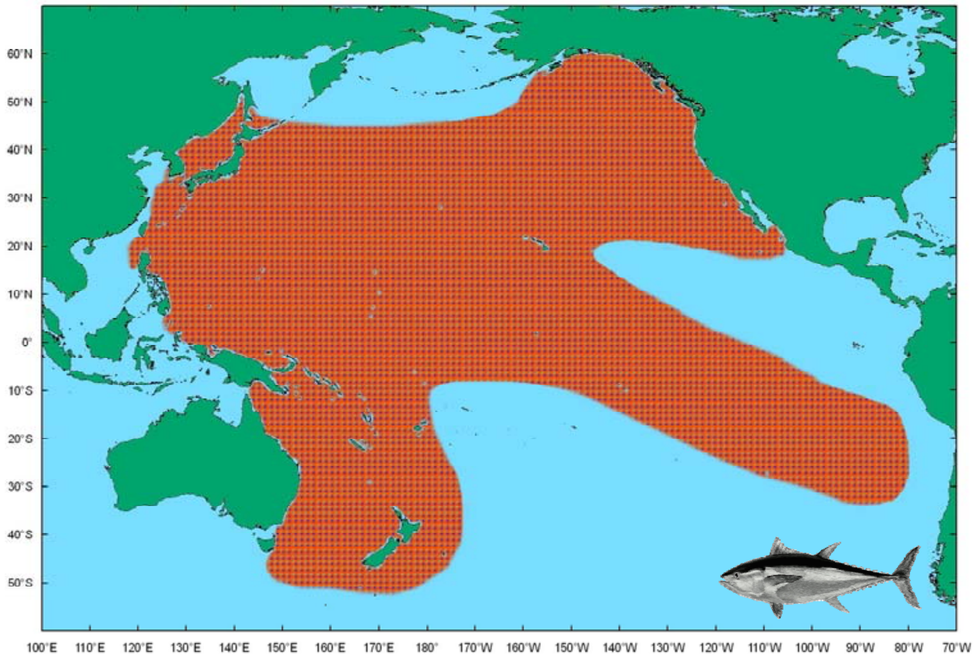

Fig. 1-1 indicates the distribution of PBF in the Pacific Ocean for the species (Collete and Nauen 1983). (Adapted from Chen Kuo-Shu)

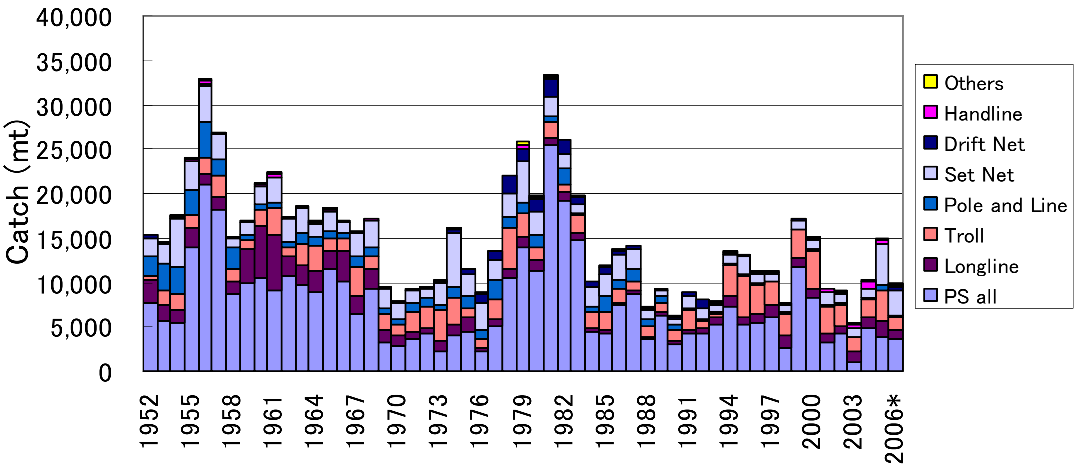

Fig. 1-2 Yearly changes of Pacific bluefin tuna catches by Japanese fleet and by fisheries. (From H. Yamada 2007)

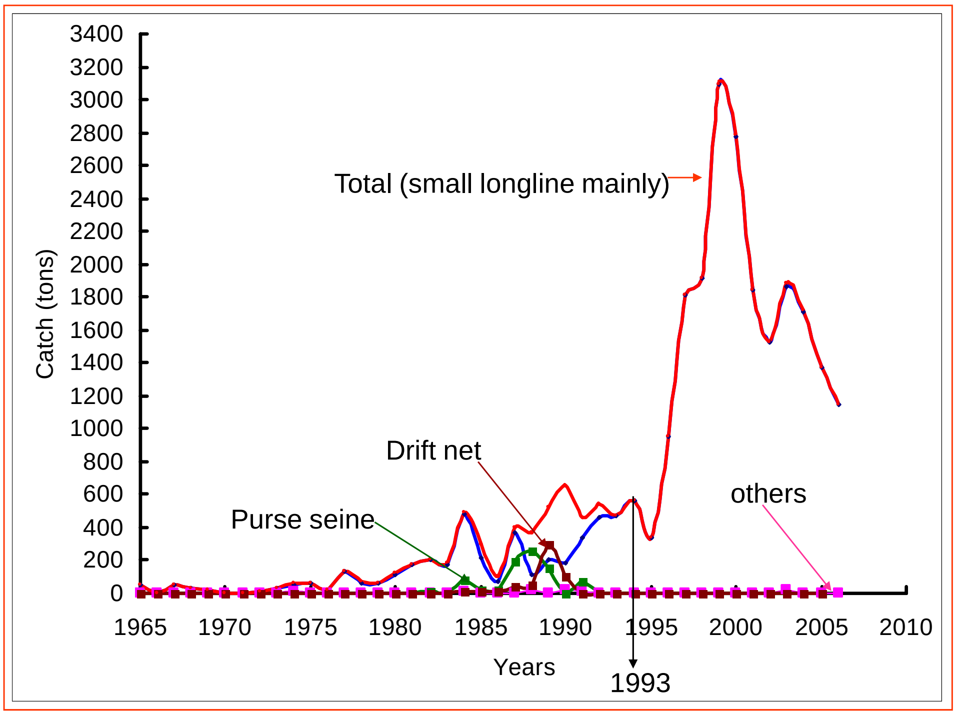

Fig. 1-3 shows the historical catches of PBF by gears.

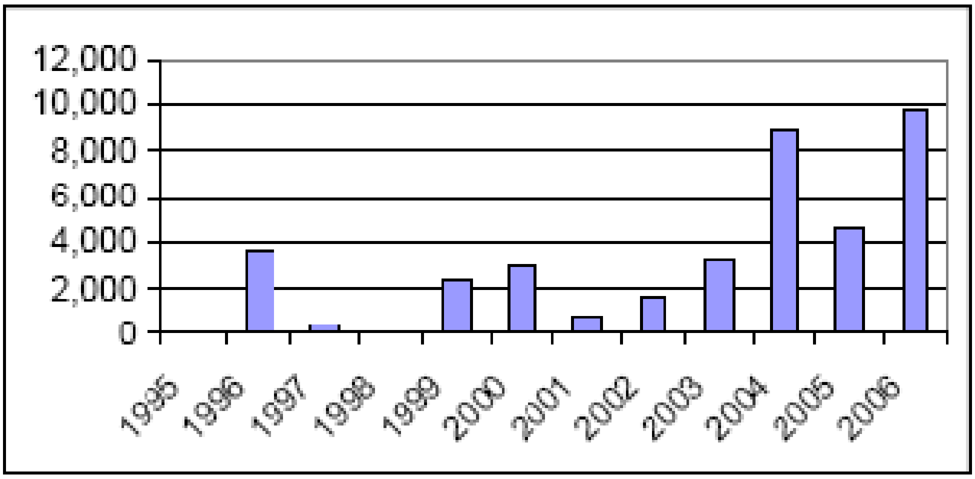

Fig. 1-4 Estimated PBF catch by Mexican fleet from 1995-2006 (From Dreyfus 2007)

2. Abundance index for the longline fishery targeting spawning Pacific bluefin tuna in the southwestern North Pacific Ocean;

Running title: Abundance index of spawning bluefin tuna

Abundance index for the longline fishery targeting spawning Pacific bluefin tuna in the southwestern North Pacific Ocean

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Key Words: Pacific bluefin tuna, abundance index, catch per unit effort (CPUE), generalized linear model (GLM)

Pacific bluefin tuna *Thunnus orientalis* Temmincks and Schlegel 1844 is a highly migratory species, distributing over the Pacific Ocean.[1] This species is among the quality tunas with high economic values and has been historically exploited mainly by Japanese, USA, Mexican, and Taiwanese fleets. Catches were taken about 10% by Taiwanese fleet after 1999,[2] particularly the individuals caught are all giant spawners.[3,4] Taiwanese small-scale longliners (vessels less than 100 GRT) target the stock in the southwestern North Pacific from late April through June. Because of significant catch on spawners, any assessment for this stock should include data from Taiwanese fleet.

Many studies and reports were issued to describe the stock status of the Pacific bluefin tuna during the past two decades, however, other than biological studies, the stock assessment was very few with the abundance index derived from Japanese fleets and purse seiners in the eastern Pacific Ocean.[2] For this species are exposed to multi-fisheries over most of a wide fishery space extent, historical statistics from different fishing parties should be very essential to indicate its different population patterns. To assess and propose a management measures for the Pacific bluefin tuna, thus, catch and effort data collection as well as developing a reliable abundance index to represent the spawning stock are urged for Taiwanese fishery. Therefore, the objective of the study was to model a time series catch per unit effort (CPUE) that can be used as an index of abundance for the Taiwanese fishery from 1999 to 2004.

Daily catch data from auction records and time records of vessels in-and-out which can trace the fishing effort of each vessel were collected and compiled at Tungkang port in which most of bluefin tuna were landed. A data flow diagram demonstrating the principal data sources, processing and storage of commercial catch and effort data is shown in Fig. 1. According to interviews with captains for small-scale longline vessels, about 1,200-1,600 hooks per day can be deployed regardless size of vessel. Large vessels can store more fish than small ones and may stay at sea longer. Fishing effort was then converted from fishing days to number of hooks operated with assumption of average 1,400 hooks lifted daily. The estimated fishing days were subtracted two days, because the vessel took about one day from Tungkang port to the fishing ground and vice versa.

The catch and effort information were summarized in the form of catch-per-unit-effort (CPUE). Based on the assumption that catch is proportional to the product of fishing effort and density, the ability to use CPUE as an index of abundance depends on being able to remove the influences of factors which change fishing efficiency among vessels and cause differences between trips for the same vessel other than abundance.[5] A generalized linear model (GLM)[6] was applied to remove the influential factors and, in the present analysis, the available factors for each vessel-trip compiled in the catch and effort data include year (1999-2004); month (May and June); size of vessel (3 levels, 10-20 GRT, 20-50 GRT and 50-100 GRT). Considering all bluefin fisheries from western North Pacific, Taiwanese fishery appears to be a local fishery with marked fishing season even though the detailed fishing positions are not available and therefore, spawning bluefin density was assumed to be spatially homogeneous.

Independent variables considered for GLM are fishing year, month, size of vessel, and two-way interaction among month and size of vessel, and the dependent variable is the logarithm of catch per unit effort (lnCPUE) assuming a Gaussian error distribution. To avoid zero CPUE causing failure taking with the logarithmic transformation, a positive constant value was added to all CPUEs, while maintaining or achieving normality of the transformed data.[7] Test runs with different values of constant were carried out to see which yielded results that are close to the normally distributed residuals before choosing the value. The assumption of a GLM is that the relationship between the expected lnCPUE and the independent variables is linear. The full model is,

$$\ln(CPUE_{ijk} + c) = \mu + Y_i + M_j + S_k + M_j \times S_k + \varepsilon_{ijk} \tag{1}$$

where μ is overall mean, c is a constant that is decided in test runs, Y_i is the effect of year *i*, M_j is the effect of month *j*, S_k is the effect of size of vessel *k*, $M_j \times S_k$ is the two-way interaction term between month j and size of vessel k, and ε_{ijk} is error term with $N\left(0, \sigma^2\right)$. Due to the difficulty of explaining interaction between year factor and other factors, only interaction between month and size of vessel was considered.

A step-wise analysis of deviance was performed to determine the set of systematic factors and interactions that significantly explained most of the observed CPUE variability. The Chi-square (χ^2) statistic was used to test the significance of an additional factor in the model.[8] Final selection of explanatory factors was conditional on significance of the χ^2 test and percent change in deviance as each factor is added to the model. The $\ln\left(CPUE + c\right)$ was estimated as the least squares means (LS means) of the factors selected and then back transformed to derive the standardized CPUE. The analyses were run with the SAS GENMOD and GLM procedures (SAS Inst. Inc.).

Figure 2 illustrates the normality of residuals from the transformed data by adding different constant values. The normality was visually diagnosed by comparing quantile of residuals with the 45 degree reference line on the Q-Q plot, indicating that the Q-Q plot derived by adding 1 or 0.01 as a constant departed from the line more than that by adding 0.1 or 10% of overall mean. More specifically, the Q-Q plot for the data with 0.01 constant departed from the left of the reference line resulting in negatively skewed distribution, whereas the Q-Q plot for the data with 1 constant departed at the right as the normal quantiles increased resulting in positively skewed distribution (left panel of Fig.

5). These data suggest that both 0.1 and 10% of overall mean as a constant capture the normality of residuals, but the value of 0.1 shows better fit of data at the right side than 10% of overall mean.

Results of deviance estimated from step-wise regression are presented in Table 1 indicating that factors of year, month, and the size of the vessel were significant for χ^2 test ($Pr(\chi^2)$<0.0001). Among these factors, year or month explained over 5% of deviance, whereas size of vessel explained 1% of deviance. Therefore, factors of year, month, and size of vessel were selected into GLM. The result of ANOVA is shown in Table 2.

Estimated CPUE by GLM is illustrated in Figure 3. Annual abundance index sharply declined from 0.46 fish per 1,000 hooks in 1999 to 0.14 fish per 1,000 hooks in 2002, and remained constant at 0.2 fish per 1,000 hooks in 2003 and 2004.

The process attempts to remove most of the annual variation in the data that do not attribute to changes in abundance and the annual index reflects population abundance. In this study, the selected factors explained about 20% of variance of the data (Table 1) and explanatory power of the model (R^2) were 0.2 (Table 2). Maunder and Punt[9] indicated that the explanatory power is not always satisfactory and it can be increased by involving in more explanatory variables. Accordingly, the explained variation is not the absolute quantity to judge the reliability of index of abundance. Instead, it is more important to consider whether the time series of abundance index accurately reflects changes in catchability and fisheries. First, declined catches from the longline fisheries[2] consists with our result shown in Fig. 3, which is low abundance of bluefin tuna in 2002. Second, abundance indices of spawning fish caught by Japanese costal longliners also declined from 1999 to 2002.[2] Third, declined abundance are consistent with falling spawning stock biomass after mid of 1990s.[2] Therefore, it was concluded that the standardized CPUE in this study is a useful abundance index for spawning bluefin tuna targeted by Taiwanese small-scale longline fishery.

The rapid development of the Taiwanese small-scale longline fishery targeting spawning stock brought about high fishing pressure on the large bluefin in recent ten years. Taking into account the size specific seasonality of fishery target spawning bluefin tuna by Taiwanese longliners, the index of abundance estimated in the present study could provide important information to advance future stock assessment.

ACKNOWLEDGEMENTS

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Figure captions

Fig. 1 Data flow diagram of Taiwanese longline fishery targeting Pacific bluefin tuna showing data sources (the top of the diagram), processing (in the middle of the diagram) and flowing into the catch and effort database, where arrows indicate the direction of data flow. T_1 and T_2 represent date of auction and disembarkation time, respectively and the time difference (T_1 -$T_2 \leq 3$) is in need of quality of fish meat.

Fig. 2 The Q-Q plots of residuals of transformed data by adding different constant values (0.01, 0.1, 1, and 10% of overall mean) to the observations from GLM against the corresponding quantiles of a standard normal distribution, where mu and sigma represent mean and standard deviance of residuals of transformed data, respectively.

Fig. 3 Estimated and observed CPUE of Pacific bluefin tuna targeted by Taiwanese longline fishery. The lines represent 1 standard error.

Fig. 1

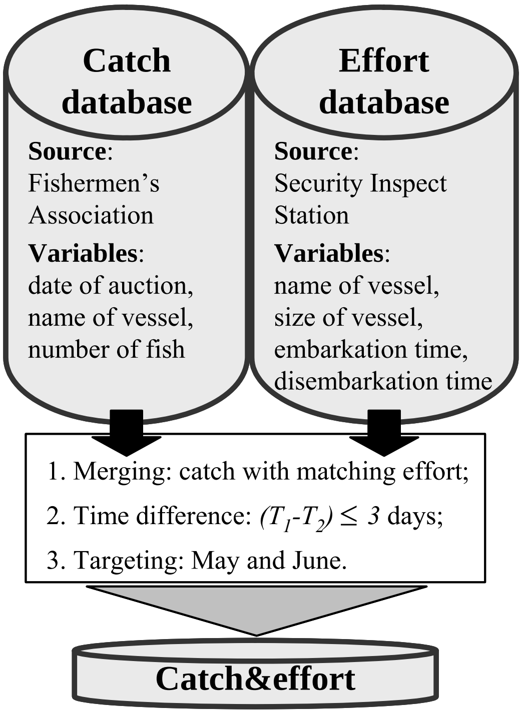
Catch database
Source:
Fishermen's Association
Variables:
date of auction,
name of vessel,
number of fish
Effort database
Source:
Security Inspect Station
Variables:
name of vessel,
size of vessel,
embarkation time,
disembarkation time
1. Merging: catch with matching effort;
2. Time difference: (T1-T2) ≤ 3 days;
3. Targeting: May and June.
Catch&effort

Fig. 2

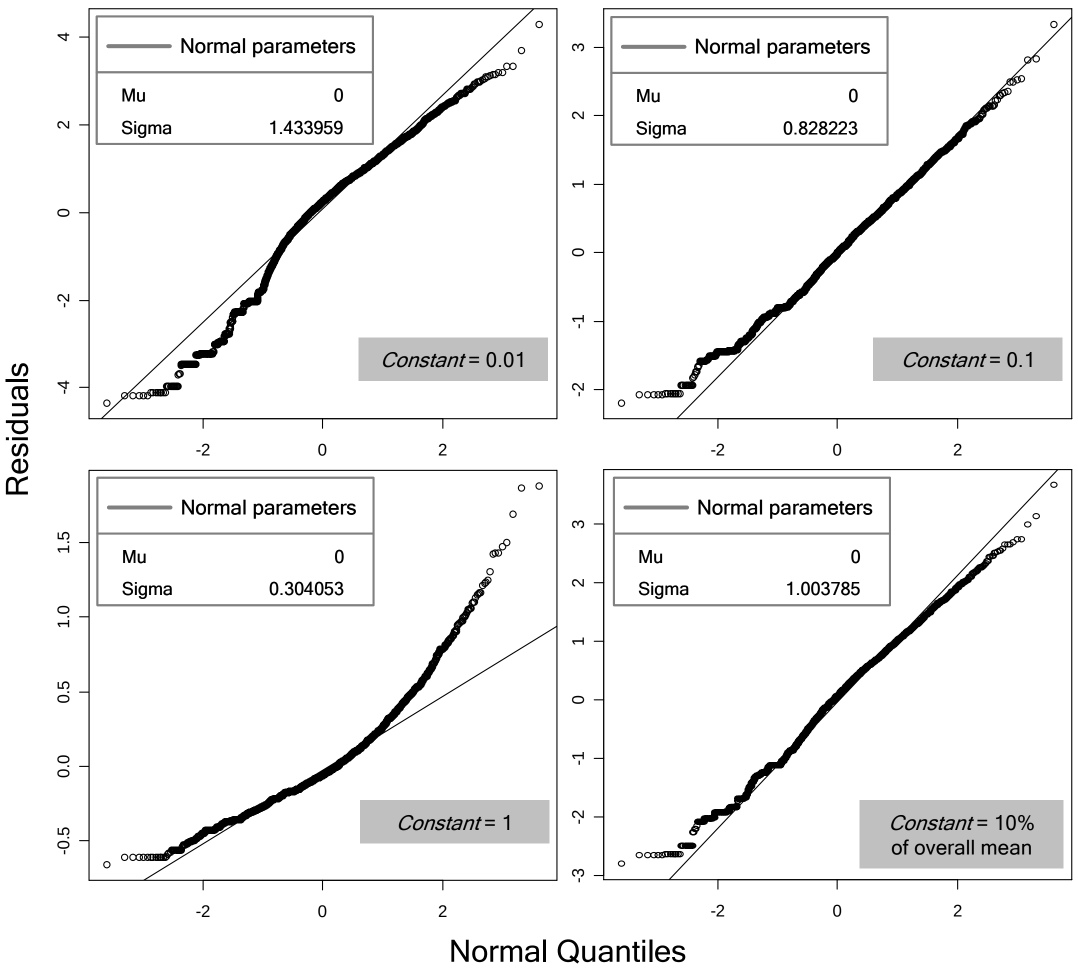
Normal parameters
Mu 0
Sigma 1.433959
Constant = 0.01
Normal parameters
Mu 0
Sigma 0.828223
Constant = 0.1
Normal parameters
Mu 0
Sigma 0.304053
Constant = 1
Normal parameters
Mu 0
Sigma 1.003785
Constant = 10% of overall mean
Residuals
Normal Quantiles
4
2
0
-2
-4
3
1
-1
1.5
1.0
0.5
0.0
-0.5
-3

Fig. 3

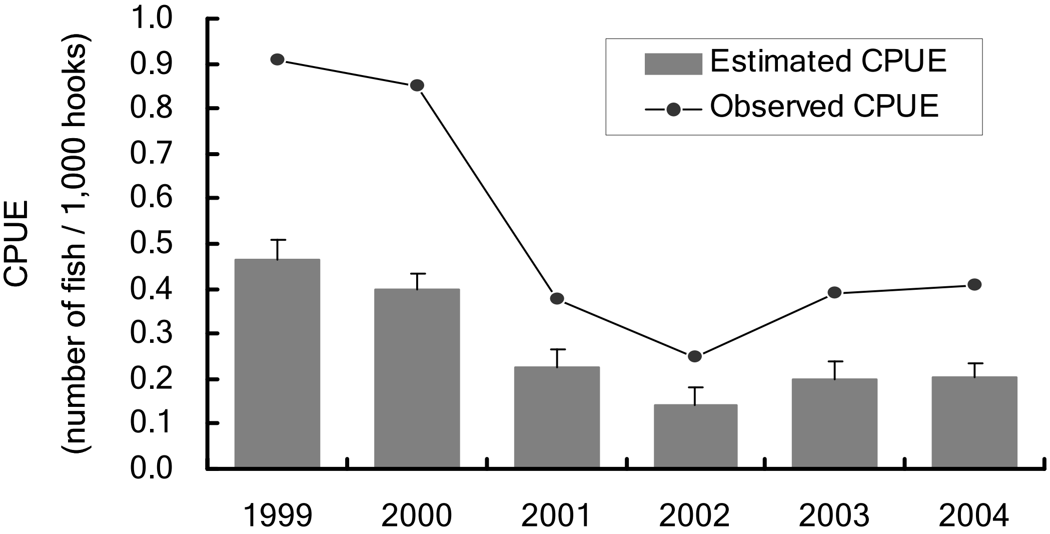
CPUE
(number of fish / 1,000 hooks)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Estimated CPUE
Observed CPUE
1999
2000
2001
2002
2003
2004

Table 1 Analysis of deviance table of explanatory variables in GLM. Percentages of deviance refer to the percentages of change in deviance divided by deviance in previous model, and $Pr(\chi^2)$ values indicate the 5% Chi-square probability between consecutive models.

Model	DF	Deviance	Change deviance	% of deviance	$Pr(\chi^2)$
Intercept	3189	2748.70			<0.0001
Y	3184	2508.26	240.44	8.75	<0.0001
$Y+M$	3183	2210.19	298.07	11.88	<0.0001
$Y+M+S$	3181	2187.51	22.68	1.03	<0.0001
$Y+M+S+M\times S$	3179	2187.27	0.24	0.01	0.8412

Table 2 Analysis of variance (ANOVA) table for the selection model in GLM.

Source	DF	Type III sum of squares	Mean square	*F*-value	*Pr(F)*
Model	8	561.19	70.15	102.01	<0.0001
Error	3181	2187.51	0.69		
Corrected Total	3189	2748.70			

$R^2 = 0.2042$

3. Incorporating uncertainty into the estimation of biomass for the Pacific bluefin tuna

Running title: production analysis by Bayesian approach for Pacific bluefin tuna

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Key Words: Pacific bluefin tuna; Bayesian approach; production analysis; uncertainty; maximum sustainable yield

Introduction

Pacific bluefin tuna *Thunnus orientalis* Temmincks and Schlegel 1844 is a highly migratory species, distributing over the Pacific Ocean (Bayliff, 1994). This species is among the quality tunas with high economic values and has been historically exploited mainly by Japanese, USA, Mexican, and Taiwanese fleets. Since 2000, Japanese fleets, which targeted all the fish sizes around the year, have taken about 66%..USA fleets, which caught almost juveniles, have taken about 2%. Mexican purse seiners for juveniles have taken about 20%. Taiwanese fleets, which targeted all giant spawners (Hsu *et al.*, 2000; Chen *et al.*, 2006), have taken bout 10%. Recently, the state of this stock was evaluated by Food and Agriculture Organization of the United Nations and the stock was listed in fully exploitation (Maguire *et al.*, 2006). However, this doesn't provide estimates of stock status such as relative biomass and its exploitation rate and reference points.

Biomass dynamic models are one of the simplest analytical methods available that focuses on the dynamics of the population as a whole. The original method of assuming equilibrium conditions has been criticized for providing overly optimistic estimates of optimum effort and maximum sustainable yield and suggestions were made to abandon the use of the models (Hilborn and Walters, 1992; Haddon, 2001; Williams and Prager, 2002). The major concerns about fitting these models to time-series data are that uncertainties and variability are not taken into consideration. Parameters are point estimates or assumed values are used and uncertainties of parameters are often ignored or additional analyses are conducted to assess uncertainties using sensitivity analysis (e.g. Goodyear, 1995), confidence intervals (e.g. Mohn, 1993) or sampling distributions using re-sampling methods (e.g. Smith et al., 1993). However, none of these provide integrated analyses to describe unknowns and parameters in the form of probability for complex model (McAllister and Kirkwood, 1998). Further uncertainties are associated with how the model handles observation and process errors. If only observation error explains randomness, then the population dynamics will be deterministic, population abundance could not be accurately estimated. If there is only process randomness, then population size would be estimated perfectly, but ignores the random errors in the observations. In reality, both types of error almost certainly occur.

In this paper, we simultaneously model both the observation error and the process error structures for Pacific bluefin tuna using the state-space modeling with a Bayesian approach. The model incorporates uncertainties about reported catch data in and abundance indices from the six major fisheries, which were weighted equally within the model. The attempt is to capture the true uncertainties about quantities of interest such as maximum sustainable yield.

Materials and methods

Data used

The building blocks for assessing Pacific bluefin tuna are observations on stock size and removal and hypothesis (model) of how they relate in time space. Reliable catch data and indices of abundance are two key inputs for population dynamic models. We obtained Pacific bluefin tuna harvest data from the International Scientific Committee on Tuna and Tuna-like Species in the North Pacific Ocean (ISC) between 1952 and 2006. Abundance indices were available for six major fisheries, Japanese offshore longliners (1952-2005), Japanese coastal longliners (1994-2005), Taiwanese coastal longliners (1999-2005), eastern Pacific Ocean purse seiners (1960-2004), Japanese purse seiners (1981-2004), and Japanese troll fisheries (1981-2004).

Surplus production models

Biomass dynamic models are one of the simplest analytical methods available that provide for a full fish stock assessment when the measurements on the fishery consist of the annual catches and measures of abundance indices for a number of years are available. The current biomass is related to previous biomass plus term for surplus production in previous time minus term for catch. The (deterministic) state equation for the total biomass is

$$\hat{B}_t = B_{t-1} + g(B_{t-1}) - C_{t-1} \tag{1}$$

where B_t is the biomass of the stock that is vulnerable to fishing at the start of year *t*, C_t is the catch during year *t*, and the surplus production function $g(B)$ quantifies the overall change in biomass due to growth, recruitment and natural mortality (Ricker, 1975). The surplus production function is assumed to be nonnegative with $g(0) = g(K) = 0$, where K is the carrying capacity resulting from the effect of finite resources in combination with environmental variability, food and space limitations. The quadratic Schaefer (1954) form of surplus production function is

$$g(B_{t-1}) = rB_{t-1}\left(1 - \frac{B_{t-1}}{K}\right) \tag{2}$$

where K is the carrying capacity and *r* is the intrinsic growth rate of population, which is the rate of increase at which a population will naturally increase according to their life history parameters (fecundity, age of maturity, maximum age, and the maximum reproductive rate). This function takes its maximum values of $rK/4$ when biomass is half of *K*. This maximum value is often regarded by management as the maximum surplus production (MSP).

Surplus production functions are fitted to annual indices of abundance. The index for each fishery is assumed to vary proportionally to stock biomass with constant catchability for that fishery. By assuming that abundance indices are correlated measures of population abundance, the model is able to incorporate multiple indices by interpreting differences among indices as sampling error. The (deterministic) observation equation is

$$I_{t,i} = q_i B_t \tag{3}$$

where $I_{t,i}$ is biomass indices for fishery *i* and q_i is the catchability coefficient for fishery *i*.

General framework for Bayesian stock assessment

The Bayesian approach to stock assessment in general consists of two steps: (i) constructing a full probability model that consists of a joint probability distribution for all observable (here the CPUEs) and unobservable quantities (here the biomasses and model parameters) and (ii) calculating the posterior distribution by conditioning on the observed data, i.e. the conditional probability distribution of the unobservable quantities of interest, given the observed data.

In the first step, the joint probability density $p(Y,\Theta)$ of the observations $Y = (y_1,...,y_N)$ and the unobservable quantities, state spaces, $\Theta = (\theta_1,...\theta_n)$ can be written as the product of two densities, referred to as the prior density $p(\Theta)$ and the sampling density or likelihood function $p(Y|\Theta)$:

$$p(Y,\Theta) = p(\Theta)p(Y|\Theta) \tag{4}$$

In the second step, parameter estimation is a procedure of updating the prior distribution $p(\Theta)$, which describes the uncertainty about the parameter values prior to seeing the data, to the posterior distribution $p(\Theta|Y)$, which describes the uncertainty about the parameter values after seeing the data. This is accomplished by an application of Bayes' theorem (Bayes, 1763), which combines the information contained in the data via the likelihood function $p(Y|\Theta)$ with the prior $p(\Theta)$.

$$p(\Theta|Y)=\frac{p(\Theta)p(Y|\Theta)}{p(Y)}=\frac{p(\Theta)p(Y|\Theta)}{\int_{\Theta}p(\Theta)p(Y|\Theta)d\Theta}\propto p(\Theta)p(Y|\Theta) \tag{5}$$

, where $p(Y)$ is a normalization constant, which involved in formidable high-dimensional integration for state-spaces Θ. Bayesian inference entails the evaluation of various summaries of a specific component θ_i, such as moments and quantiles. This requires integration, with respect to θ_i, of the joint posterior $p(\Theta|Y)$. These integrals are evaluated via Markov chain Monte Carlo (MCMC) methods (Gilks *et al.* 1996), which Monte Carlo simulation from a Markov chain that is constructed whose stationary distribution is the joint posterior distribution. After running sufficiently long Markov chain to find the region of the state space with the highest density and burning-in pre-convergence values, one obtains (correlated) samples from the posterior distribution. Then the histogram of samples is used as an approximation.

The Gibbs sampling (Geman and Geman, 1984) is a specific MCMC method for sampling from the joint posterior distribution, $p(\theta_1,\theta_2,...,\theta_n|Y)$, where $\Theta=(\theta_1,...\theta_n)$ are the unknowns and *Y* denotes the observables. Given an arbitrary set of starting vector $\Theta^{(0)}=(\theta_1^{(0)},...,\theta_n^{(0)})$, the algorithm proceeds by sampling from the each of the full conditional posteriors as follows:

Simulate $\theta_1^{(1)}\sim p(\theta_1|\theta_2^{(0)},...,\theta_n^{(0)},Y)$

Simulate $\theta_2^{(1)}\sim p(\theta_2|\theta_1^{(1)},\theta_3^{(0)},...,\theta_n^{(0)},Y)$

$\vdots$

Simulate $\theta_n^{(1)}\sim p(\theta_n|\theta_1^{(1)},...,\theta_{n-1}^{(1)},Y)$

We obtain an updated vector $\theta^1=(\theta_1^1,...,\theta_n^1)$ and start the procedures again by using previous vector to get θ^2. Repeat *m* iterations until convergence, this yields $\theta^{(m)}=(\theta_1^{(m)},...,\theta_n^{(m)})$. Thus, this defines a Markov chain with transition kernel

$$k(\theta^{(m)},\theta^{(m-1)})=\prod_{i=1}^{n}p(\theta_i^{(m)}|\theta_1^{(m)},...,\theta_{i-1}^{(m)},\theta_{i+1}^{(m-1)},...,\theta_n^{(m-1)},Y)$$

which depend on the previous draw $\theta^{(m-1)}$ and converges to the joint posterior as its stationary distribution.

State-space modeling of biomass dynamics using a Bayesian approach

A Bayesian state-space formulation of the Schaefer surplus production model was developed by Millar and Meyer (2000) and an extension of their model forms the basis for biomass dynamics analyses of Pacific bluefin tuna. The model includes observation errors in indices of abundance and process errors between model-derived biomass and the true biomass. The model also takes into account uncertainties in catch data and estimates biomass from the six primary fisheries. There are 54 years of indices of abundance data and catch biomass (1952-2005). In the model, the years are sequentially named from year1 for 1952 to year 54 for 2005.

Modeling

The Bayesian surplus production (BSP) model uses a re-parameterized form of the Schaefer surplus production model (equ. 2). Re-parameterization was carried out to increase the Markov chain mixing speed and to reduce parameter correlations (Gill, 2002). The re-parameterized form relates the fraction of carrying capacity ($P_t = B_t / K$) to intrinsic growth rate, carrying capacity, and the catch time series. The expected $\hat{P}_t$ is calculated as:

$$\begin{cases} \hat{P}_1 = 1 \quad \text{for } t\text{=1} \\ \\ \hat{P}_t = P_{t-1} + rP_{t-1}(1 - P_{t-1}) - \dfrac{C_{t-1}}{K} \quad \text{for } \ t \geq 2 \end{cases} \tag{6}$$

Index for each fishery is assumed to be proportional to stock biomass with constant catchability for each fishery, *i*, proportionality assumption. The expected $\hat{I}_{t,i}$ for each fishery is calculated as:

$$\hat{I}_{t,i} = q_i K P_t \tag{7}$$

where q_i is the catchability coefficient for each fishery. These relationships are the basis of the state equations for the state-space model, which errors exist between expected CPUE and observed CPUE and between model-derived biomass and true biomass. Both error structures are assumed to follow a lognormal distribution. The stochastic forms of the process and observation equations then become:

$$\begin{cases} \log(P_t) = \log(\hat{P}_t) + \mu_t \\ \\ \end{cases}$$

$$\log(I_{t,i}) = \log(\hat{I}_{t,i}) + v_{t,i} \tag{8}$$

where μ_t and $v_{t,i}$ are independent and identically normal distributed $N(0,\sigma^2)$ and $N(0,\tau_i^2)$ random variables, respectively. Abundance indices were weighted equally within the model.

Uncertainties about true catches

Errors of catch biomass are likely made from various sources of catch estimation and raised catch values etc. Reported catch biomass were likely measured with error but were unbiased. Therefore to incorporate this uncertainty, we modeled the true catch for entire time series using a uniform distribution with a 10% coefficient of variation to describe variability of reported catch.

$$C_t \sim uniform[(\hat{C}_t - \sigma_{\hat{C}_t}),(\hat{C}_t + \sigma_{\hat{C}_t})] \tag{9}$$

where C_t and $\hat{C}_t$ are the true and reported catches in year *t* and $\sigma_{\hat{C}_t}$ (=10% $\hat{C}_t$) is the standard deviation for the true catch in year *t*.

The likelihood

Due to $v_{t,i}$ is assumed to be normal distributions with parameters τ_i^2, the $I_{t,i}$ then follow lognormal distributions by the equation 8.

Given $\hat{I}_{t,i}$, the likelihood for $I_{t,i}$ is

$$L(I_{t,i}|\tau_i^2) = \frac{1}{\sqrt{2\pi}\tau_i}\exp\left(-\frac{\left(\log(I_{t,i}) - \log(\hat{I}_{t,i})\right)^2}{2\tau_i^2}\right) \tag{10}$$

Specifying prior distribution

The Bayesian analysis requires prior probability distributions for each of the model parameters. There are 69 unknowns in the model: *r*, *K*, σ^2,6 catchability coefficients (q_i : i = $JPOFFLL, JPCOLL, TWCOLL, EPOPS, JPPS$ and $JPTL$),6 observation errors ($\tau_i^2 : i = JPOFFLL, JPCOLL, TWCOLL, EPOPS, JPPS$ and $JPTL$)

and 54 ratios of biomass to the carrying capacity ($P_t : 1 \le t \le 54$).

The joint prior density $p(K, r, \sigma^2, q_i, \tau_i^2, P_t)$ is obtained from the prior $p(K, r, \sigma^2, q_i, \tau_i^2)$ and the distribution of $(P_t \mid K, r, \sigma^2)$ determined from the state equation (equ. 6),

$$p(K, r, \sigma^2, q_i, \tau_i^2, P_t) = p(K, r, \sigma^2, q_i, \tau_i^2)\, p(P_t \mid K, r, \sigma^2)$$

$$= p(K, r, \sigma^2, q_i, \tau_i^2)\ \ p(P_1 \mid \sigma^2) \prod_{t=2}^{54} p(P_t \mid P_{t-1}, K, r, \sigma^2) \qquad (11)$$

which $p(P_t \mid P_{t-1}, K, r, \sigma^2)$ terms are implicitly conditioning on the catches C_t.

For simplicity, it will be assumed that each if the parameters is mutually independent in the joint prior density of $(K, r, \sigma^2, q_i, \tau_i^2)$. Therefore, priors for each of the parameters can be constructed independently

$$p(K, r, \sigma^2, q_i, \tau_i^2) = \ p(K)\ p(r)\ p(\sigma^2)\ p(q_i)\ p(\tau_i^2) \qquad (12)$$

where $p(K)$, $p(r)$, $p(\sigma^2)$, $p(q_i)$, and $p(\tau_i^2)$ are the prior for the parameter value K, r, σ^2, q_i, and τ_i^2.

K — carrying capacity

A prior distribution for *K* that is fully no informative because there is no previous work on production model for Pacific bluefin tuna and carrying capacity is stock-specific, which means that values for other related species might not be incorporated.

Thus, the prior for *K* can be regarded as scale parameters and a no informative prior is therefore uniform on log scale, $K \sim uniform[\log(33), \log(500)]$ (in thousands of tons). The lowest bound is approximately equal to the largest observed catch in the time series and the upper bound is arbitrary but specified to the largest biomass estimated from virtual population analysis (ISC, 2006). All values greater than or equal to the lower bound and less than or equal to the upper bound have an equal probability. The log scale was set so as to avoid implausibly large posterior expected values for *K* when there is little information in data about *K*.

r — intrinsic growth rate of population

A prior for *r* that is non-informative would be restricted to *r*~*uniform* [0.01, 1], where the lower and upper bounds are considered to be very small and large values for *r* for tuna, respectively.

σ^2 and τ_i^2 — process error variance and observation error variance

Conjugate priors can be constructed for the process error variance σ^2 and the observation error variance τ_i^2 in the normal models and therefore, their posterior distributions follow the same parametric form as the priors (Appendix A). An inverse gamma distribution with parameters α (>0) and β (>0) was specified for the prior of both σ^2 and τ_i^2. The inverse gamma specification is articulated from the gamma statements through convention of specifying precisions instead of variances in normal specification. Carlin and Louis (2001) suggest solving the moment equations for α and β using empirical mean and standard deviation as follows.

The first and second moments for the inverse gamma distribution are:

$$\mu = \frac{\beta}{\alpha - 1}, \text{ for } \alpha > 1$$

$$s^2 = \frac{\beta^2}{(\alpha - 1)^2(\alpha - 2)}, \text{ for } \alpha > 2$$

Then,

$$\alpha = \frac{\mu^2}{s^2} + 2$$

$$\beta = \mu\left(\frac{\mu^2}{s^2} + 1\right)$$

A vague inverse gamma prior with high standard deviation was chosen and mean was set to be equal to its standard deviation so as to the fraction μ^2/s^2 is unity. Thus, a vague inverse gamma distribution with mean and standard deviation equal to 50 was chosen so that α is 3 and β is 100. The inverse gamma specification is articulated from the gamma statements through convention of specifying precisions instead of variances in normal specification. For example, the variance for a normal distribution follows inverse gamma distribution with parameters α (>0) and β (>0) and then its precisions (1/variance) is a gamma distribution with parameters α and β^{-1}, which can be calculated through transformation (Casella and Berger, 2002).

q_i — catchability for each fishery

There was no information available that could be used to develop an informative prior for catchability coefficient for each fishery. Therefore, a uniform prior was chosen for q_i on log scale, $q_i \sim uniform[\log(10^{-5}), \log(10^{2})]$. The quantity $\log(q_i)$ can be regarded as an intercept term in the observation-error model (Kass and Wasserman, 1996).

Sampling from the posterior distribution

In order to construct a posterior probability density function of model input parameter, the steps referred to the Bayesian estimation are described as follows. In the first step, the joint posterior probability density was the product of the prior density and likelihood of the data.

$$p(K, r, \sigma^2, q_i, \tau_i^2, P_t \left| I_{t,i} \right.) \propto p(K, r, \sigma^2, q_i, \tau_i^2, P_t) \prod_{t=1}^{54} L(I_{t,i} \left| P_t, q_i, \tau_i^2 \right.)$$

$$= p(K, r, \sigma^2, q_i, \tau_i^2)\, p(P_1 \left| \sigma^2 \right.) \prod_{t=2}^{54} p(P_t \left| P_{t-1}, K, r, \sigma^2 \right.) \prod_{t=1}^{54} L(I_{t,i} \left| P_t, q_i, \tau_i^2 \right.) \qquad (13)$$

In the second step, the Gibbs sampler was used to sample from the joint posterior density (equ. 13). This requires each of the univariate full conditional posterior densities for all 69 unobservable in the model to be sampled in turn. The full condition posterior density of a certain parameter θ_i can be constructed from the joint posterior of Θ by extracting the terms that involve θ_i (Appendix B). The other terms in the posterior simply are regarded as the normalizing constant.

We performed 100, 000 cycles of the Gibbs sampler and the results of the first 5,000 cycles were discarded as a burn-in period. For the remaining 95,000 cycles, every 10th observation was thinned (saved) to avoid highly correlated values, which yielded a final chain of length 9,500. Convergence of the simulations was tested using the Geweke test (1992), the Heidelberger and Welch test (1983), the Rftery and Lewis (1992) from the package BOA ("Bayesian Output Analysis") (Smith 2005) of R software (R Development Core Team 2004).

Results

Empirical tests and graphical diagnostics for convergence were calculated for the states P_1 and P_{54} and the parameters K, r, q_i, σ^2, and τ_i^2 using the BOA package from R. All chains passed the Heidelberger and Welch stationarity and halfwidth test.

The Raftery and Lewis convergence diagnostics confirmed that the thinning of the chain, burn-in period, and the number of iterations were sufficient. Lags and autocorrelations within each parameter chain were reasonably low. Geweke's Z scores do not fall within the extreme tails of a standard normal distribution, suggesting that the chain fully converged. Trace plots and running mean from the end of the burn-in period are shown in Fig. 1. All parameters and the states appear to be stable in the trace plots of path of the Gibbs sampler runs and have settled into a stable running mean. All together, the tests and graphical diagnostics showed no evidence against convergence.

Kernel estimates for the marginal posterior densities for the above unknowns are demonstrated in Fig. 2. Summary statistics including mean, standard deviation, and 25, 50, and 75% quantiles are given in Table 1. As can be seen from the kernel density plots in Fig. 2, the posterior distributions show single mode and become sharper than priors distributions for *K*, *r*, and q_i with the uniform priors and σ^2 and τ_i^2 with the vague inverse gamma priors.

There are considerable correlations between parameters of *K*, *r*, q_i and σ^2, whereas the correlations between the other parameters are low (Table 2). Correlations among q_i are higher than those between parameters of *K*, *r*, q_i and σ^2 whereas correlations among τ_i^2 are low. This implies that abundance indices are correlated measures of population abundance and the difference among them is mainly from sampling error.

The posterior distributions showed that most of the observation error variances (τ^2) are substantially larger than the process error variance (σ^2) except for the Japanese coastal longliners (Table 1, Fig. 2). The higher posterior densities on the observation error variances correspond to more variability in the data than in the dynamics model.

The posterior distribution of the maximum surplus production MSP has a mean of 25.01 ± 6.976 (thousand tons). The biomass that could produce maximum surplus production was estimated as 214.05 (thousand tons) which is the half of the estimated mean of K (Table 1). The posterior medians and uncertainties of the biomasses were shown in Fig. 3. Estimated medians vary from 60 to 500 thousand tons over the period from 1952 to 2005. The biomasses after 1980's are more likely lower than 2.5% quantile of biomass at maximum surplus production in which 75% quantile of biomass exceed the 2.5% threshold for several years. It is also noted that biomass tend to increase in recent years. As for the forecast, the surplus production model predicts a biomass with posterior mean equal to 116.8 ± 57.22 for the following year 2006.

The posterior medians and uncertainties of the exploitation rate (catch/biomass) were shown in Fig. 4. The exploitation rates prior to 1970 are relatively low, whereas those after 1970 fluctuate over 2.5% quantile of exploitation rate at maximum surplus production. The situation is severe in the beginning of 1980s and in recent years probably due to the commencement of the surface fisheries and the longliners (Fig. 5).

A comparison between the observed CPUEs and the posterior predictive distribution of the CPUEs was made by overlaying the 95% posterior predictive intervals for CPUEs onto a plot of the observed CPUEs (Fig. 5). Predicted CPUEs do not follow strictly the observed CPUEs. In particular, poorly prediction were found in the early years for the Japanese offshore longliners resulting in large observation error variance with high standard deviation (Table 1 and Fig. 2). It might imply that catchability is not constant over the time period for the Japanese offshore longliners. Outliners are detected for others fisheries but most of the 95% predicted CPUEs overlaid by the observed CPUEs.

Discussion

This paper has presented a fully specified stochastic population dynamics for Pacific bluefin tuna containing both deterministic equations and the assumption about randomness. This is accomplished using a Bayesian approach to statistical inference via the Gibbs sampler and unrealistic assumptions made by the original population were overcome. The harvest was not assumed to equal surplus production (Quinn and Deriso, 1999) and the parameters were not assumed to be constant. This allows us to build hierarchical models with random-effect, handle arbitrary distributional assumptions for priors, and simultaneously estimate process and observation error. Further extension on stochastic historical catches was also considered because the catch figures usually provide the mean of catches.

A Bayesian stock assessment requires prior knowledge of various parameters to be incorporated into the analysis and careful consideration of the choice of prior (Punt and Hilborn, 1997; 2001). In the surplus production model, all parameters are defined on the positive real number and thus the lognormal, gamma and uniform distributions that include the positive are appropriate. Informative prior can be referred to similar stocks, but this is not the case for Pacific bluefin tuna because there is little information about parameters q, r and K for similar species. Walters and Ludwig (1994) and McAllister and Kirkwood (1998) point out that use of precise informative priors in a stock assessment can result in over-confident conclusions and neglect of potential biases. These have led us to use of non-informative priors for these parameters (uniform on log scale). Gelman *et al.* (1995) recommended using vaguely informative priors to allow the data to have more weight in shaping the posterior distribution. Accordingly, we formulated vague inverse gamma distributions for the process and observation error variances. The posterior distributions for these key parameters showed sharper distributions than uniform and vague inverse gamma prior distributions (Fig. 2). This implies that the prior loses its influence on the shape of the posterior and data are informative. The choice of priors seems to be reasonable in the present study.

The Bayesian state–space model improves on the two estimators, the observation error estimator and process error estimator. The observation error estimator includes the observation error but ignores the process error, whereas the process error estimator includes the process error but disregards the observation error. In the Bayesian analysis, measurement and process errors are clearly separated and the precision of error variance estimates can be assessed in detail from the posterior densities (Fig. 2). Hilborn and Walters (1992) and Polacheck *et al.* (1993) found that the process error estimator produces less reliable estimates than the observation error estimator, which is generally regarded to be the best approach when only one error structure is considered. Our study indicates that the observation error variances excluding the Japanese coastal longliners are larger than the process error for modeling Pacific bluefin tuna population using the biomass dynamic model (Table 1). The prediction of CPUEs for Japanese coastal longliners was superior to those for others fisheries, resulting in a small observation error variance. These findings may suggest that when more than one index was used in the models, the observation errors should be incorporated into modeling to produce reliable parameter estimates.

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Appendix A. Conjugate inverse gamma prior

The process error is assumed to follow a normal distribution with zero mean and process error variance, that is $\mu_t \sim N(0, \sigma^2)$.

Given a vector $\boldsymbol{\mu}$ of *n* iid observations, the likelihood function is:

$$p(\boldsymbol{\mu} | \sigma^2) \propto (\frac{1}{\sigma^2})^{\frac{n}{2}} \exp\left(-\frac{1}{2\sigma^2}\sum_{t=1}^{n}\mu_t^2\right)$$

$$= \left(\sigma^2\right)^{-\frac{n}{2}} \exp\left(-\frac{1}{2\sigma^2}\sum_{t=1}^{n}\left(\log(P_t) - \log(\hat{P}_t)\right)^2\right)$$

If the prior for σ^2 follows an inverse gamma with parameters α and β, its probability density function is given by:

$$p(\sigma^2 | \alpha, \beta) = \frac{\beta^\beta}{\Gamma(\alpha)}\left(\sigma^2\right)^{-(\alpha+1)} \exp\left(-\frac{\beta}{\sigma^2}\right)$$

where $\alpha > 0$, $\beta > 0$.

The posterior probability density was the product of the prior density and likelihood of the data.

$$p(\sigma^2 | \mu) \propto p(\boldsymbol{\mu} | \sigma^2)\; p(\sigma^2 | \alpha, \beta)$$

$$= \left(\sigma^2\right)^{-\frac{n}{2}} \exp\left(-\frac{1}{2\sigma^2}\sum_{t=1}^{n}\left(\log(P_t) - \log(\hat{P}_t)\right)^2\right) \frac{\beta^\beta}{\Gamma(\alpha)}\left(\sigma^2\right)^{-(\alpha+1)} \exp\left(-\frac{\beta}{\sigma^2}\right)$$

$$\propto \left(\sigma^2\right)^{-((\alpha+\frac{n}{2})+1)} \exp\left(-\frac{1}{\sigma^2}\left(\frac{\sum_{t=1}^{n}\left(\log(P_t) - \log(\hat{P}_t)\right)^2}{2} + \beta\right)\right)$$

Then,

$$p(\sigma^2 | \mu) \sim inv.gamma\left(\alpha + \frac{n}{2}, \beta + \frac{\sum_{t=1}^{n}\left(\log(P_t) - \log(\hat{P}_t)\right)^2}{2}\right)$$

Appendix B. Full conditional distributions for the model parameters

Full conditional posterior density of P_t, t=2,…,53

$$p(\, P_t | P_1,...,P_{t-1}, P_{t+1},...,P_{54}\,, I_{t,i}\,, K, r, \sigma^2\,, q_i\,, \tau_i^2\,)$$

$$\propto p(\, P_t | P_{t-1}\,, K, r, \sigma^2\,)\, p(\, I_{t,i} | P_t\,, q_i\,, \tau_i^2\,)\, p(\, P_{t+1} | P_t\,, K, r, \sigma^2\,)$$

$$\propto \exp\left(-\frac{\left(\log(P_t) - \log(\hat{P}_t)\right)^2}{2\sigma^2} - \frac{\left(\log(I_{t,i}) - \log(\hat{I}_{t,i})\right)^2}{2\tau_i^2} - \frac{\left(\log(P_{t+1}) - \log(\hat{P}_{t+1})\right)^2}{2\sigma^2} \right)$$

where $\hat{P}_t$ is:

$$\begin{cases} \hat{P}_1 = 1 \quad \text{for } t{=}1 \\ \hat{P}_t = P_{t-1} + rP_{t-1}(1 - P_{t-1}) - \dfrac{C_{t-1}}{K} \quad \text{for } \; t \geq 2 \end{cases}$$

and $\hat{I}_{t,i}$ is:

$$\hat{I}_{t,i} = q_i K P_t$$

Similar expressions are obtained for P_1 and P_{54} by omitting respective terms, which are proportional to $p(P_1 | \sigma^2)$ and $p(P_{54} | P_{53}\,,\; K,\; r, \sigma^2\,)\, p(\, I_{54,i} | P_{54}\,, q_i\,, \tau_i^2\,)$, respectively.

Full conditional posterior density of K:

$$p(K | P_t\,, I_{t,i}\,, r, \sigma^2\,, q_i\,, \tau_i^2\,) \propto p(\, K, r, \sigma^2\,, q_i\,, \tau_i^2\,) \prod_{t=2}^{54} p(P_t | P_{t-1}, K, r, \sigma^2)$$

$$\propto p(K)\, \exp\left(-\frac{1}{2\sigma^2} \sum_{t=2}^{54} \left(\log(P_t) - \log(\hat{P}_t)\right)^2 \right)$$

$$\propto \frac{1}{K} \exp\left(-\frac{1}{2\sigma^2} \sum_{t=2}^{54} \left(\log(P_t) - \log(\hat{P}_t)\right)^2 \right)$$

Full conditional posterior density of r

$$p(r | P_t\,, I_{t,i}\,, K, \sigma^2\,, q_i\,, \tau_i^2\,) \propto p(\, K, r, \sigma^2\,, q_i\,, \tau_i^2\,) \prod_{t=2}^{54} p(P_t | P_{t-1}, K, r, \sigma^2)$$

$$\propto p(r)\exp\left(-\frac{1}{2\sigma^2}\sum_{t=2}^{54}\left(\log(P_t)-\log(\hat{P}_t)\right)^2\right)$$

$$\propto \frac{1}{r}\exp\left(-\frac{1}{2\sigma^2}\sum_{t=2}^{54}\left(\log(P_t)-\log(\hat{P}_t)\right)^2\right)$$

Full conditional posterior density of q_i

$$p(q_i \mid P_t, I_{t,i}, K, r, \sigma^2,\ \tau_i^2) \propto p(K, r, \sigma^2, q_i, \tau_i^2)\prod_{t=1}^{54} p(I_{t,i} \mid P_t, q_i, \tau_i^2)$$

$$\propto p(\ q_i)\exp\left(-\frac{1}{2\tau_i^2}\sum_{t=1}^{54}\left(\log(I_{t,i})-\log(\hat{I}_{t,i})\right)^2\right)$$

$$\propto \frac{1}{q_i}\exp\left(-\frac{1}{2\tau_i^2}\sum_{t=1}^{54}\left(\log(I_{t,i})-\log(\hat{I}_{t,i})\right)^2\right)$$

Full conditional posterior density of σ^2 and τ_i^2

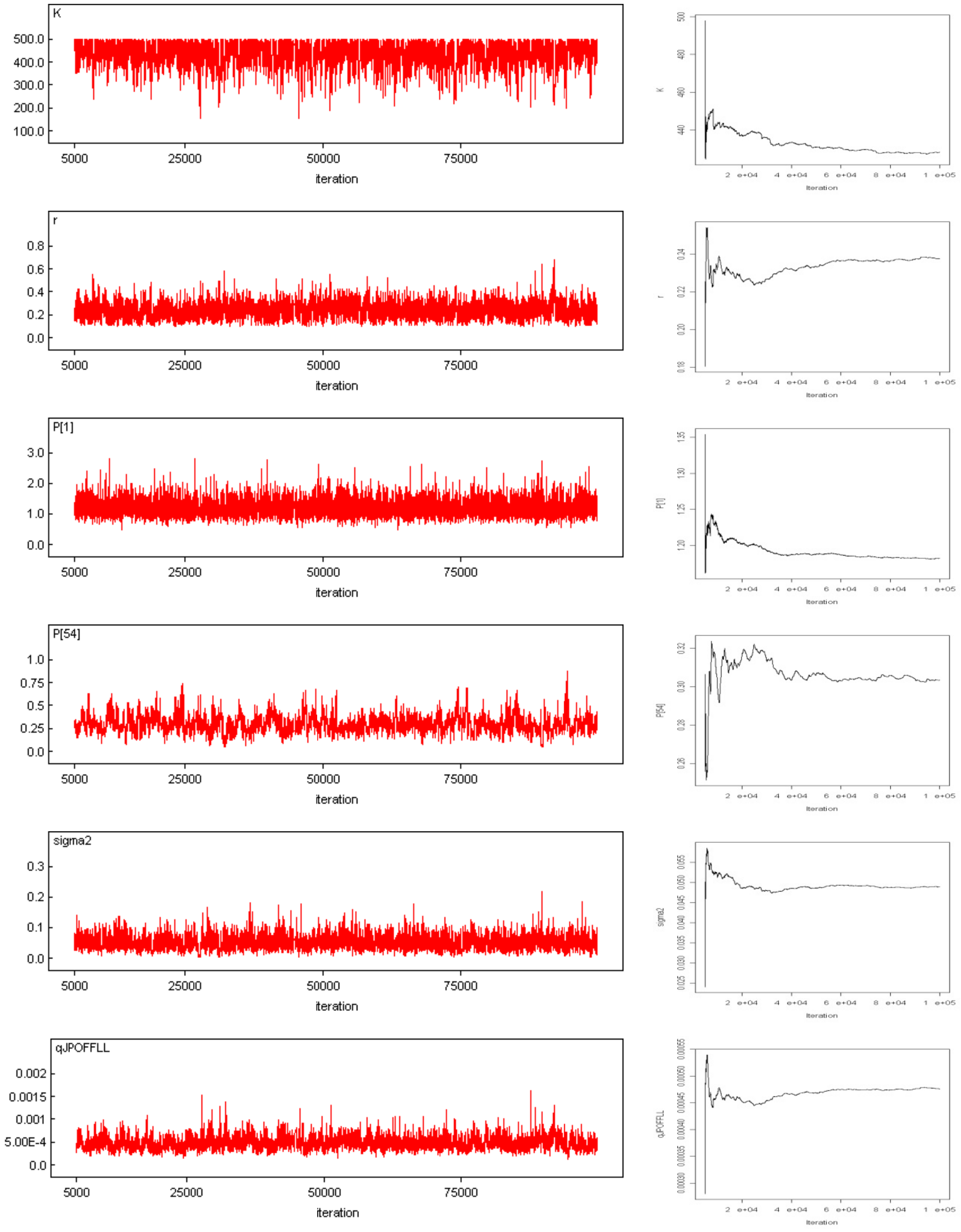
Since we use a conjugate inverse gamma prior for σ^2 with parameters α and β, their full condition posterior density is inverse gamma with parameters α' and β' (Appendix A).

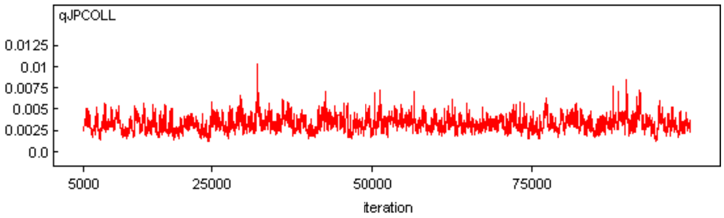
$$p(\sigma^2 \mid P_t, I_{t,i}, K, r, q_i, \tau_i^2) \sim inv.gamma(\alpha', \beta')$$

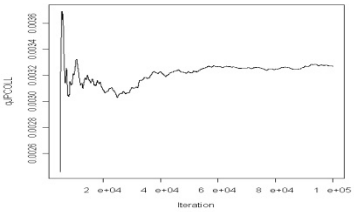
where $\alpha' = \alpha + \frac{n}{2}$ and $\beta' = \beta + \frac{1}{2}\sum_{t=1}^{n}\left(\log(P_t)-\log(\hat{P}_t)\right)^2$ for $n = 54$.

Similar calculation can be obtained for τ_i^2.

Fig. 1. Trace plots (left panel) and running means (right panel) of the MCMC simulations for carrying capacity *K*, intrinsic growth rate of population *r*, process error variance σ^2, depletion in year 1 P_1, depletion in year in year 54 P_{54}, catchability q and observation error variance τ^2 for six fisheries, Japanese offshore longliners, Japanese coastal longliners, Taiwanese coastal longliners, Japanese purse seiners, purse seiners in eastern Pacific Ocean, and Japanese troll.




qJPCOLL
0.0125
0.01
0.0075
0.005
0.0025
0.0
5000
25000
50000
75000
iteration


qJPCOLL
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0.0028
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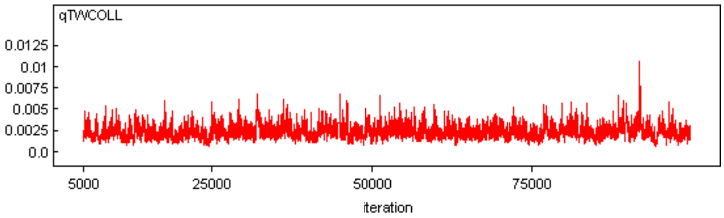
0.0032
0.0034
0.0036
2 e+04
4 e+04
6 e+04
8 e+04
1 e+05
Iteration


qTWCOLL
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0.01
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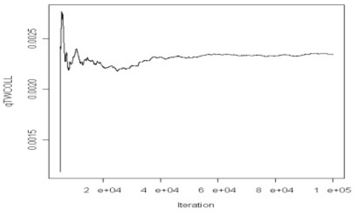
0.005
0.0025
0.0
5000
25000
50000
75000
iteration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0.0020
0.0025
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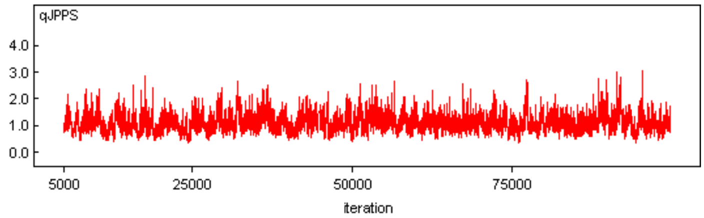
6 e+04
8 e+04
1 e+05
Iteration


qJPPS
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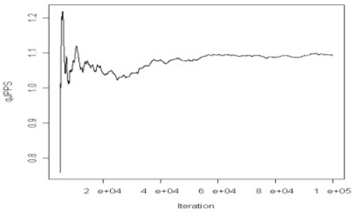
3.0
2.0
1.0
0.0
5000
25000
50000
75000
iteration


qJPPS
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2 e+04
4 e+04
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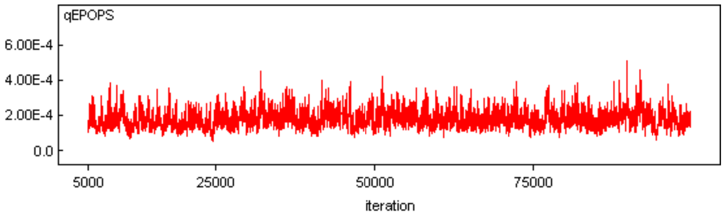
8 e+04
1 e+05
Iteration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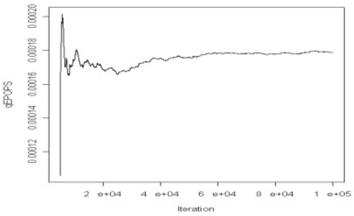
2.00E-4
0.0
5000
25000
50000
75000
iteration


qEPOPS
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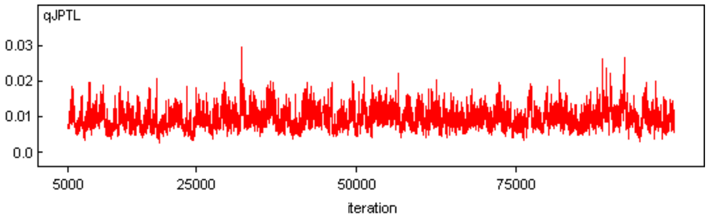
0.00014
0.00016
0.00018
0.00020
2 e+04
4 e+04
6 e+04
8 e+04
1 e+05
Iteration


qJPTL
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0.02
0.01
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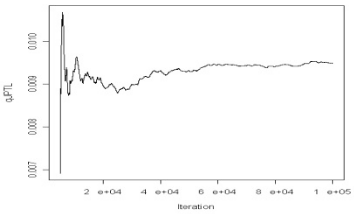
5000
25000
50000
75000
iteration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0.008
0.009
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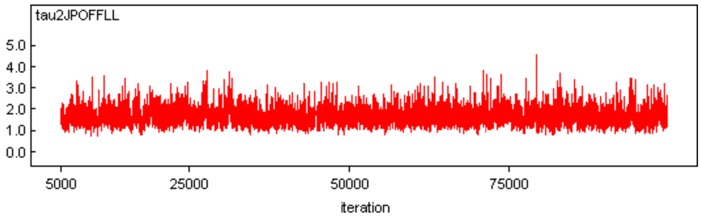
4 e+04
6 e+04
8 e+04
1 e+05
Iteration


tau2JPOFFLL
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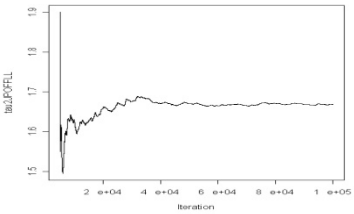
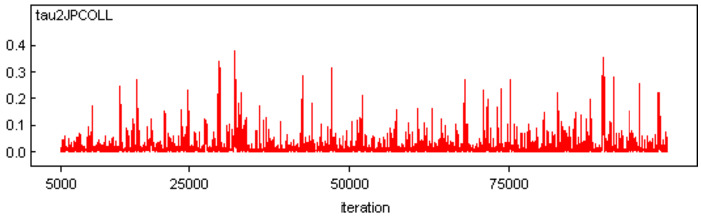
4.0
3.0
2.0
1.0
0.0
5000
25000
50000
75000
iteration


tau2JPOFFLL
1.5
1.6
1.7
1.8
1.9
2 e+04
4 e+04
6 e+04
8 e+04
1 e+05
Iteration


tau2JPCOLL
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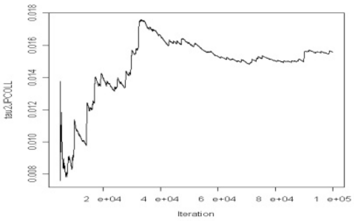
0.3
0.2
0.1
0.0
5000
25000
50000
75000
iteration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0.014
0.016
0.018
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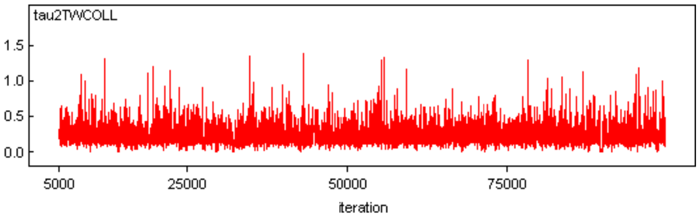
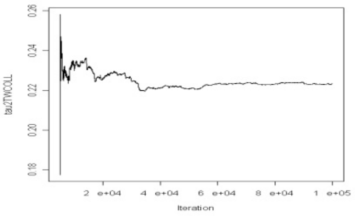
4 e+04
6 e+04
8 e+04
1 e+05
Iteration


tau2TWCOLL
1.5
1.0
0.5
0.0
5000
25000
50000
75000
iteration


tau2TWCOLL
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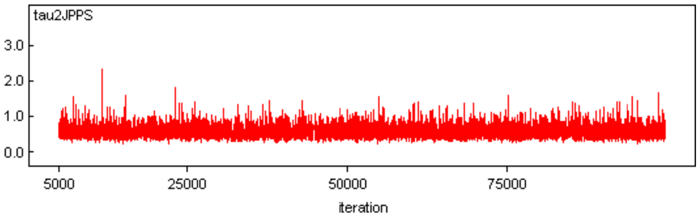
4 e+04
6 e+04
8 e+04
1 e+05
Iteration


tau2JPPS
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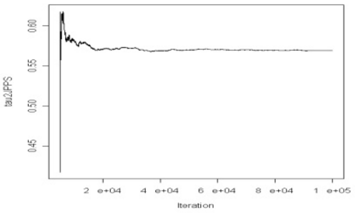
1.0
0.0
5000
25000
50000
75000
iteration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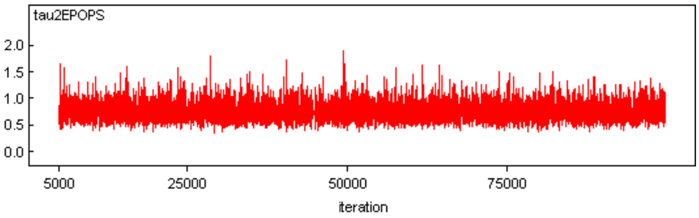
4 e+04
6 e+04
8 e+04
1 e+05
Iteration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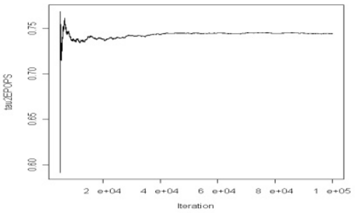
1.5
1.0
0.5
0.0
5000
25000
50000
75000
iteration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0.70
0.65
0.60
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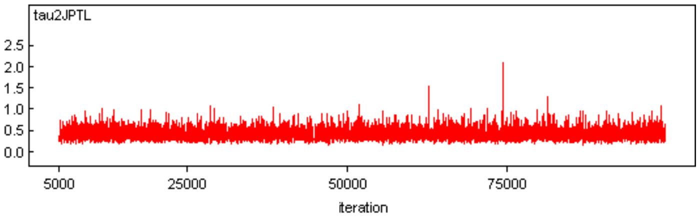
4 e+04
6 e+04
8 e+04
1 e+05
Iteration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2.0
1.5
1.0
0.5
0.0
5000
25000
50000
75000
iteration

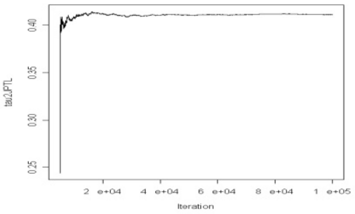
tau2JPTL
0.40
0.35
0.30
0.25
2 e+04
4 e+04
6 e+04
8 e+04
1 e+05
Iteration

Fig. 2. Kernel densities estimates of the MCMC simulations for carrying capacity K, intrinsic growth rate of population r, process error variance σ^2, depletion in year 1 P_1, depletion in year in year 54 P_{54}, catchability q and observation error variance τ^2 for six fisheries, Japanese offshore longliners, Japanese coastal longliners, Taiwanese coastal longliners, Japanese purse seiners, purse seiners in eastern Pacific Ocean, and Japanese troll.

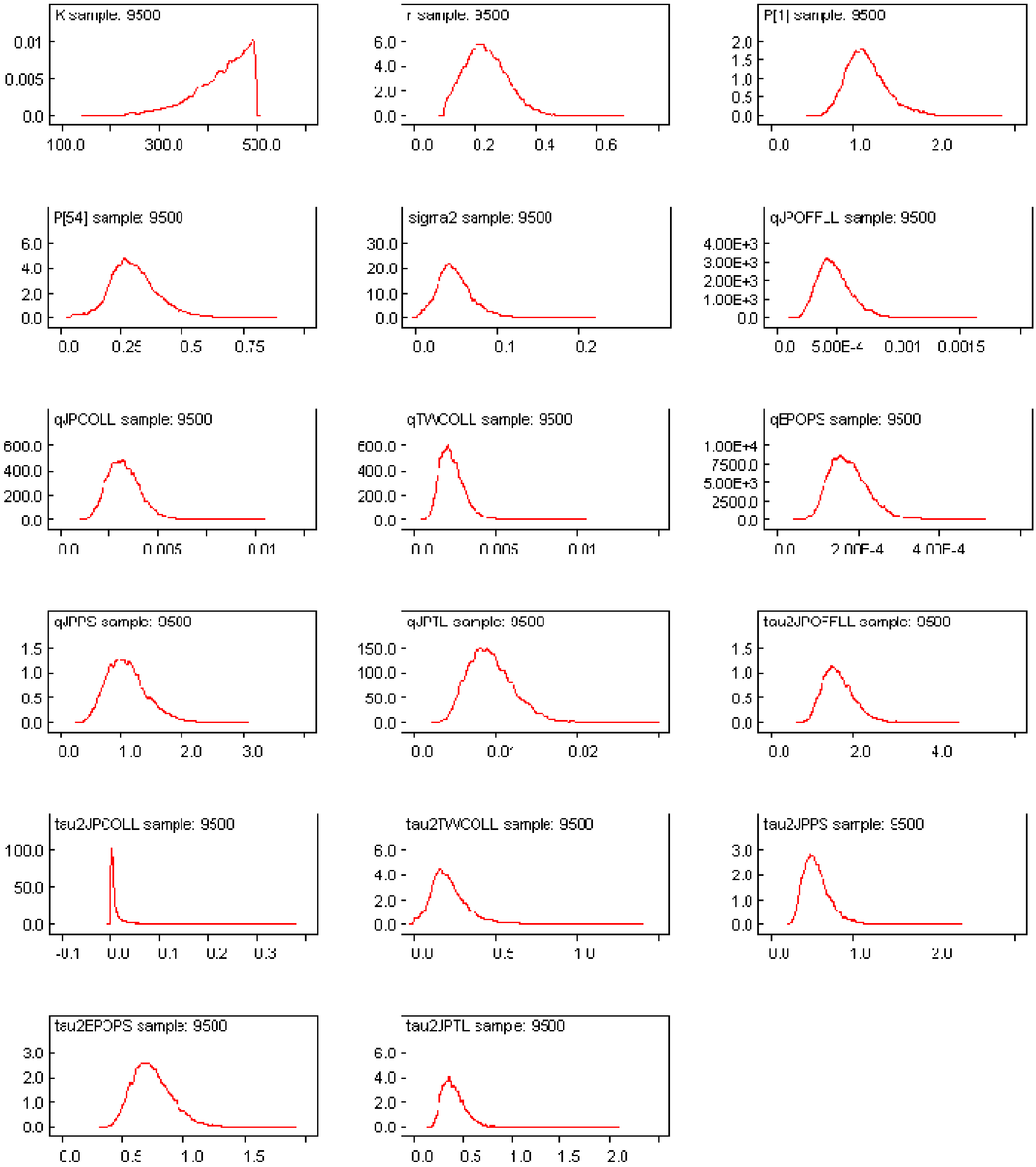

Fig. 3. Posterior median, 25% and 75% quantiles of annual biomass of Pacific bluefin tuna (1952-2005) obtained from the MCMC simulations using the Bayesian state-space approach to parameter estimation in the surplus production model. Dotted line indicates posterior 2.5% and 97.5% quantiles of biomass at maximum surplus production (BMSP).

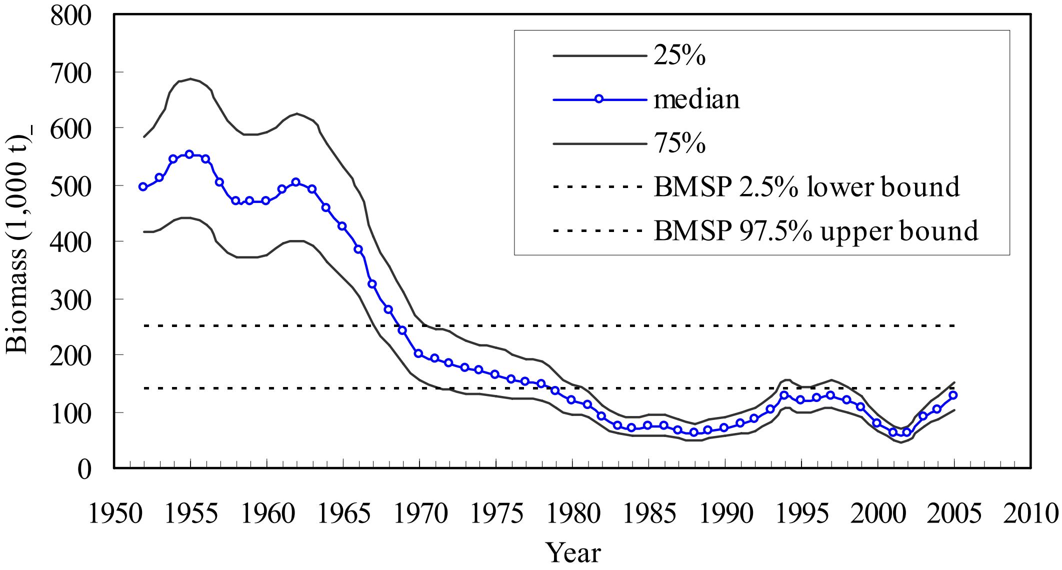

Fig. 4. Posterior median, 25% and 75% quantiles of exploitation rate (catch/biomass) of Pacific bluefin tuna (1952-2005) obtained from the MCMC simulations using the Bayesian state-space approach to parameter estimation in the surplus production model. Dotted line indicates posterior 2.5% and 97.5% quantiles of exploitation rate at maximum surplus production (HMSP).

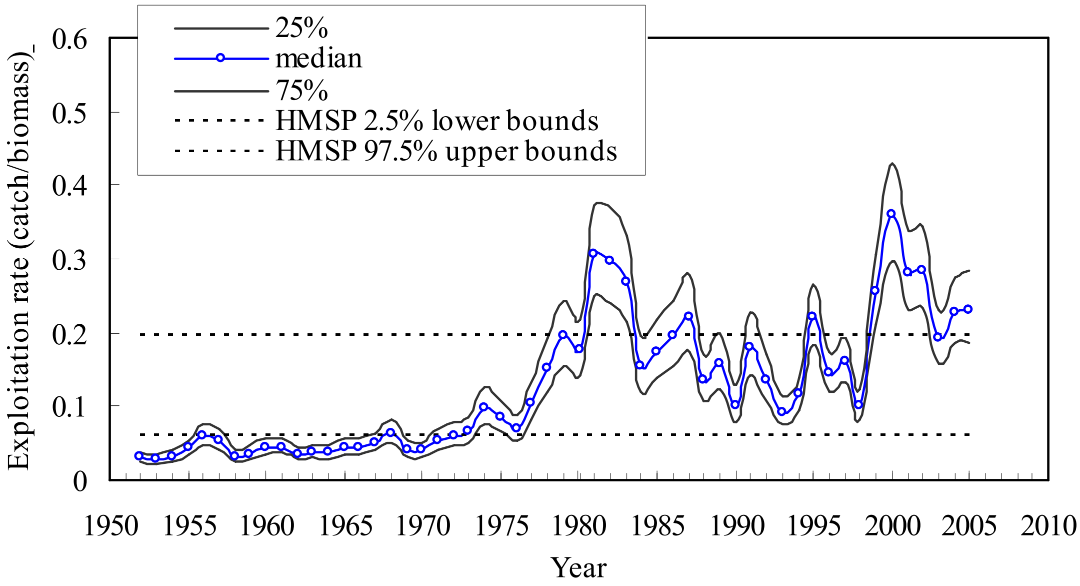

Fig. 5. Observed CPUEs and posterior means of the predicted CPUEs for Pacific bluefin tuna (1952-2005) obtained from MCMC samples using the Bayesian state-space approach to parameter estimation in the surplus production model.

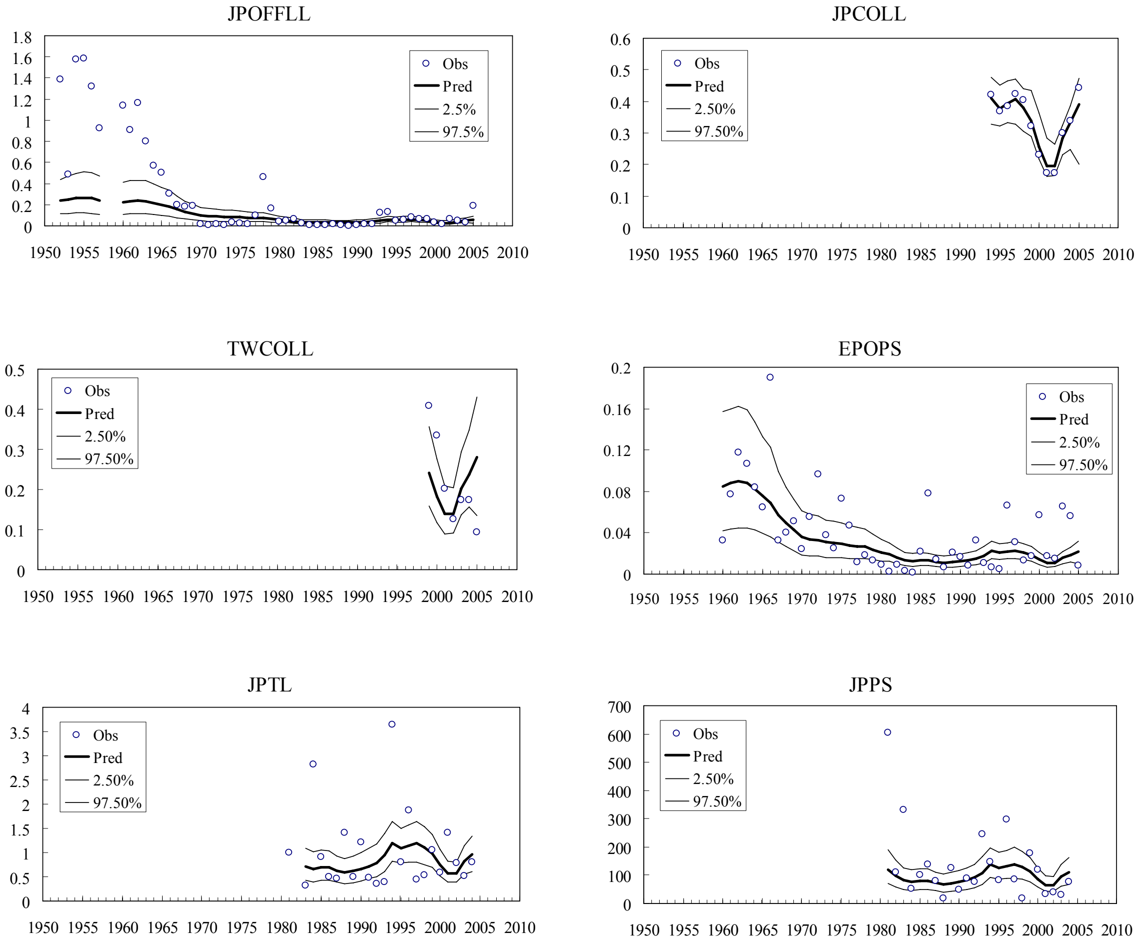

Table 1. Summary for sample size of 9,500 from posterior density.

Parameter	Mean	SD	25%	Median	75%
P_1	1.182	0.2588	1.004	1.148	1.322
P_{54}	0.3034	0.0974	0.2385	0.2936	0.3586
K (1,000’s t)	428.1	58.34	395.5	442	474.6
r	0.2375	0.07083	0.1865	0.231	0.2814
MSP	25.01	6.976	19.96	24.4	29.44
σ^2	0.04894	0.02186	0.03421	0.04623	0.06074
$q_{JPOFFLL}$	0.000476	0.000142	0.000377	0.000457	0.000554
q_{JPCOLL}	0.00327	0.000870	0.002657	0.003188	0.003784
q_{TWCOLL}	0.002344	0.000771	0.001797	0.002239	0.002764
q_{JPPS}	1.095	0.3378	0.8519	1.055	1.283
q_{EPOPS}	0.000179	0.00005	0.000143	0.000173	0.000208
q_{JPTL}	0.00949	0.002838	0.007454	0.009148	0.01117
$\tau^2_{JPOFFLL}$	1.668	0.4011	1.384	1.617	1.899
τ^2_{JPCOLL}	0.01557	0.02884	0.003387	0.005898	0.01308
τ^2_{TWCOLL}	0.2232	0.1288	0.1415	0.1998	0.2758
τ^2_{JPPS}	0.5692	0.1684	0.4501	0.541	0.6566
τ^2_{EPOPS}	0.7444	0.1689	0.6244	0.7224	0.8404
τ^2_{JPTL}	0.4112	0.1238	0.3239	0.3905	0.4741

Table 2. Correlation coefficients between the model parameters.

	q_{EPOPS}	q_{JPCOLL}	$q_{JPOFFLL}$	q_{JPPS}	q_{JPTL}	q_{TWCOLL}	r	σ^2	τ^2_{EPOPS}	τ^2_{JPCOLL}	$\tau^2_{JPOFFLL}$	τ^2_{JPPS}	τ^2_{JPTL}	τ^2_{TWCOLL}
K	-0.33	-0.28	-0.38	-0.24	-0.24	-0.24	-0.39	0.09	-0.02	-0.10	-0.21	0.03	0.02	0.05
q_{EPOPS}		0.79	0.70	0.72	0.74	0.65	0.58	0.24	0.05	0.09	-0.21	-0.01	0.02	-0.01
q_{JPCOLL}			0.69	0.80	0.83	0.80	0.59	0.26	0.06	0.17	-0.20	-0.08	0.00	-0.05
$q_{JPOFFLL}$				0.63	0.64	0.57	0.53	0.16	0.03	0.10	-0.12	-0.02	0.00	-0.02
q_{JPPS}					0.76	0.67	0.56	0.30	0.02	0.04	-0.24	0.00	0.02	0.00
q_{JPTL}						0.69	0.57	0.30	0.02	0.05	-0.24	-0.02	0.03	0.00
q_{TWCOLL}							0.50	0.24	0.05	0.11	-0.17	-0.06	0.01	0.01
r								0.28	0.01	-0.08	-0.08	0.02	0.04	0.07
σ^2									0.06	-0.27	-0.32	0.03	0.08	0.18
τ^2_{EPOPS}										-0.01	-0.05	-0.07	0.01	0.00
τ^2_{JPCOLL}											0.12	-0.06	-0.09	-0.37
$\tau^2_{JPOFFLL}$												0.00	-0.05	-0.07
τ^2_{JPPS}													0.02	0.01
τ^2_{JPTL}														0.05
τ^2_{TWCOLL}														

4. Stock assessment of bluefin tuna in the North Pacific Ocean by virtual population analysis with adaptive framework

Hui-Hua Lee[1] and Chien-Chung Hsu[1,*]

Running title: virtual population analysis of Pacific bluefin tuna

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[*] corresponding author: e-mail: hsucc@ntu.edu.tw

Keywords: virtual population analysis; spawning stock biomass; exploitation rate;

Introduction

The virtual population analysis (VPA) is an important age-structured model using in the fish population dynamics study. The population size of Pacific bluefin tuna by using a tuned VPA called VPA-2Box (Porch 2003).

Materials and Methods

Data used

Virtual population analysis needs mainly annual catch at age and abundance index by fisheries. Those information were Japanese longline fishery, troll fishery, purse seine fisheries, eastern Pacific Ocean purse seine fishery and Taiwanese longline fishery (Yamada et al. 2006; Lee and Hsu 2007). The corresponding standardized catch per unit effort used as abundance index and catch at age for those fisheries are listed in Appendices I and II.

1. Basic population dynamics

The virtual population analysis (VPA) needs catch at age or number at age of catch and abundance index for each fishery information. For the number at age estimation we formulated the equations as:

$$\mathrm{N}_{\mathrm{y+1,1}} = \mathrm{R}_{\mathrm{y+1}}$$

To represent the recruitment in year $\mathrm{y}+1$. And for the age $1 < a \leq m-2$,

$$\mathrm{N}_{\mathrm{y+1,a+1}} = \left(\mathrm{N}_{\mathrm{y,a}} \mathrm{e}^{-\frac{-\mathrm{M_a}}{2}} - \mathrm{C}_{\mathrm{y,a}}\right) \mathrm{e}^{-\frac{\mathrm{M_a}}{2}}$$

And the plus group, the abundance in number can be estimated as

$$\mathrm{N}_{\mathrm{y+1,m}} = \left(\mathrm{N}_{\mathrm{y,m-1}} \mathrm{e}^{-\frac{\mathrm{M_{m-1}}}{2}} - \mathrm{C}_{\mathrm{y,m-1}}\right) \mathrm{e}^{-\frac{\mathrm{M_{m-1}}}{2}} + \left(\mathrm{N}_{\mathrm{y,m}} \mathrm{e}^{-\frac{\mathrm{M_m}}{2}} - \mathrm{C}_{\mathrm{y,m}}\right) \mathrm{e}^{-\frac{\mathrm{M_m}}{2}}$$

where $\mathrm{N}_{\mathrm{y,a}}$ us the abundance in number for age a in the year y; R_{y} is the recruitment in year y; M_{a} is the instantaneous natural mortality for age a fish; and $\mathrm{C}_{\mathrm{y,a}}$ is the catch at age a in year y.

2. Recruitment estimation

Assuming that recruitments occur at age 1, then obviously, the recruitment at year y is only from reproduction from year $\mathrm{y}-1$, indicating that the reproduction is affected by the spawning stock biomass in year $\mathrm{y}-1$. Usually, the Beverton and Holt stock-recruit relationship (Beverton and Holt 1975) was applied with the yearly variation, that is

$$\mathrm{R}_{\mathrm{y}} = \frac{\alpha \mathrm{B}^{\mathrm{sp}}_{\mathrm{y-1}}}{\beta + \mathrm{B}^{\mathrm{sp}}_{\mathrm{y-1}}} \mathrm{e}^{\left(\epsilon_{\mathrm{y}} - \frac{\sigma_{\mathrm{k}}^{2}}{2}\right)}$$

where B_y^{sp} is the spawning stock biomass in year y; α and β are the parameters of the stock-recruit relationship; ϵ_y is the yearly variation in year y assuming that obeys a log-normal distribution with zero mean and standard deviation σ_k. The spawning stock biomass and recruits by years can be estimated from the virtual population analysis.

3. Estimation of spawning stock biomass

The stock's spawning biomass in year y can be estimated as:

$$B_y^{sp} = \sum_{a=1}^{m} f_a \times W_a \times N_{y,a}$$

where W_a is the average biomass of individual fish at age a; and f_a is the probability of mature fish at age a.

To estimate the parameters of stock-recruit relationship and to make the parameters with significantly biological implications, the reparameterization was used (Punt 199?) and the spawning stock biomass under equilibrium and unexploited is K^{SP}, and defined the steepness is h, then the parameters α and β can be parameterized as:

$$\alpha = \frac{4hR_1}{5h-1}$$

and

$$\beta = \frac{K^{sp}(1-h)}{5h-1}$$

For the R_1 (recruits at the start year), we can define it as:

$$R_1 = K^{sp} \Bigg/ \left[\sum_{a=1}^{m-1} f_a W_a e^{-\sum_{a'=0}^{a-1} M_{a'}} + f_m W_m \frac{e^{-\sum_{a'=0}^{a-1} M_{a'}}}{1-e^{-M_m}} \right]$$

Thus, a log-normal distribution of the stock-recruit relationship residuals, then the negative log likelihood function was

$$-\ln L = \sum_{j=y1}^{y2} \ln\sigma_R + \frac{\varepsilon_j^2}{2\sigma_R^2}$$

where ε_j is the residual of recruitment in year j and σ_R is the standard deviation of logarithm of residuals.

4. Total catch and catch at age estimation

Total catch (C_y^f) of a vessel f in a year y can be expressed as:

$$C_y^f = \sum_{a=1}^{m} W_{\frac{a+1}{2}} \times C_{y,a}^f = \sum_{a=1}^{m} W_{\frac{a+1}{2}} \times N_{y,a} e^{-\frac{M_a}{2}} \times S_{y,a}^f \times F_y^f$$

where $W_{\frac{a+1}{2}}$ is the individual weight in kg of a fish in the middle of age a; $C^f_{y,a}$ is the catch at age a of caught by a vessel f in a year y, and the $C^f_{y,a}$ can be expressed as:

$$C^f_{y,a} = S^f_{y,a} \times F^f_y \times N_{y,a}$$

and $S^f_{y,a}$ is the selectivity of a vessel f in a year y for a fish age a; and F^f_y is the catch proportion of fully exploited individual for a vessel f in a year y.

5. Selectivity

A logistic curve was selected for modeling the selectivity for a fishery f to catch a fish with age a, S^f_a:

$$S^f_a = \frac{1}{1 + e^{-\frac{(a - a^f_c)}{\delta^f}}}$$

where a^f_c is the age of 50% selectivity for a fishery f; and δ^f is the steepness of the logistic selectivity curve.

6. Exploitable biomass

Then exploitable biomass can be estimated by the equation using the natural and fishing mortality with the weight at the middle age:

$$B^f_y = \sum_{a=1}^{m} W_{\frac{a+1}{2}} \times S^f_{y,a} \times N_{y,a} e^{-\frac{M_a}{2}} \times \left(1 - \frac{S^f_{y,a} \times F^f_y}{2}\right)$$

The likelihood function can be used to estimate the corresponding parameters using standardized abundance indices and catch at age by fisheries. Assuming the abundance index is obeying log-normal distribution with zero mean and standard deviationσ_f, then the observed abundance index of a vessel f in year y, assuming it be I^f_y, with the expected abundance index as $\hat{I}^f_y$, then

$$I^f_y = \hat{I}^f_y \times e^{\varepsilon^f_y}$$

or

$$\varepsilon^f_y = \ln(I^f_y) - \ln(\hat{I}^f_y)$$

And the expected abundance index can be estimated as:

$$\hat{I}^f_y = W^f_y \times \hat{q}^f \times \widehat{B}^f_y$$

where $\widehat{B}^f_y$ is the expected exploitable stock biomass by vessel f in year y; and $\hat{q}^f$ is the catchability for the vessel f.

The negative log-likelihood of the catch per unit effort (abundance index) can be expressed as:

$$-\ln L^{cpue} = \sum_{f}\sum_{y}\left[\ln(\sigma^{f}) + (\varepsilon_{y}^{f})^{2}/2(\sigma^{f})^{2}\right]$$

Similarly, the negative log likelihood for catch at age, also assuming as a log-normal distribution as:

$$-\ln L^{CAA} = \sum_{f}\sum_{y}\sum_{a}\left[\ln\left(\frac{\sigma_{com}^{f}}{\sqrt{p_{y,a}^{f} + \delta}}\right) + \left(p_{y,a}^{f} + \delta\right)\left(\ln\{p_{y,a}^{f} + \delta\} - \ln(\hat{p}_{y,a}^{f} + \delta)\right)^{2}/2\left(\sigma_{com}^{f}\right)^{2}\right]$$

For preventing the zero catch being used in the estimation, a δ =0.01 was set. The proportion of observed catch and expected catch with age a for vessel f in year y were:

$$p_{y,a}^{f} = \frac{C_{y,a}^{f}}{\sum_{a} C_{y,a}^{f}}$$

And

$$\hat{p}_{y,a}^{f} = \frac{\hat{C}_{y,a}^{f}}{\sum_{a} \hat{C}_{y,a}^{f}}$$

And the expected catch can be:

$$\hat{C}_{y,a}^{f} = N_{y,a} \times e^{-\frac{M_a}{2}} \times S_{y,a}^{f} \times F_{y}^{f}$$

And σ_{com}^{f} is the standard deviation of catch for vessel f, which is estimated as:

$$\sigma_{com}^{f} = \sqrt{\frac{\sum_{y}\sum_{a}\left(\ln p_{y,a}^{f} - \ln\hat{p}_{y,a}^{f}\right)^{2}}{\sum_{y}\sum_{a} 1}}$$

Biological parameters used in the VPA runs

1. Natural mortality

According to Bayliff et al (1991) and Yamada et al. (2004) studies, the PBF natural mortality is high and can be expressed as:

$$M_a = \begin{cases} M_a & a \leq 2 \\ \alpha^{M} + \dfrac{\beta^{M}}{\alpha + 1} & a > 2 \end{cases}$$

In which the parameters α and β were estimated from fitting

2. Maturity oogive

Usually the probability of maturity at age was expressed as:

$$f_a = \begin{cases} 0 & \text{for} \quad a < a_{50\%\ \mathrm{maturation}} \\ 0.5 & \text{for} \quad a = a_{50\%\ \mathrm{maturation}} \\ 1 & \text{for} \quad a > a_{50\%\ \mathrm{maturation}} \end{cases}$$

As well as using in several studies, the $a_{50\%\ \mathrm{maturation}}$ was set equal to 4.

3. Individual mean weight at age

The individual mean weight was estimated from the von Bertalanffy growth equation in length (Yukinawa and Yabuta 1967) and the length weight relationship (Hsu et al. 2000) for the present study.

Consequently, the parameters mentioned above were tabulated in Table 1. And the estimation of abundance and fishing mortality by age was computed by the program of VPA-2BOX (Porch 2003).

Results

The virtual population analysis is based on the catch at age and standardized catch per unit effort by fisheries as abundance indices to tune the abundance estimation. The data of catch at age by fisheries were listed as appendix I and depicted in Figure 1. The catch At age shows that ages 0-3 fish were major groups in the bluefin tuna catch, and particularly, the catches after 1994 were very significant for age 0 and age 1 fish. Figure 2 indicates that the catches of age 0 were about 40% from 1990, and of age 1 about 30%. Regarding to the selectivity, Figure 3 depicts that the selectivity seemed not very coincident with the catch at age by fisheries (Appendix I).

Total abundance in number as shown in Figure 4 indicates that there were two peaked period for the Pacific bluefin tuna from 1960 to 2004, those are 1970s and 1990s, in particular, the total abundance occurred in 1990s, however, a lower abundance appeared in 1997, and 2000 then after as low as 4.2 million fish, which is very close to the historical lowest in 1987 about 4.0 million fish. Even the abundance by ages (Figure 5) and total biomass and spawning stock biomass (Figure 6) were also coincident as the total abundance in number. However, the lowest biomass occurred in 1969 and the second from 1983 to 1988. The overall biomass trend (figure 6) seems not very similar to the trend of total number of fish. The later seems flat in average at 6.0 million for the entire estimated series, but there were an overall increasing trend in biomass from 1970 to 2004. The inconsistent for recent estimation between abundance in number and in biomass indicates that recent catches may have more small sizes than before to make the total biomass increasing. The fact is evidenced in spawning stock biomass (Figure 6).

To judge this inference, Figure 7 shows the fishing mortality by ages, indicating that there were very significantly high fishing mortality for age 0 and age 1 after 1994 similar to the previous stages in some years around 1971, 1976 and 1986. For the spawning stock, over age 5, the fishing mortality related to this group was high during the recent decade (Figure 7), especially for ages 8 and older.

To support the high fishing mortality for old aged fish, Figure 8 indicates that there are two strong year-classes recruited in around 1994 and 2000 and a high average level recruited (average about 3.5 million fish) during this period. The stock recruit relationship (Figure 9) shows that the spawning stock biomass was between 10,000 t and 45,000 t and the recruits were between one million fish and 5.3 million fish except in 1994 (about 8.1 million fish) and in 2000 (about 9.3 million fish). If not consider the two high recruited level in 1994 and 2000, the spawner and recruits relationship seems stable during the study period (1960-2004).

The standardized catch per unit effort in using in the present study were shown in Figures 10-14 with their expected catch per unit effort and residuals for Japanese far-seas longline fishery (Figure 10), Japanese purse seine fishery (Figure 11), Japanese troll fishery (Figure 12), Taiwanese small scale longline fishery (figure 13) and the eastern Pacific purse seine fishery (Figure 14). Those selected abundance indices can represent the Pacific bluefin tuna stock through the justification of residuals and expected indices as shown in those figures.

Discussion

Virtual population analysis is one of the most powerful assessment models for multiple gears fisheries. It uses catch at age by fisheries and standardized catch per unit effort as abundance indices by fisheries to tune the abundance and fishing mortality estimation. The virtual population analysis used to assess bluefin tuna in the North Pacific Ocean were found seldom in the ISC (International Scientific Committee for the Assessment on Tuna and Tuna-like Species in the North Pacific Ocean) Pacific Bluefin Tuna Workshop, e.g. Yamada et al. (2006) recently. Moreover, the studies, unfortunately including the present study, on this issue may not fully solve the stock status problem for the North Pacific bluefin tuna.

The biological parameters were the first issue to influence the assessment of Pacific bluefin tuna. The growth equation of Pacific bluefin tuna was developed in 1967 by Yukinawa and Yabuta, using samples from Japanese purse seine fishery. The largest size used in the growth study was 215 cm FL. However, the sizes in catch from Japanese and Taiwanese longline fisheries were mostly over 215 cm FL, then if the equation formulated by Yukinawa and Yabuta (1967) was used, the estimated catch at age for fish larger than 215 cm may be problematic. Also, the maturity schedule used was only a inferred value. Due to the great varieties of body sizes and maturity condition in catch by different fisheries, to figure out an useful maturity schedule is difficult. Although several studies for reproductive biology of Pacific bluefin tuna have published previously (Chen et al. 2006; and Pers. Comm. with Dr. Sho Tanaka, professor of Tokai University, Shimizu), the maturity oogive is still wanted. This work may be achieved by the national cooperation from Japan and Taiwan, because they are fishing different size groups of Pacific bluefin tuna in different times and regions. And moreover, the natural mortality used in all the virtual population analysis was by a theoretical guess. The reality seems needed to be investigated.

Regarding the abundance indices, there were no candidates to evidence validation in representing the Pacific bluefin tuna stock (Table 2 in Anonymous 2006). In the present study, 5 standardized catch per unit effort, Japanese far-seas longline fishery, Japanese coastal longline fishery, Japanese troll fishery, Japanese purse seine fishery, Taiwanese small scale longline fishery, and purse seine fishery in the eastern Pacific Ocean were used as abundance indices. To validate those indices, in the results of the current study (Figures 10-14), the fitting residuals seem in great outbreak. For further assessment of the stock accurately, the abundance index study for each fishery may be the most important issue as well as the collection of catch statistics.

The increasing catches in juveniles for aquaculture and giant spawners for Sashimi market may result in threatening the stock. The four stocks of bluefin tuna around the World Ocean, western Atlantic stock, eastern and Mediterranean stock, North Pacific Ocean stock and southern bluefin tuna stock, are likely to be fully exploited or possibly over-exploited. The western Atlantic stock is depleted since early 1980s, and is rebuilding currently; the southern bluefin tuna stock is also in depletion; the eastern Atlantic and Mediterranean stock is obviously in over-exploited overfishing; Moreover, the North Pacific Ocean stock status is not well-known, but full exploitation is assured. Therefore, to verify catch data for each fishery by its corresponding nation is absolutely needed and the stock status can be clarified after those data are available. Before that, the precautionary action seems in process as soon as possible.

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Table 1 Biological parameters of bluefin tuna in the North Pacific Ocean.

Parameters (Units)	Symbols	Value (Taiwan)	Value (Japan)
Length-weight relationship	α^{*1}	2.3058×10^{-5}	4.073×10^{-5}
Length-weight relationship	β^{*1}	2.9342	2.8344
Asymptotic for length (cm)	L_{∞}^{*2}	366.7	320.5
Asymptotic weight (kg)	W_{∞}	771.6	515.7
Rate of growth (/year)	k^{*2}	0.086	0.104
Age at $FL = 0$ (year)	t_0^{*2}	-0.926	-0.703
Natural mortality (/Year)	M_a^{*3}		$M_0 = 1.60$
			$M_1 = 0.80$
			$M_2 = 0.40$
			$M_3 = 0.25$
Seual maturity at age (percent)	f_a^{*4}		$f_4 = 20$
			$f_5 = 100$

*1 Weight (kg)=$\alpha \times FL^{\beta}$, which adopted from Yukinawa and Yabuta (1967) and Hsu et Al. (2000).

*2 von Bertalanffy growth parameters from Ishizuka (1989) and Wu and Hsu (2002).

*3 Natural mortality rate at age from Yamada (2003).

*4 Sexual maturity at age from Yorita (1981), Bayliff (1994) and Ishizuka (1994).

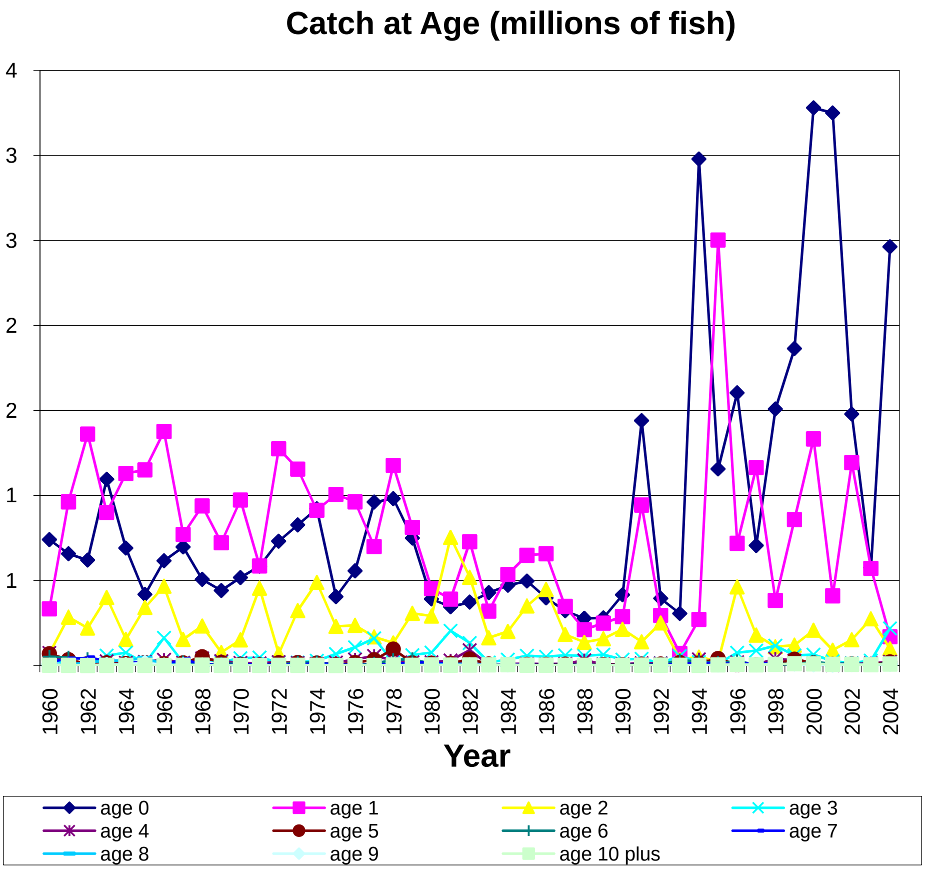


Figure 1. The catch at age variation of bluefin tuna in North Pacific Ocean from 1960 to 2004.

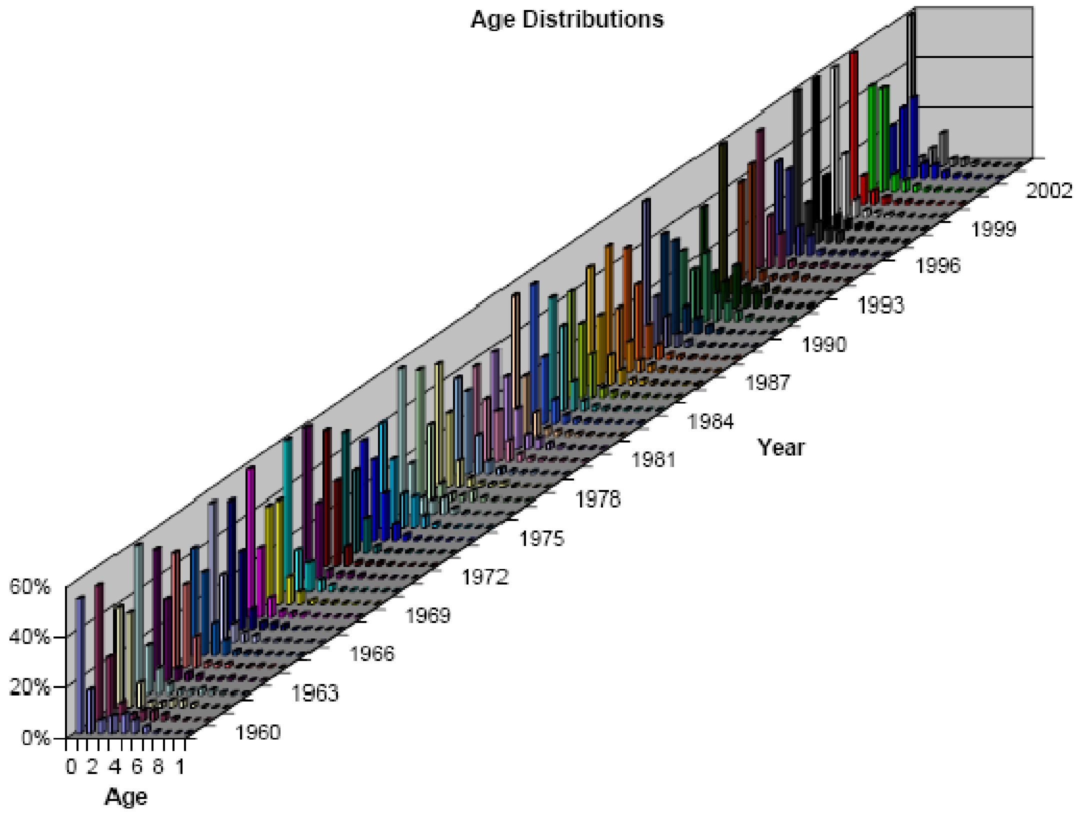


Figure 2. The age composition of bluefin tuna in the North Pacific Ocean from 1960 to 2004.

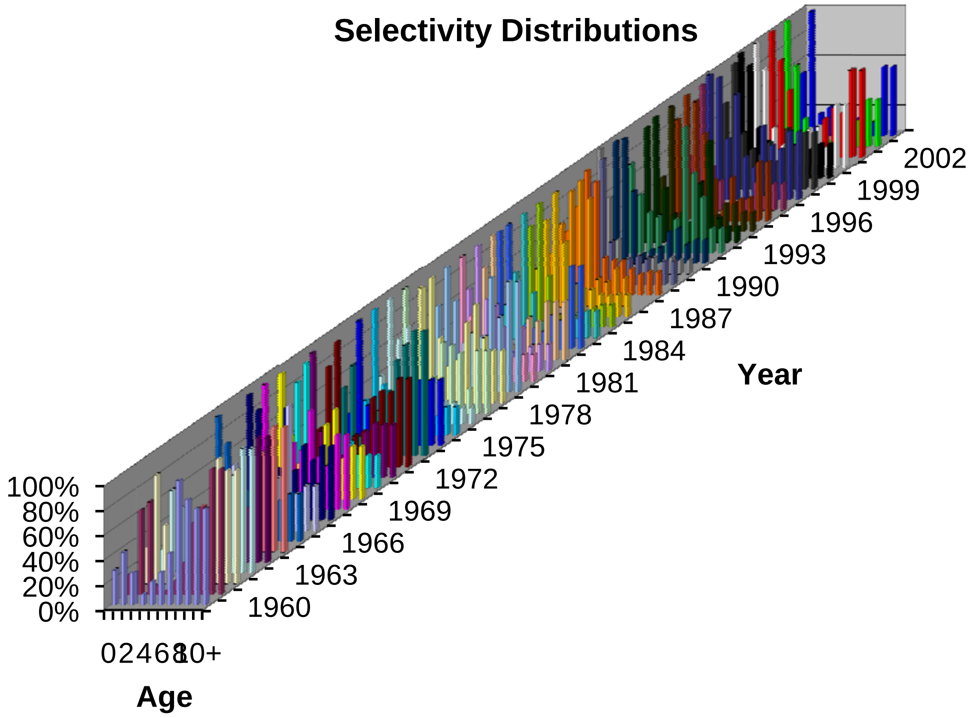


Figure 3. The selectivity of all gear combined for fishing bluefin tuna in the North Pacific Ocean.

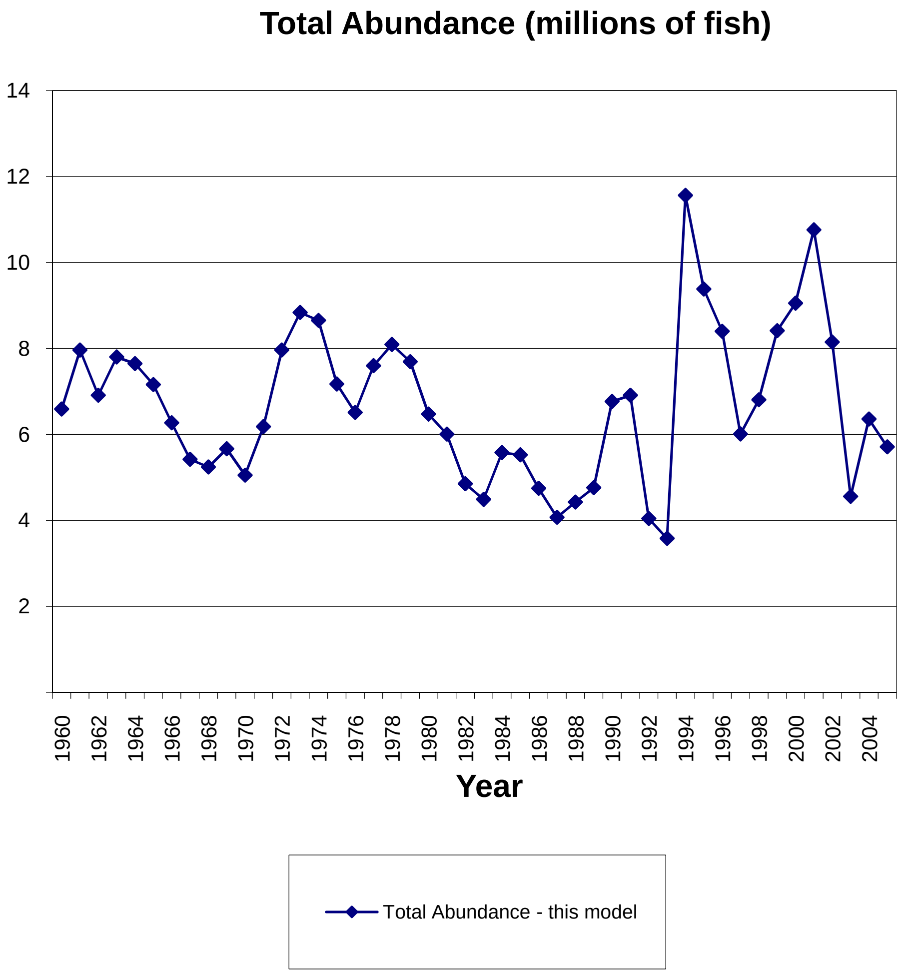


Figure 4. The total number of bluefin tuna in the North Pacific Ocean estimated by the adaptive virtual population analysis from 1960 to 2004.

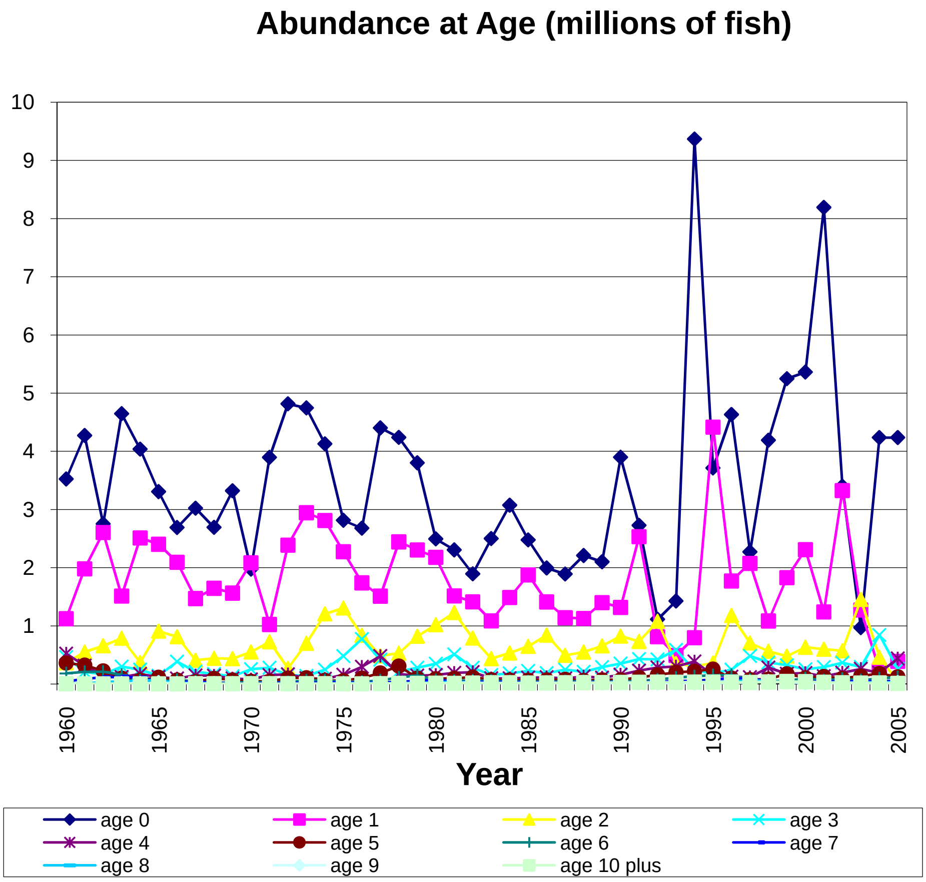
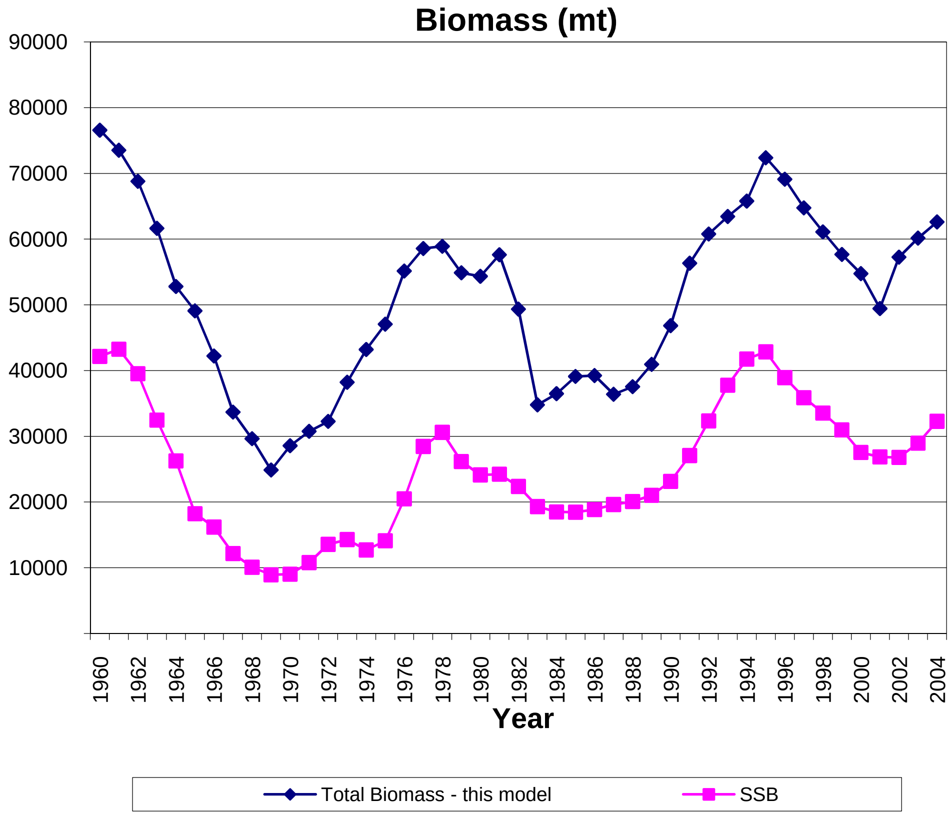


Figure 5. The estimated abundance at age of bluefin tuna in the North Pacific Ocean from 1960 to 2004, which was estimated by the adaptive virtual population analysis, the abundance at age was broken down from total abundance as in Figure 4.



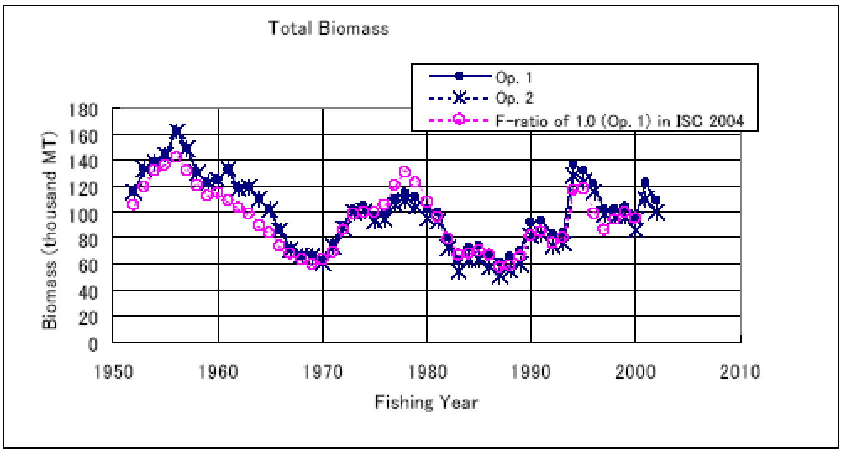


Figure 6. The total biomass and spawning stock biomass fo bluefin tuna in the North Pacific Ocean, estimated from the adaptive virtual population analysis from 1960 to 2004.

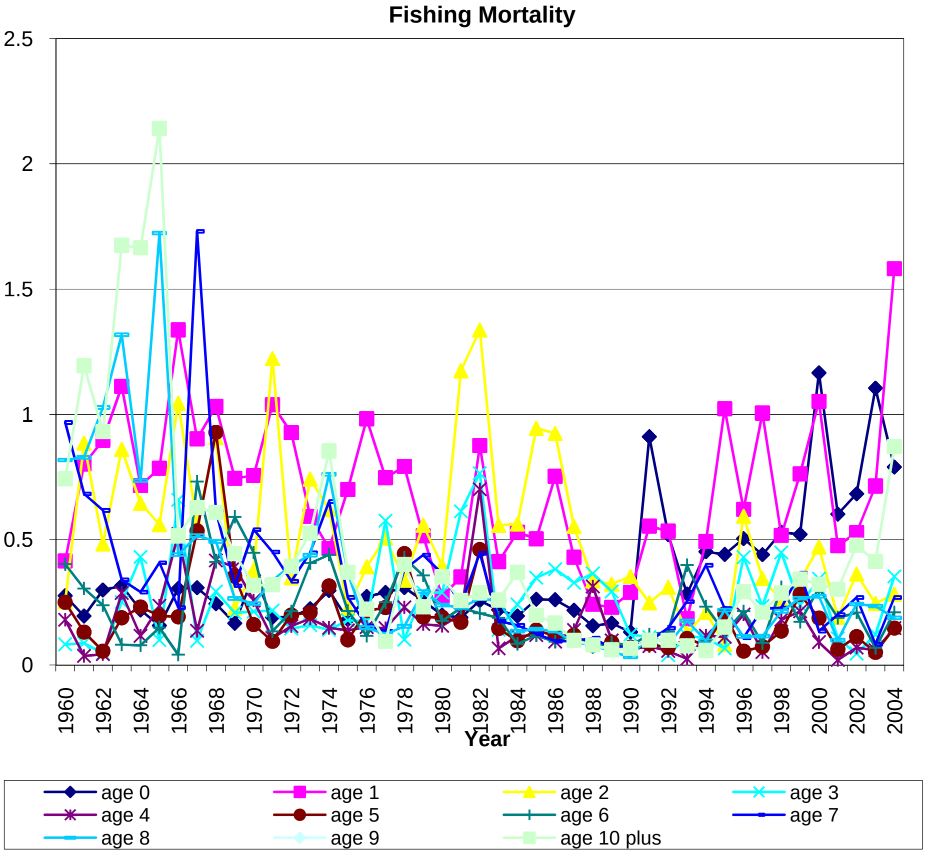


Figure 7. The fishing mortality by ages for bluefin tuna in the North Pacific Ocean from 1960 to 2004, in which the age-specific fishing mortality was estimated by the adaptive virtual population analysis.

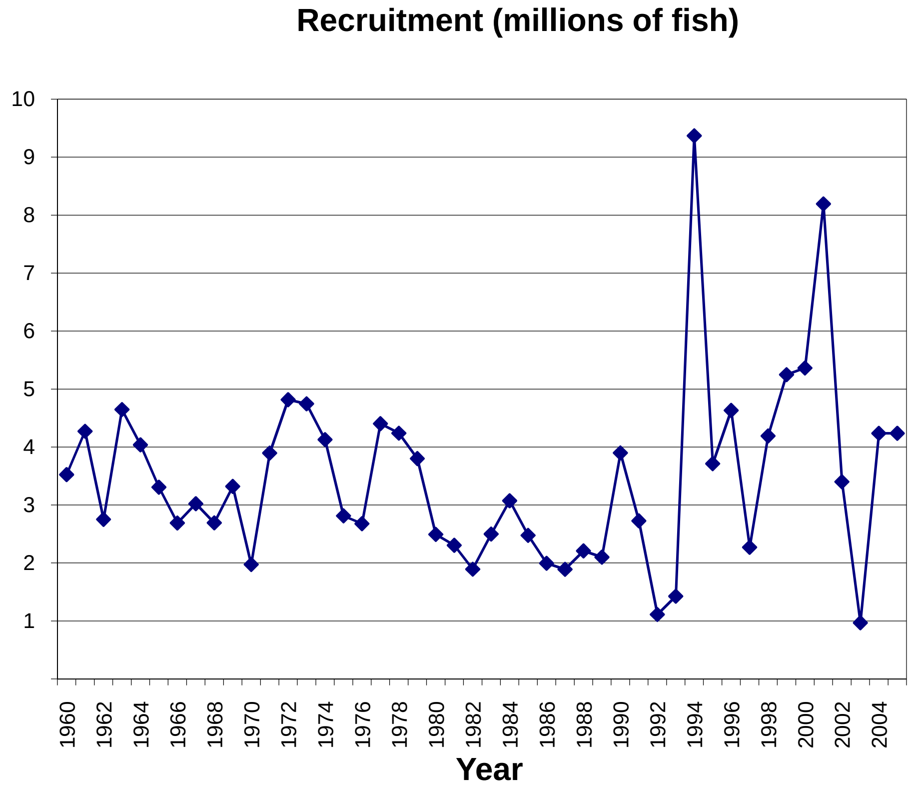


Figure 8. The recruits in number estimated from the present analysis for bluefin tuna in the North Pacific Ocean.

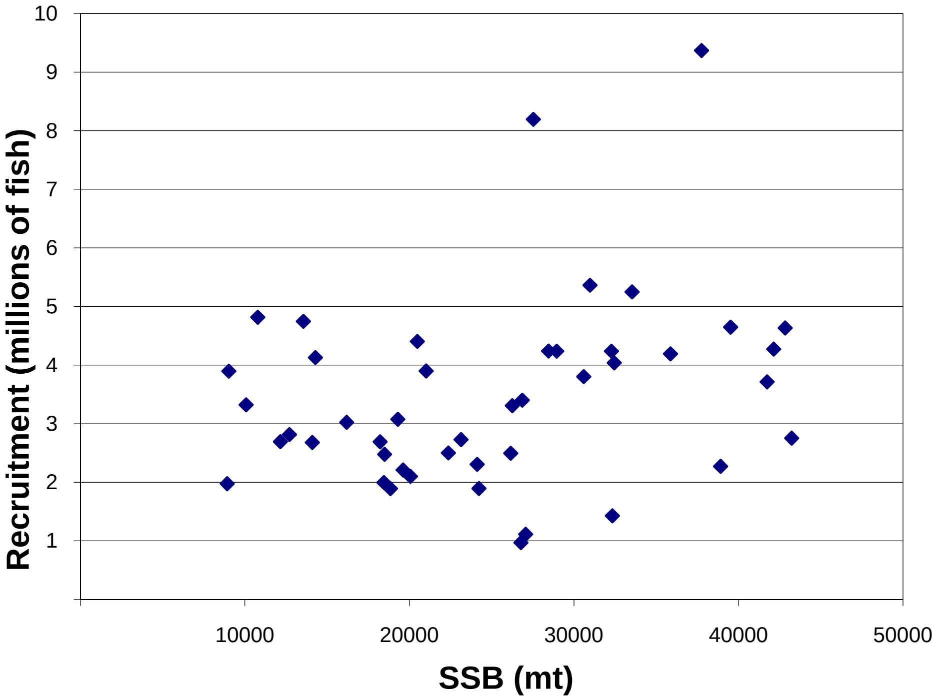


Figure 9. The stock recruit relationship of bluefin tuna in the North Pacific Ocean, Spawner and recruits were estimated from the virtual population analysis.

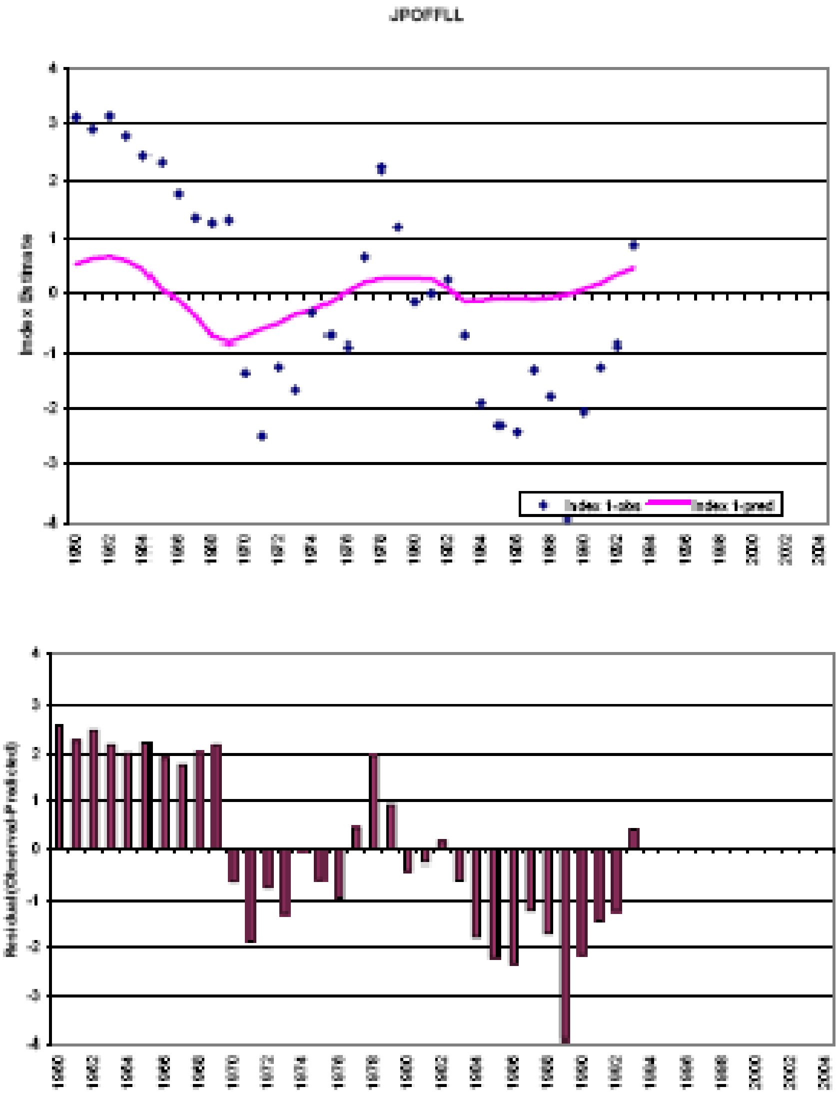


Figure 10. Time series catch per unit effort of Japanese far-seas longline fishery (upper panel) with the expected (red curve), the fitting residual was shown as the lower panel.

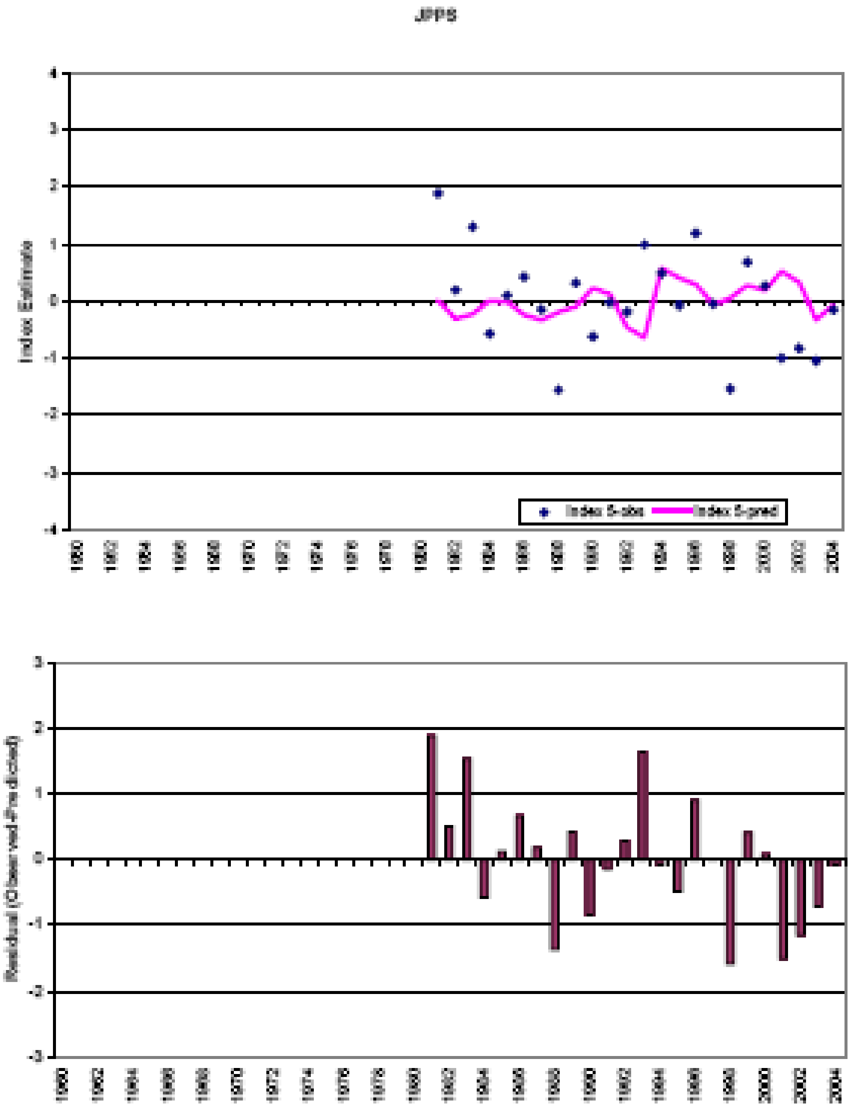


Figure 11. Time series catch per unit effort of Japanese purse seine fishery (upper panel) with the expected (red curve), the fitting residual was shown as the lower panel.

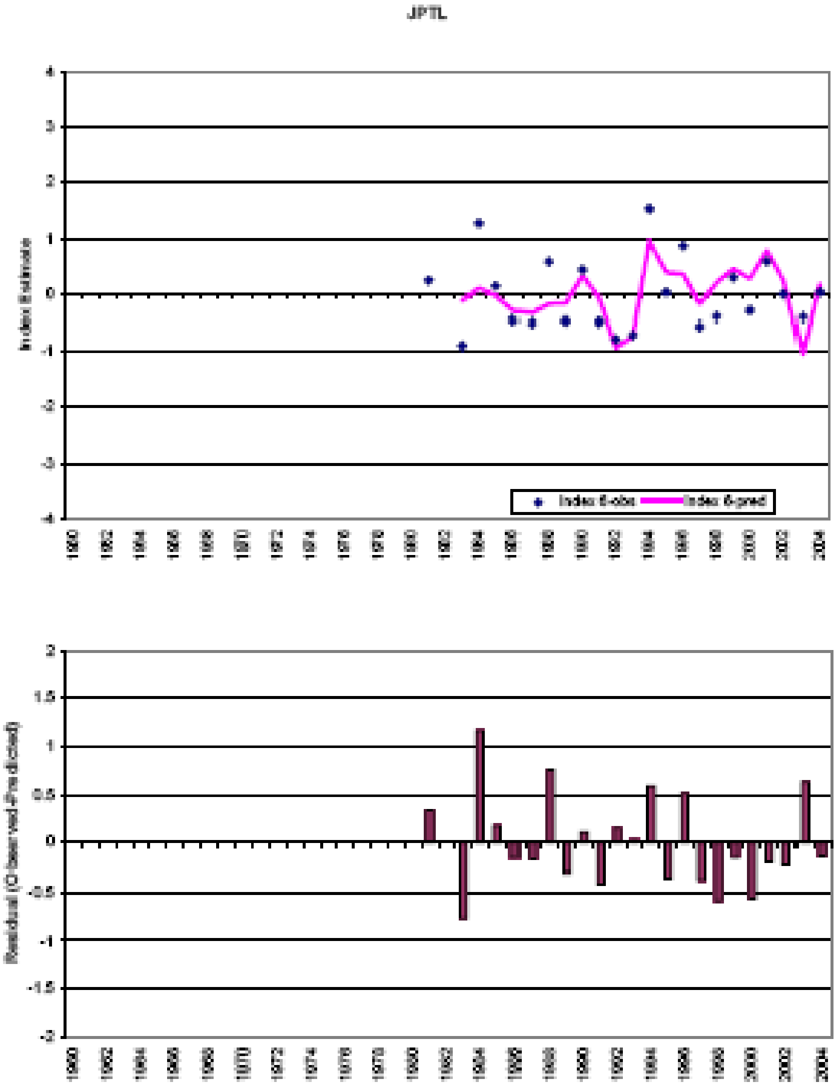


Figure 12. Time series catch per unit effort of Japanese troll fishery (upper panel) with the expected (red curve), the fitting residual was shown as the lower panel.

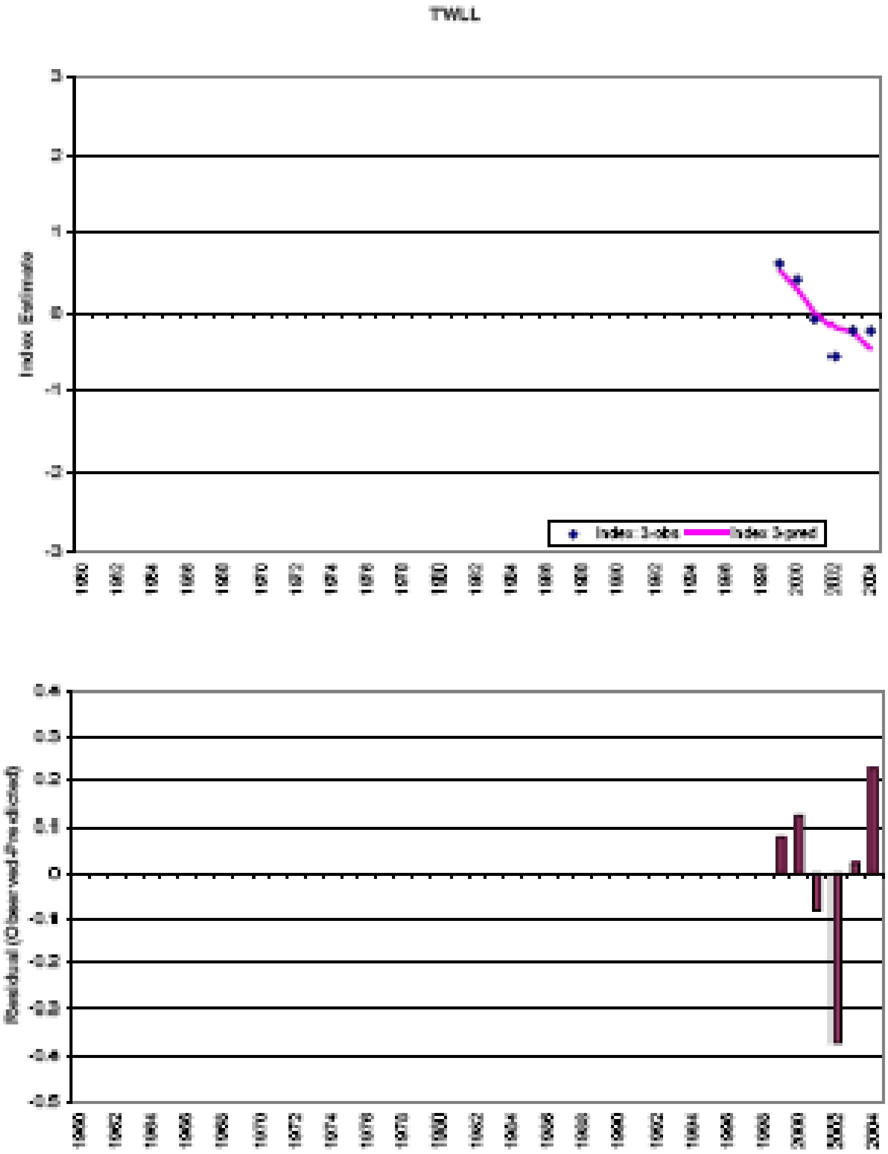


Figure 13. Time series catch per unit effort of Taiwanese small scale longline fishery (upper panel) with the expected (red curve), the fitting residual was shown as the lower panel.

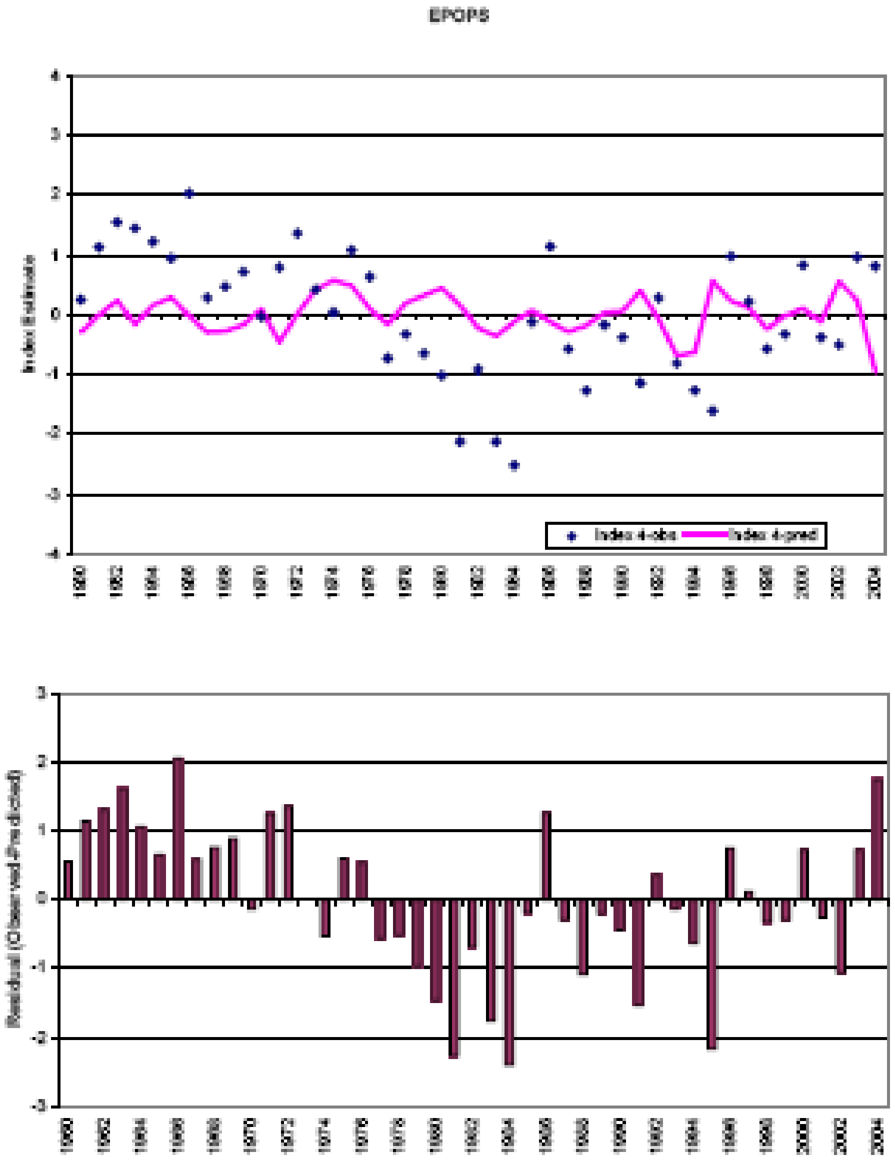
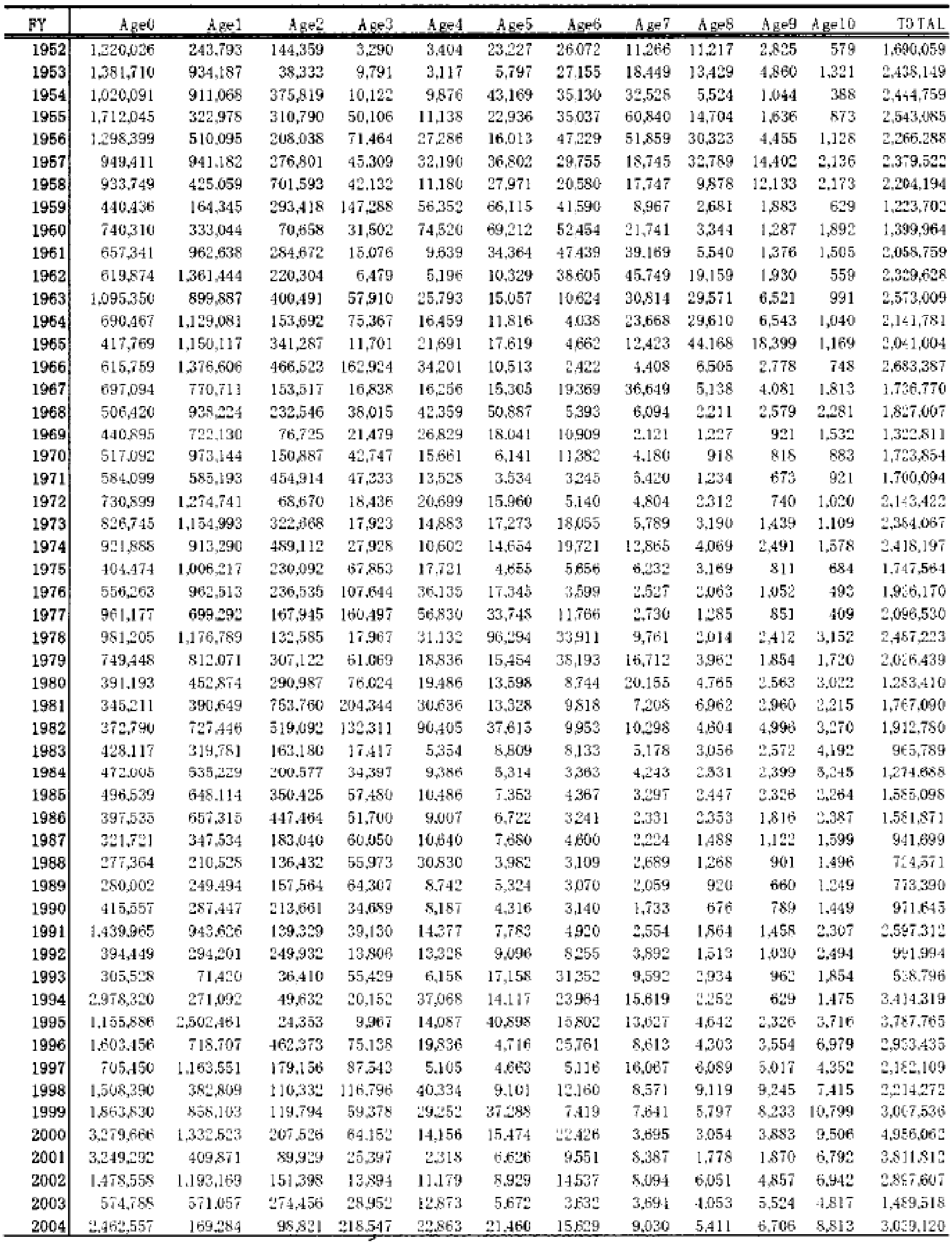


Figure 14. Time series catch per unit effort of purse seine fishery (upper panel) with the expected (red curve) in the eastern Pacific Ocean; the fitting residual was shown as the lower panel.

Appendix I. Abundance indices used in the present study, in which Index 1: Japanese far-sea fishery; Index 2: Japanese coastal longline fishery; Index 3: Taiwanese small scale longline fishery; Index 4: Eastern Pacific Ocean purse seine fishery and Index 5: Japanese troll fishery.

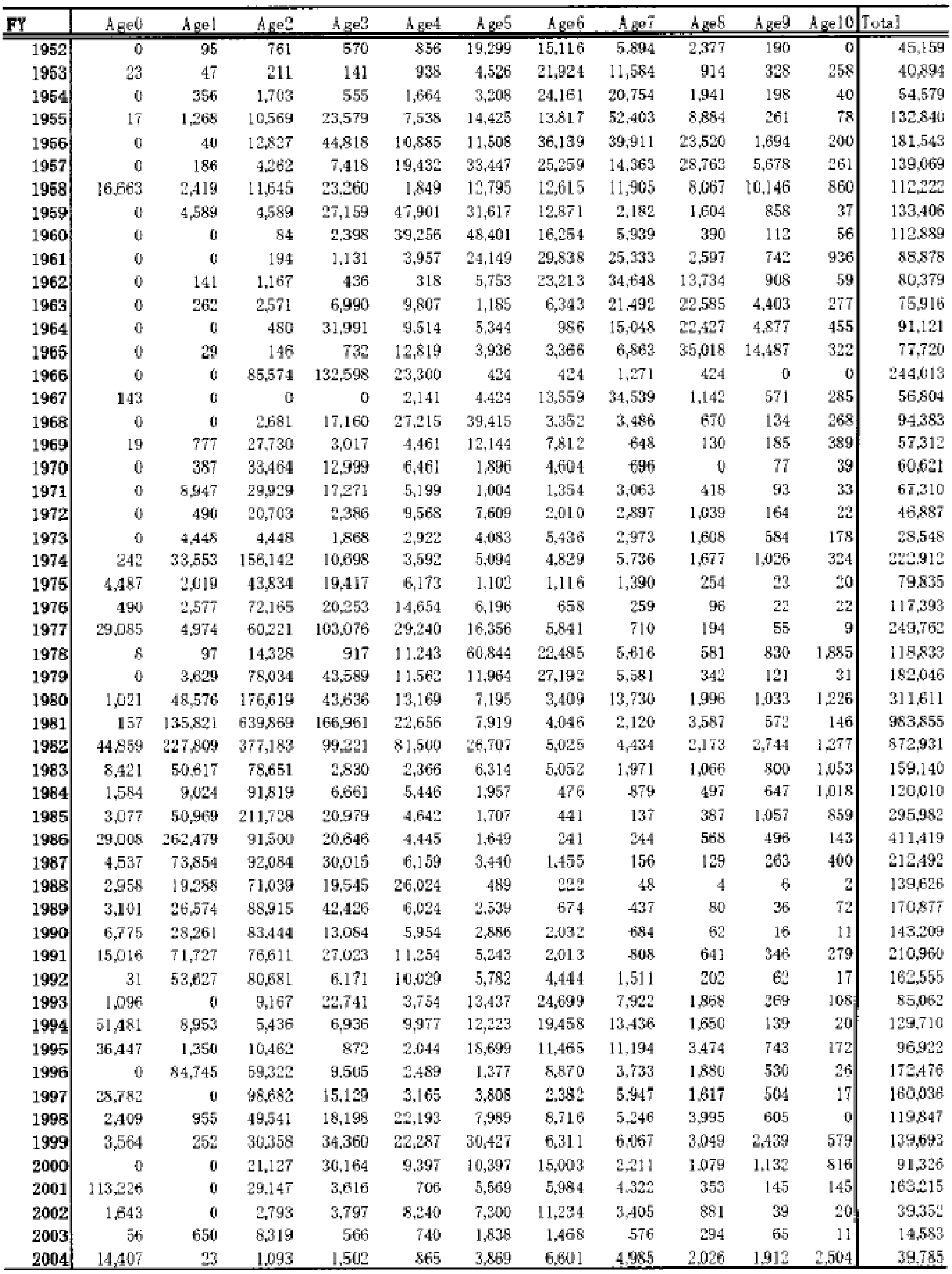
year	Index 1	Index 2	Index 3	Index 4	Index 5	Index 6
1960	3.11			0.25		
1961	2.89			1.13		
1962	3.13			1.55		
1963	2.77			1.45		
1964	2.42			1.22		
1965	2.3			0.943		
1966	1.79			2.03		
1967	1.36			0.281		
1968	1.27			0.473		
1969	1.32			0.716		
1970	-1.37			-0.0373		
1971	-2.49			0.792		
1972	-1.26			1.36		
1973	-1.67			0.422		
1974	-0.338			0.0427		
1975	-0.738			1.08		
1976	-0.914			0.635		
1977	0.658			-0.73		
1978	2.22			-0.325		
1979	1.2			-0.65		
1980	-0.145			-1.02		
1981	0.0012			-2.12	1.89	0.238
1982	0.248			-0.913	0.194	
1983	-0.743			-2.12	1.3	-0.896
1984	-1.9			-2.52	-0.576	1.27
1985	-2.3			-0.124	0.0972	0.137
1986	-2.42			1.14	0.426	-0.455
1987	-1.31			-0.576	-0.149	-0.511
1988	-1.78			-1.27	-1.56	0.581
1989	-3.92			-0.171	0.319	-0.47
1990	-2.07			-0.382	-0.624	0.429
1991	-1.27			-1.14	-0.0328	-0.488
1992	-0.899			0.281	-0.189	-0.784
1993	0.869			-0.817	0.987	-0.709
1994		0.315		-1.27	0.49	1.53
1995		0.183		-1.61	-0.0814	0.0257
1996		0.223		0.974	1.19	0.864
1997		0.322		0.219	-0.0539	-0.559
1998		0.276		-0.576	-1.54	-0.395
1999		0.0417	0.636	-0.325	0.678	0.289
2000		-0.283	0.433	0.828	0.268	-0.298
2001		-0.568	-0.0748	-0.382	-1	0.582
2002		-0.576	-0.55	-0.507	-0.828	-0.00442
2003		-0.0297	-0.219	0.959	-1.05	-0.407
2004		0.0959	-0.225	0.81	-0.153	0.0269

Appendix II -1. Estimated catch at age (0 – 10+) in number of bluefin tuna in the North Pacific Ocean by overall fisheries combined. (Data were adopted from Yamada et al. 2006)



FY	Age0	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10	TOTAL
1952	1,220,026	243,793	144,359	3,290	3,404	23,227	26,072	11,266	11,217	2,825	579	1,690,059
1953	1,381,710	934,187	38,333	9,791	3,117	5,797	27,155	18,449	13,429	4,860	1,321	2,438,149
1954	1,020,091	911,068	375,819	10,122	9,876	43,169	35,130	32,528	5,524	1,044	388	2,444,759
1955	1,712,045	322,978	310,790	50,106	11,138	22,936	35,037	60,840	14,704	1,636	873	2,543,085
1956	1,298,399	510,095	208,038	71,464	27,286	16,013	47,229	51,859	30,323	4,455	1,128	2,266,288
1957	949,411	941,182	276,801	45,309	32,190	36,802	29,755	18,745	32,789	14,402	2,136	2,379,522
1958	933,749	425,059	701,593	42,132	11,180	27,971	20,580	17,747	9,878	12,133	2,173	2,204,194
1959	440,436	164,345	293,418	147,288	56,352	66,115	41,590	8,967	2,681	1,883	629	1,223,702
1960	740,310	333,044	70,658	31,502	74,520	69,212	52,454	21,741	3,344	1,287	1,892	1,399,964
1961	657,341	962,638	284,672	15,076	9,639	34,364	47,439	39,169	5,540	1,376	1,505	2,058,759
1962	619,874	1,361,444	220,304	6,479	5,196	10,329	38,605	45,749	19,159	1,930	559	2,329,628
1963	1,095,350	899,887	400,491	57,910	25,793	15,057	10,624	30,814	29,571	6,521	991	2,573,009
1964	690,467	1,129,081	153,692	75,367	16,459	11,816	4,038	23,668	29,610	6,543	1,040	2,141,781
1965	417,769	1,150,117	341,287	11,701	21,691	17,619	4,662	12,423	44,168	18,399	1,169	2,041,004
1966	615,759	1,376,606	466,523	162,924	34,201	10,513	2,422	4,408	6,505	2,778	748	2,683,387
1967	697,094	770,713	153,517	16,838	16,256	15,305	19,369	36,649	5,138	4,081	1,813	1,736,770
1968	506,420	938,224	232,546	38,015	42,359	50,887	5,393	6,094	2,211	2,579	2,281	1,827,007
1969	440,895	722,130	76,725	21,479	26,829	18,041	10,909	2,121	1,227	921	1,532	1,322,811
1970	517,092	973,144	150,887	42,747	15,661	6,141	11,382	4,180	918	818	883	1,723,854
1971	584,099	585,193	454,914	47,333	13,528	3,534	3,245	5,420	1,234	673	921	1,700,094
1972	730,899	1,274,741	68,670	18,436	20,699	15,960	5,140	4,804	2,312	740	1,020	2,143,422
1973	826,745	1,154,993	322,868	17,923	14,883	17,273	18,055	5,789	3,190	1,439	1,109	2,384,067
1974	921,888	913,290	489,112	27,928	10,602	14,654	19,721	12,865	4,069	2,491	1,578	2,418,197
1975	404,474	1,006,217	230,092	67,853	17,721	4,655	5,656	6,232	3,169	811	684	1,747,564
1976	556,263	962,513	236,535	107,644	36,135	17,345	3,599	2,527	2,063	1,052	493	1,926,170
1977	961,177	699,292	167,945	160,497	56,830	33,748	11,766	2,730	1,285	851	409	2,096,530
1978	981,205	1,176,789	132,585	17,967	31,132	96,294	33,911	9,761	2,014	2,412	3,152	2,487,223
1979	749,448	812,071	307,122	61,069	18,836	15,454	38,193	16,712	3,962	1,854	1,720	2,026,439
1980	391,193	452,874	290,987	76,024	19,486	13,598	8,744	20,155	4,765	2,563	3,022	1,283,410
1981	345,211	390,649	753,760	204,344	30,636	13,328	9,818	7,208	6,962	2,960	2,215	1,767,090
1982	372,790	727,446	519,092	132,311	90,405	37,613	9,953	10,298	4,604	4,996	3,270	1,912,780
1983	428,117	319,781	163,180	17,417	5,354	8,809	8,133	5,178	3,056	2,572	4,192	965,789
1984	472,005	535,229	200,577	34,397	9,386	5,314	3,363	4,243	2,531	2,399	5,245	1,274,688
1985	496,539	648,114	350,425	57,480	10,486	7,353	4,367	3,297	2,447	2,326	2,264	1,585,098
1986	397,535	657,315	447,464	51,700	9,007	6,722	3,241	2,331	2,353	1,816	2,387	1,581,871
1987	321,721	347,534	183,040	60,050	10,640	7,680	4,600	2,224	1,488	1,122	1,599	941,699
1988	277,364	210,528	136,432	55,973	30,830	3,982	3,109	2,689	1,268	901	1,496	724,571
1989	280,002	249,494	157,564	64,307	8,742	5,324	3,070	2,059	920	660	1,249	773,390
1990	415,557	287,447	213,661	34,689	8,187	4,316	3,140	1,733	676	789	1,449	971,645
1991	1,439,965	943,626	139,329	39,130	14,377	7,783	4,920	2,554	1,864	1,458	2,307	2,597,312
1992	394,449	294,201	249,932	13,806	13,328	9,096	8,255	3,892	1,513	1,030	2,494	991,994
1993	305,528	71,420	36,410	55,429	6,158	17,158	31,352	9,592	2,934	962	1,854	538,796
1994	2,978,320	271,092	49,632	20,152	37,068	14,117	23,964	15,619	2,252	629	1,475	3,414,319
1995	1,155,886	2,502,461	24,353	9,967	14,087	40,898	15,802	13,627	4,642	2,326	3,716	3,787,765
1996	1,603,456	718,707	462,373	75,138	19,836	4,716	25,761	8,613	4,303	3,554	6,979	2,933,435
1997	705,450	1,163,551	179,156	87,543	5,105	4,663	5,116	16,067	6,089	5,017	4,352	2,182,109
1998	1,508,390	382,809	110,332	116,796	40,334	9,101	12,160	8,571	9,119	9,245	7,415	2,214,272
1999	1,863,830	858,103	119,794	59,378	29,252	37,288	7,419	7,641	5,797	8,233	10,799	3,007,536
2000	3,279,666	1,332,523	207,526	64,152	14,156	15,474	22,426	3,695	3,054	3,883	9,506	4,956,062
2001	3,249,292	409,871	89,929	25,397	2,318	6,626	9,551	8,387	1,778	1,870	6,792	3,811,812
2002	1,478,558	1,193,169	151,398	13,894	11,179	8,929	14,537	8,094	6,051	4,857	6,942	2,897,607
2003	574,788	571,057	274,456	28,952	12,873	5,672	3,632	3,694	4,053	5,524	4,817	1,489,518
2004	2,462,557	169,284	98,821	218,547	22,863	21,460	15,629	9,030	5,411	6,706	8,813	3,039,120

Appendix II-2. Estimated catch at age in number for age 0 – age 10+ of bluefin tuna in the North Pacific Ocean by Japanese purse seine fishery. (Data were adopted from Yamada et al. 2006)

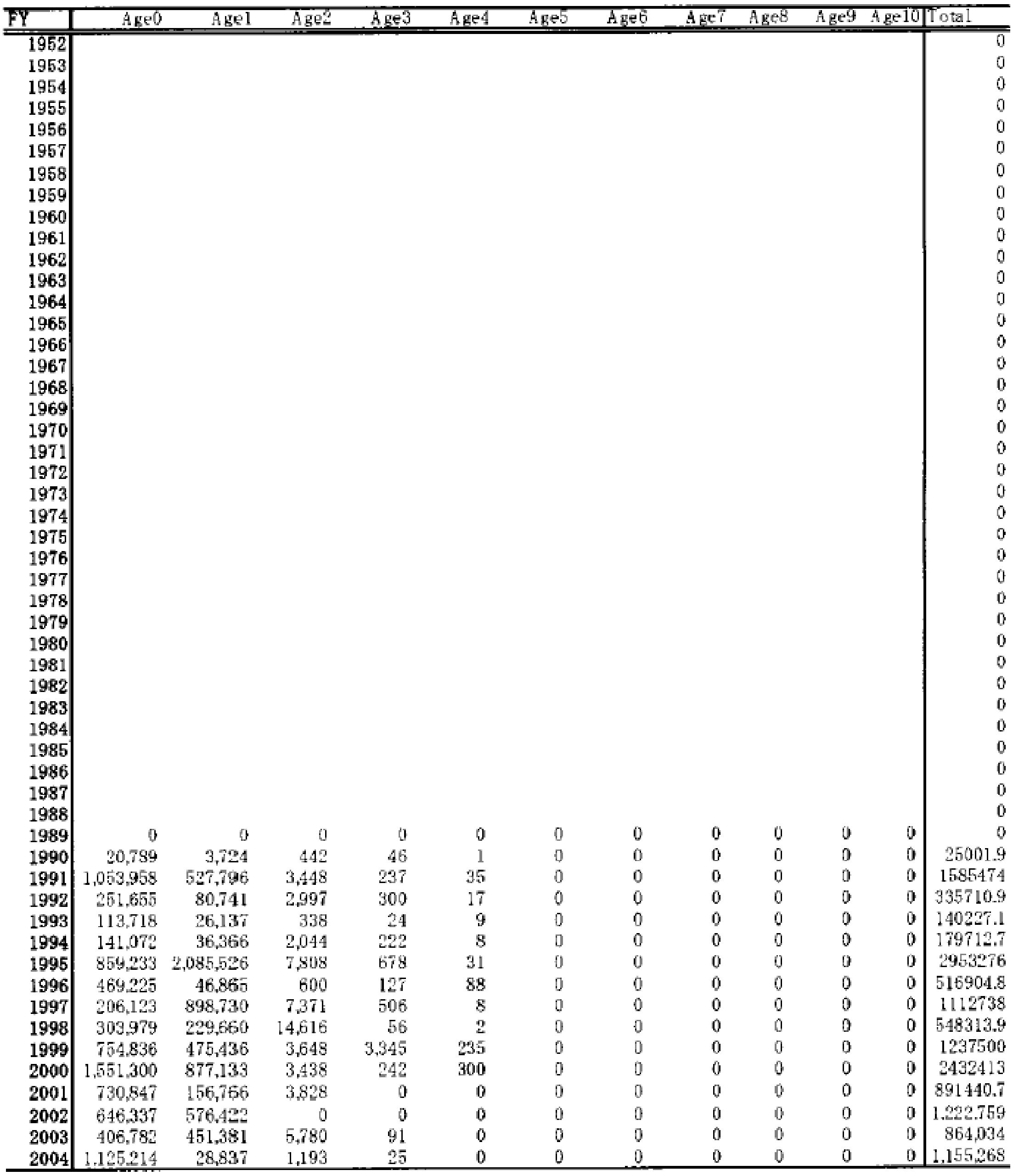


FY	Age0	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10	Total
1952	0	95	761	570	856	19,299	15,116	5,894	2,377	190	0	45,159
1953	23	47	211	141	938	4,526	21,924	11,584	914	328	258	40,894
1954	0	356	1,703	555	1,664	3,208	24,161	20,754	1,941	198	40	54,579
1955	17	1,268	10,569	23,579	7,538	14,425	13,817	52,403	8,884	261	78	132,840
1956	0	40	12,827	44,818	10,885	11,508	36,139	39,911	23,520	1,694	200	181,543
1957	0	186	4,262	7,418	19,432	33,447	25,259	14,363	28,763	5,678	261	139,069
1958	16,663	2,419	11,645	23,260	1,849	12,795	12,615	11,905	8,067	10,146	860	112,222
1959	0	4,589	4,589	27,159	47,901	31,617	12,871	2,182	1,604	858	37	133,406
1960	0	0	84	2,398	39,256	48,401	16,254	5,939	390	112	56	112,889
1961	0	0	194	1,131	3,957	24,149	29,838	25,333	2,597	742	936	88,878
1962	0	141	1,167	436	318	5,753	23,213	34,648	13,734	908	59	80,379
1963	0	262	2,571	6,990	9,807	1,185	6,343	21,492	22,585	4,403	277	75,916
1964	0	0	480	31,991	9,514	5,344	986	15,048	22,427	4,877	455	91,121
1965	0	29	146	732	12,819	3,936	3,366	6,863	35,018	14,487	322	77,720
1966	0	0	85,574	132,598	23,300	424	424	1,271	424	0	0	244,013
1967	143	0	0	0	2,141	4,424	13,559	34,539	1,142	571	285	56,804
1968	0	0	2,681	17,160	27,215	39,415	3,352	3,486	670	134	268	94,383
1969	19	777	27,730	3,017	4,461	12,144	7,812	648	130	185	389	57,312
1970	0	387	33,464	12,999	6,461	1,896	4,604	696	0	77	39	60,621
1971	0	8,947	29,929	17,271	5,199	1,004	1,354	3,063	418	93	33	67,310
1972	0	490	20,703	2,386	9,568	7,609	2,010	2,897	1,039	164	22	46,887
1973	0	4,448	4,448	1,868	2,922	4,083	5,436	2,973	1,608	584	178	28,548
1974	242	33,553	156,142	10,698	3,592	5,094	4,829	5,736	1,677	1,026	324	222,912
1975	4,487	2,019	43,834	19,417	6,173	1,102	1,116	1,390	254	23	20	79,835
1976	490	2,577	72,165	20,253	14,654	6,196	658	259	96	22	22	117,393
1977	29,085	4,974	60,221	103,076	29,240	16,356	5,841	710	194	55	9	249,762
1978	8	97	14,328	917	11,243	60,844	22,485	5,616	581	830	1,885	118,833
1979	0	3,629	78,034	43,589	11,562	11,964	27,192	5,581	342	121	31	182,046
1980	1,021	48,576	176,619	43,636	13,169	7,195	3,409	13,730	1,996	1,033	1,226	311,611
1981	157	135,821	639,869	166,961	22,656	7,919	4,046	2,120	3,587	572	146	983,855
1982	44,859	227,809	377,183	99,221	81,500	26,707	5,025	4,434	2,173	2,744	1,277	872,931
1983	8,421	50,617	78,651	2,830	2,366	6,314	5,052	1,971	1,066	800	1,053	159,140
1984	1,584	9,024	91,819	6,661	5,446	1,957	476	879	497	647	1,018	120,010
1985	3,077	50,969	211,728	20,979	4,642	1,707	441	137	387	1,057	859	295,982
1986	29,008	262,479	91,500	20,646	4,445	1,649	241	244	568	496	143	411,419
1987	4,537	73,854	92,084	30,015	6,159	3,440	1,455	156	129	263	400	212,492
1988	2,958	19,288	71,039	19,545	26,024	489	222	48	4	6	2	139,626
1989	3,101	26,574	88,915	42,426	6,024	2,539	674	437	80	36	72	170,877
1990	6,775	28,261	83,444	13,084	5,954	2,886	2,032	684	62	16	11	143,209
1991	15,016	71,727	76,611	27,023	11,254	5,243	2,013	808	641	346	279	210,960
1992	31	53,627	80,681	6,171	10,029	5,782	4,444	1,511	202	62	17	162,555
1993	1,096	0	9,167	22,741	3,754	13,437	24,699	7,922	1,868	269	108	85,062
1994	51,481	8,953	5,436	6,936	9,977	12,223	19,458	13,436	1,650	139	20	129,710
1995	36,447	1,350	10,462	872	2,044	18,699	11,465	11,194	3,474	743	172	96,922
1996	0	84,745	59,322	9,505	2,489	1,377	8,870	3,733	1,880	530	26	172,476
1997	28,782	0	98,682	15,129	3,165	3,808	2,382	5,947	1,617	504	17	160,036
1998	2,409	955	49,541	18,198	22,193	7,989	8,716	5,246	3,995	605	0	119,847
1999	3,564	252	30,358	34,360	22,287	30,427	6,311	6,067	3,049	2,439	579	139,693
2000	0	0	21,127	30,164	9,397	10,397	15,003	2,211	1,079	1,132	816	91,326
2001	113,226	0	29,147	3,616	706	5,569	5,984	4,322	353	145	145	163,215
2002	1,643	0	2,793	3,797	8,240	7,300	11,234	3,405	881	39	20	39,352
2003	56	650	8,319	566	740	1,838	1,468	576	294	65	11	14,583
2004	14,407	23	1,093	1,502	865	3,869	6,601	4,985	2,026	1,912	2,504	39,785

Appendix II-3. Estimated catch at age in number for age 0 – age 10+ of bluefin tuna in the Sea of Japan in summer by Japanese purse seine fishery. (Data were adopted from Yamada et al. 2006)

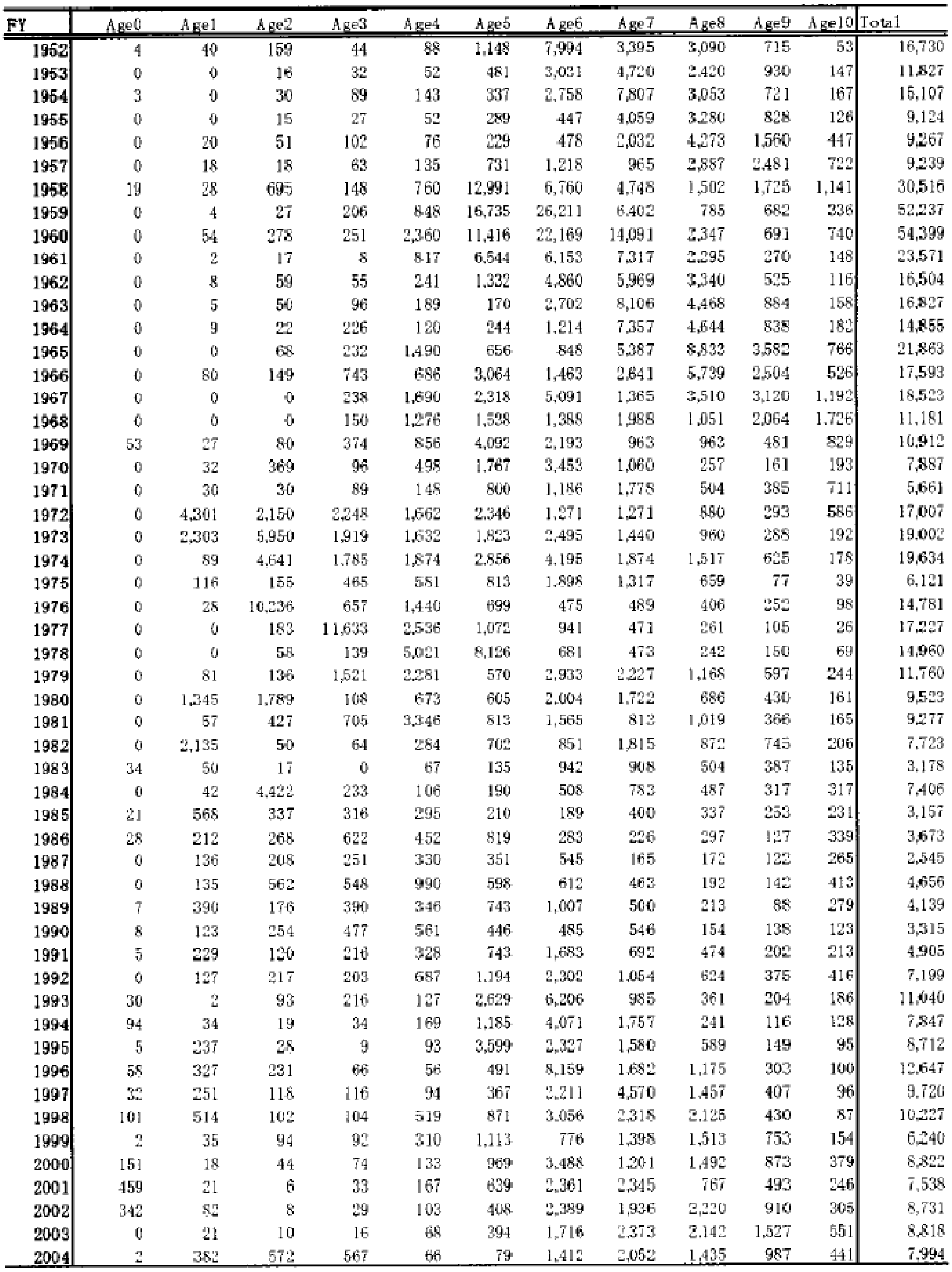
FY	Age0	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10	Total
1952	0	0	0	0	0	0	0	0	0	0	0	0
1953	0	0	0	0	0	0	0	0	0	0	0	0
1954	0	0	0	0	0	0	0	0	0	0	0	0
1955	0	0	0	0	0	0	0	0	0	0	0	0
1956	0	0	0	0	0	0	0	0	0	0	0	0
1957	0	0	0	0	0	0	0	0	0	0	0	0
1958	0	0	0	0	0	0	0	0	0	0	0	0
1959	0	0	0	0	0	0	0	0	0	0	0	0
1960	0	0	0	0	0	0	0	0	0	0	0	0
1961	0	0	0	0	0	0	0	0	0	0	0	0
1962	0	0	0	0	0	0	0	0	0	0	0	0
1963	0	0	0	0	0	0	0	0	0	0	0	0
1964	0	0	0	0	0	0	0	0	0	0	0	0
1965	0	0	0	0	0	0	0	0	0	0	0	0
1966	0	0	0	0	0	0	0	0	0	0	0	0
1967	0	0	0	0	0	0	0	0	0	0	0	0
1968	0	0	0	0	0	0	0	0	0	0	0	0
1969	0	0	0	0	0	0	0	0	0	0	0	0
1970	0	0	0	0	0	0	0	0	0	0	0	0
1971	0	0	0	0	0	0	0	0	0	0	0	0
1972	0	0	0	0	0	0	0	0	0	0	0	0
1973	0	0	0	0	0	0	0	0	0	0	0	0
1974	0	0	0	0	0	0	0	0	0	0	0	0
1975	0	0	0	0	0	0	0	0	0	0	0	0
1976	0	0	0	0	0	0	0	0	0	0	0	0
1977	0	0	0	0	0	0	0	0	0	0	0	0
1978	0	0	0	0	0	0	0	0	0	0	0	0
1979	0	0	0	0	0	0	0	0	0	0	0	0
1980	0	10	190	498	522	514	425	409	128	53	36	2,786
1981	0	47	916	2,399	2,514	2,474	2,044	1,970	618	255	174	13,411
1982	0	71	1,377	3,606	3,780	3,719	3,073	2,961	930	383	261	20,160
1983	0	25	478	1,253	1,314	1,293	1,068	1,029	323	133	91	7,007
1984	0	35	683	1,790	1,876	1,846	1,526	1,470	462	190	130	10,008
1985	0	16	314	822	861	848	700	675	212	87	59	4,595
1986	0	0	0	0	0	0	0	0	0	0	0	0
1987	0	13	248	650	681	670	554	534	168	69	47	3,633
1988	0	23	452	1,184	1,241	1,221	1,009	972	305	126	86	6,620
1989	0	12	234	614	643	633	523	504	158	65	44	3,432
1990	0	0	0	0	0	0	0	0	0	0	0	0
1991	0	10	191	501	525	517	427	411	129	53	36	2,800
1992	0	0	65	3,567	531	744	542	588	119	119	28	6,305
1993	0	0	163	3,874	1,451	343	111	45	15	6	15	6,023
1994	0	0	10	1,735	7,368	207	184	107	36	19	3	9,669
1995	0	0	4	326	416	4,229	622	456	119	62	43	6,277
1996	0	0	0	24	731	496	2,697	398	70	33	25	4,472
1997	0	46	2,456	1,944	170	310	388	4,521	369	78	40	10,321
1998	0	143	1,816	1,183	1,015	24	38	233	349	84	16	4,901
1999	0	35	731	101	2,358	3,205	29	52	217	287	32	7,047
2000	0	0	0	211	271	3,240	3,102	86	131	480	269	7,788
2001	0	0	0	33	156	156	658	1,080	35	31	58	2,206
2002	0	0	0	223	506	444	652	2,158	1,717	179	310	6,191
2003	0	0	1,764	2,054	1,563	801	173	302	415	559	197	7,828
2004	0	0	1,467	20,343	5,512	7,321	3,215	1,124	733	1,436	942	42,095

Appendix II-4. Estimated catch at age in number for age 0 – age 10+ of bluefin tuna in the Sea of Japan in winter by Japanese purse seine fishery. (Data were adopted from Yamada et al. 2006)



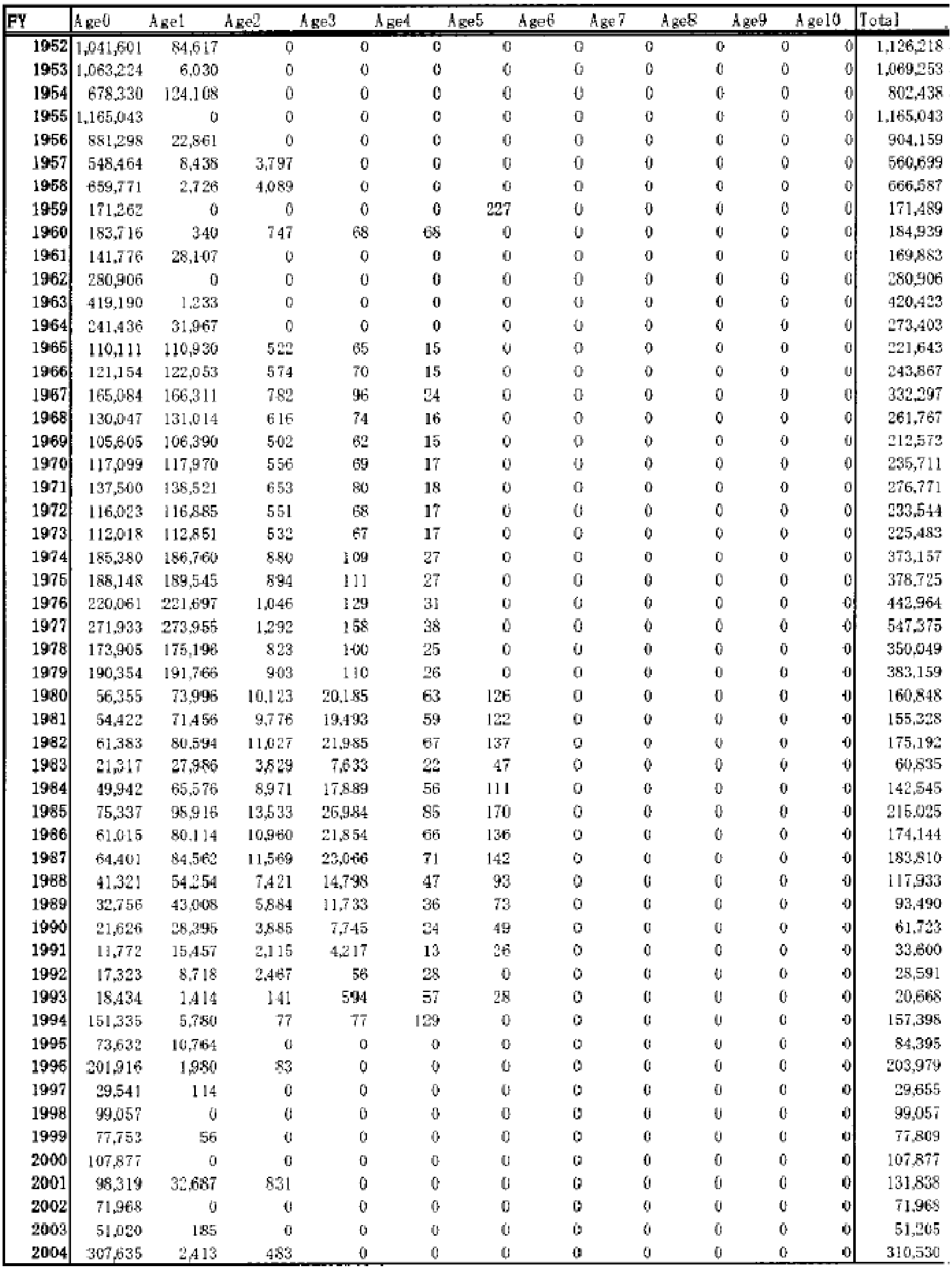
FY	Age0	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10	Total
1952												0
1953												0
1954												0
1955												0
1956												0
1957												0
1958												0
1959												0
1960												0
1961												0
1962												0
1963												0
1964												0
1965												0
1966												0
1967												0
1968												0
1969												0
1970												0
1971												0
1972												0
1973												0
1974												0
1975												0
1976												0
1977												0
1978												0
1979												0
1980												0
1981												0
1982												0
1983												0
1984												0
1985												0
1986												0
1987												0
1988												0
1989	0	0	0	0	0	0	0	0	0	0	0	0
1990	20,789	3,724	442	46	1	0	0	0	0	0	0	25001.9
1991	1,053,958	527,796	3,448	237	35	0	0	0	0	0	0	1585474
1992	251,655	80,741	2,997	300	17	0	0	0	0	0	0	335710.9
1993	113,718	26,137	338	24	9	0	0	0	0	0	0	140227.1
1994	141,072	36,366	2,044	222	8	0	0	0	0	0	0	179712.7
1995	859,233	2,085,526	7,808	678	31	0	0	0	0	0	0	2953276
1996	469,225	46,865	600	127	88	0	0	0	0	0	0	516904.8
1997	206,123	898,730	7,371	506	8	0	0	0	0	0	0	1112738
1998	303,979	229,660	14,616	56	2	0	0	0	0	0	0	548313.9
1999	754,836	475,436	3,648	3,345	235	0	0	0	0	0	0	1237500
2000	1,551,300	877,133	3,438	242	300	0	0	0	0	0	0	2432413
2001	730,847	156,766	3,828	0	0	0	0	0	0	0	0	891440.7
2002	646,337	576,422	0	0	0	0	0	0	0	0	0	1,222,759
2003	406,782	451,381	5,780	91	0	0	0	0	0	0	0	864,034
2004	1,125,214	28,837	1,193	25	0	0	0	0	0	0	0	1,155,268

Appendix II-5. Estimated catch at age in number for age 0 – age 10+ of bluefin tuna in the North Pacific Ocean by Japanese longline fishery. (Data were adopted from Yamada et al. 2006)



FY	Age0	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10	Total
1952	4	40	159	44	88	1,148	7,994	3,395	3,090	715	53	16,730
1953	0	0	16	32	52	481	3,031	4,720	2,420	930	147	11,827
1954	3	0	30	89	143	337	2,758	7,807	3,053	721	167	15,107
1955	0	0	15	27	52	289	447	4,059	3,280	828	126	9,124
1956	0	20	51	102	76	229	478	2,032	4,273	1,560	447	9,267
1957	0	18	18	63	135	731	1,218	965	2,887	2,481	722	9,239
1958	19	28	695	148	760	12,991	6,760	4,748	1,502	1,725	1,141	30,516
1959	0	4	27	206	848	16,735	26,211	6,402	785	682	336	52,237
1960	0	54	278	251	2,360	11,416	22,169	14,091	2,347	691	740	54,399
1961	0	2	17	8	817	6,544	6,153	7,317	2,295	270	148	23,571
1962	0	8	59	55	241	1,332	4,860	5,969	3,340	525	116	16,504
1963	0	5	50	96	189	170	2,702	8,106	4,468	884	158	16,827
1964	0	9	22	226	120	244	1,214	7,357	4,644	838	182	14,855
1965	0	0	68	232	1,490	656	848	5,387	8,832	3,582	766	21,863
1966	0	80	149	743	686	3,064	1,463	2,641	5,739	2,504	526	17,593
1967	0	0	0	238	1,690	2,318	5,091	1,365	3,510	3,120	1,192	18,523
1968	0	0	0	150	1,276	1,538	1,388	1,988	1,051	2,064	1,726	11,181
1969	53	27	80	374	856	4,092	2,193	963	963	481	829	10,912
1970	0	32	369	96	498	1,767	3,453	1,060	257	161	193	7,887
1971	0	30	30	89	148	800	1,186	1,778	504	385	711	5,661
1972	0	4,301	2,150	2,248	1,662	2,346	1,271	1,271	880	293	586	17,007
1973	0	2,303	5,950	1,919	1,632	1,823	2,495	1,440	960	288	192	19,002
1974	0	89	4,641	1,785	1,874	2,856	4,195	1,874	1,517	625	178	19,634
1975	0	116	155	465	581	813	1,898	1,317	659	77	39	6,121
1976	0	28	10,236	657	1,440	699	475	489	406	252	98	14,781
1977	0	0	183	11,633	2,536	1,072	941	471	261	105	26	17,227
1978	0	0	58	139	5,021	8,126	681	473	242	150	69	14,960
1979	0	81	136	1,521	2,281	570	2,933	2,227	1,168	597	244	11,760
1980	0	1,345	1,789	108	673	605	2,004	1,722	686	430	161	9,523
1981	0	57	427	705	3,346	813	1,565	812	1,019	366	165	9,277
1982	0	2,135	50	64	284	702	851	1,815	872	745	206	7,723
1983	34	50	17	0	67	135	942	908	504	387	135	3,178
1984	0	42	4,422	233	106	190	508	783	487	317	317	7,406
1985	21	568	337	316	295	210	189	400	337	253	231	3,157
1986	28	212	268	622	452	819	283	226	297	127	339	3,673
1987	0	136	208	251	330	351	545	165	172	122	265	2,545
1988	0	135	562	548	990	598	612	463	192	142	413	4,656
1989	7	390	176	390	346	743	1,007	500	213	88	279	4,139
1990	8	123	254	477	561	446	485	546	154	138	123	3,315
1991	5	229	120	216	328	743	1,683	692	474	202	213	4,905
1992	0	127	217	203	687	1,194	2,302	1,054	624	375	416	7,199
1993	30	2	93	216	127	2,629	6,206	985	361	204	186	11,040
1994	94	34	19	34	169	1,185	4,071	1,757	241	116	128	7,847
1995	5	237	28	9	93	3,599	2,327	1,580	589	149	95	8,712
1996	58	327	231	66	56	491	8,159	1,682	1,175	303	100	12,647
1997	32	251	118	116	94	367	2,211	4,570	1,457	407	96	9,720
1998	101	514	102	104	519	871	3,056	2,318	2,125	430	87	10,227
1999	2	35	94	92	310	1,113	776	1,398	1,513	753	154	6,240
2000	151	18	44	74	133	969	3,488	1,201	1,492	873	379	8,822
2001	459	21	6	33	167	639	2,361	2,345	767	493	246	7,538
2002	342	82	8	29	103	408	2,389	1,936	2,220	910	305	8,731
2003	0	21	10	16	68	394	1,716	2,373	2,142	1,527	551	8,818
2004	2	382	572	567	66	79	1,412	2,052	1,435	987	441	7,994

Appendix II-6. Estimated catch at age in number for age 0 – age 10+ of bluefin tuna in the North Pacific Ocean by Japanese pole and line fishery. (Data were adopted from Yamada et al. 2006)

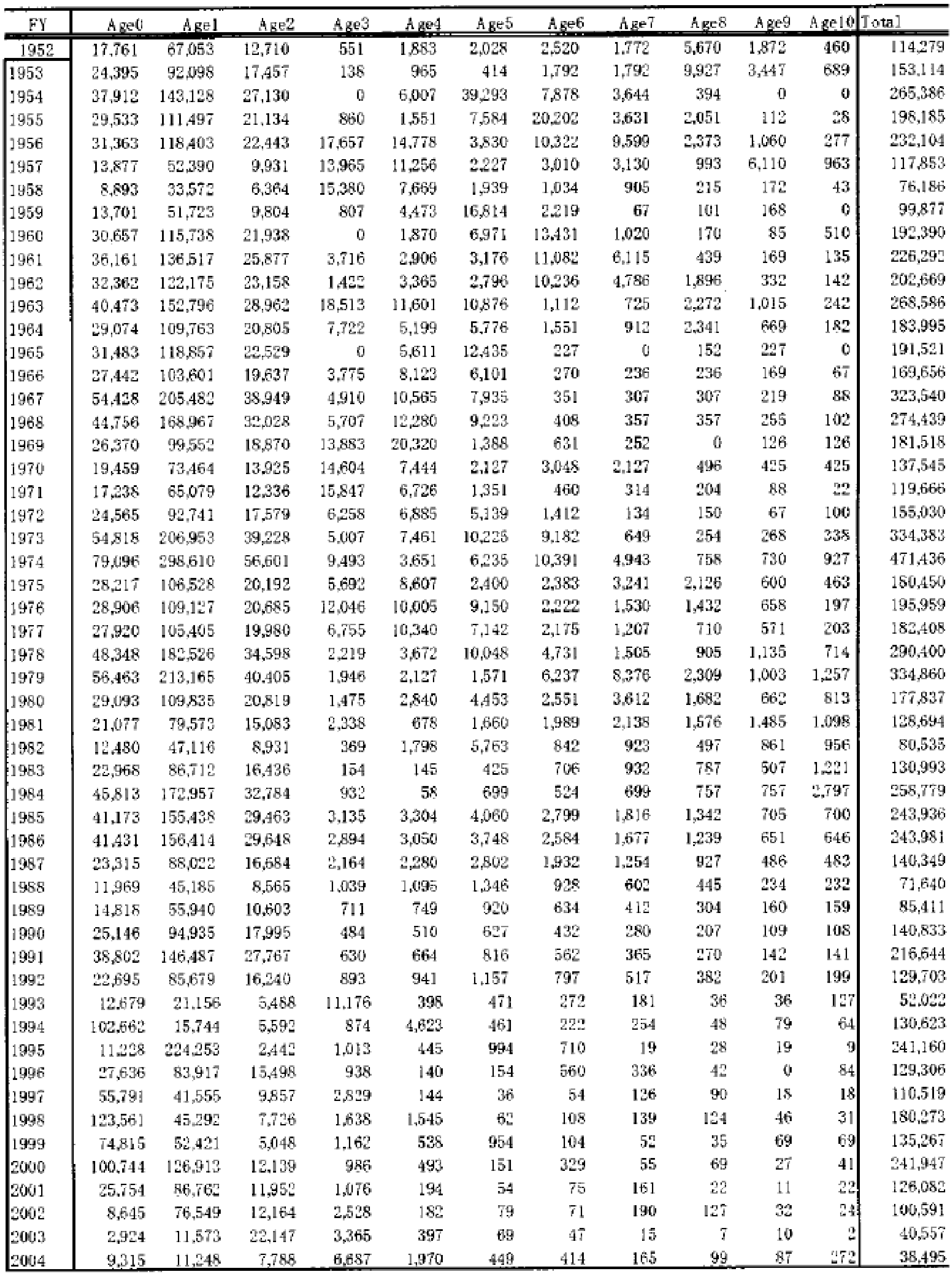


FY	Age0	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10	Total
1952	1,041,601	84,617	0	0	0	0	0	0	0	0	0	1,126,218
1953	1,063,224	6,030	0	0	0	0	0	0	0	0	0	1,069,253
1954	678,330	124,108	0	0	0	0	0	0	0	0	0	802,438
1955	1,165,043	0	0	0	0	0	0	0	0	0	0	1,165,043
1956	881,298	22,861	0	0	0	0	0	0	0	0	0	904,159
1957	548,464	8,438	3,797	0	0	0	0	0	0	0	0	560,699
1958	659,771	2,726	4,089	0	0	0	0	0	0	0	0	666,587
1959	171,262	0	0	0	0	227	0	0	0	0	0	171,489
1960	183,716	340	747	68	68	0	0	0	0	0	0	184,939
1961	141,776	28,107	0	0	0	0	0	0	0	0	0	169,883
1962	280,906	0	0	0	0	0	0	0	0	0	0	280,906
1963	419,190	1,233	0	0	0	0	0	0	0	0	0	420,423
1964	241,436	31,967	0	0	0	0	0	0	0	0	0	273,403
1965	110,111	110,930	522	65	15	0	0	0	0	0	0	221,643
1966	121,154	122,053	574	70	15	0	0	0	0	0	0	243,867
1967	165,084	166,311	782	96	24	0	0	0	0	0	0	332,297
1968	130,047	131,014	616	74	16	0	0	0	0	0	0	261,767
1969	105,605	106,390	502	62	15	0	0	0	0	0	0	212,573
1970	117,099	117,970	556	69	17	0	0	0	0	0	0	235,711
1971	137,500	138,521	653	80	18	0	0	0	0	0	0	276,771
1972	116,023	116,885	551	68	17	0	0	0	0	0	0	233,544
1973	112,018	112,851	532	67	17	0	0	0	0	0	0	225,483
1974	185,380	186,760	880	109	27	0	0	0	0	0	0	373,157
1975	188,148	189,545	894	111	27	0	0	0	0	0	0	378,725
1976	220,061	221,697	1,046	129	31	0	0	0	0	0	0	442,964
1977	271,933	273,955	1,292	158	38	0	0	0	0	0	0	547,375
1978	173,905	175,196	823	100	25	0	0	0	0	0	0	350,049
1979	190,354	191,766	903	110	26	0	0	0	0	0	0	383,159
1980	56,355	73,996	10,123	20,185	63	126	0	0	0	0	0	160,848
1981	54,422	71,456	9,776	19,493	59	122	0	0	0	0	0	155,328
1982	61,383	80,594	11,027	21,985	67	137	0	0	0	0	0	175,192
1983	21,317	27,986	3,829	7,633	22	47	0	0	0	0	0	60,835
1984	49,942	65,576	8,971	17,889	56	111	0	0	0	0	0	142,545
1985	75,337	98,916	13,533	26,984	85	170	0	0	0	0	0	215,025
1986	61,015	80,114	10,960	21,854	66	136	0	0	0	0	0	174,144
1987	64,401	84,562	11,569	23,066	71	142	0	0	0	0	0	183,810
1988	41,321	54,254	7,421	14,798	47	93	0	0	0	0	0	117,933
1989	32,756	43,008	5,884	11,733	36	73	0	0	0	0	0	93,490
1990	21,626	28,395	3,885	7,745	24	49	0	0	0	0	0	61,723
1991	11,772	15,457	2,115	4,217	13	26	0	0	0	0	0	33,600
1992	17,323	8,718	2,467	56	28	0	0	0	0	0	0	28,591
1993	18,434	1,414	141	594	57	28	0	0	0	0	0	20,668
1994	151,335	5,780	77	77	129	0	0	0	0	0	0	157,398
1995	73,632	10,764	0	0	0	0	0	0	0	0	0	84,395
1996	201,916	1,980	83	0	0	0	0	0	0	0	0	203,979
1997	29,541	114	0	0	0	0	0	0	0	0	0	29,655
1998	99,057	0	0	0	0	0	0	0	0	0	0	99,057
1999	77,753	56	0	0	0	0	0	0	0	0	0	77,809
2000	107,877	0	0	0	0	0	0	0	0	0	0	107,877
2001	98,319	32,687	831	0	0	0	0	0	0	0	0	131,838
2002	71,968	0	0	0	0	0	0	0	0	0	0	71,968
2003	51,020	185	0	0	0	0	0	0	0	0	0	51,205
2004	307,635	2,413	483	0	0	0	0	0	0	0	0	310,530

Appendix II-7. Estimated catch at age in number for age 0 – age 10+ of bluefin tuna in the North Pacific Ocean by Japanese troll fishery. (Data were adopted from Yamada et al. 2006)

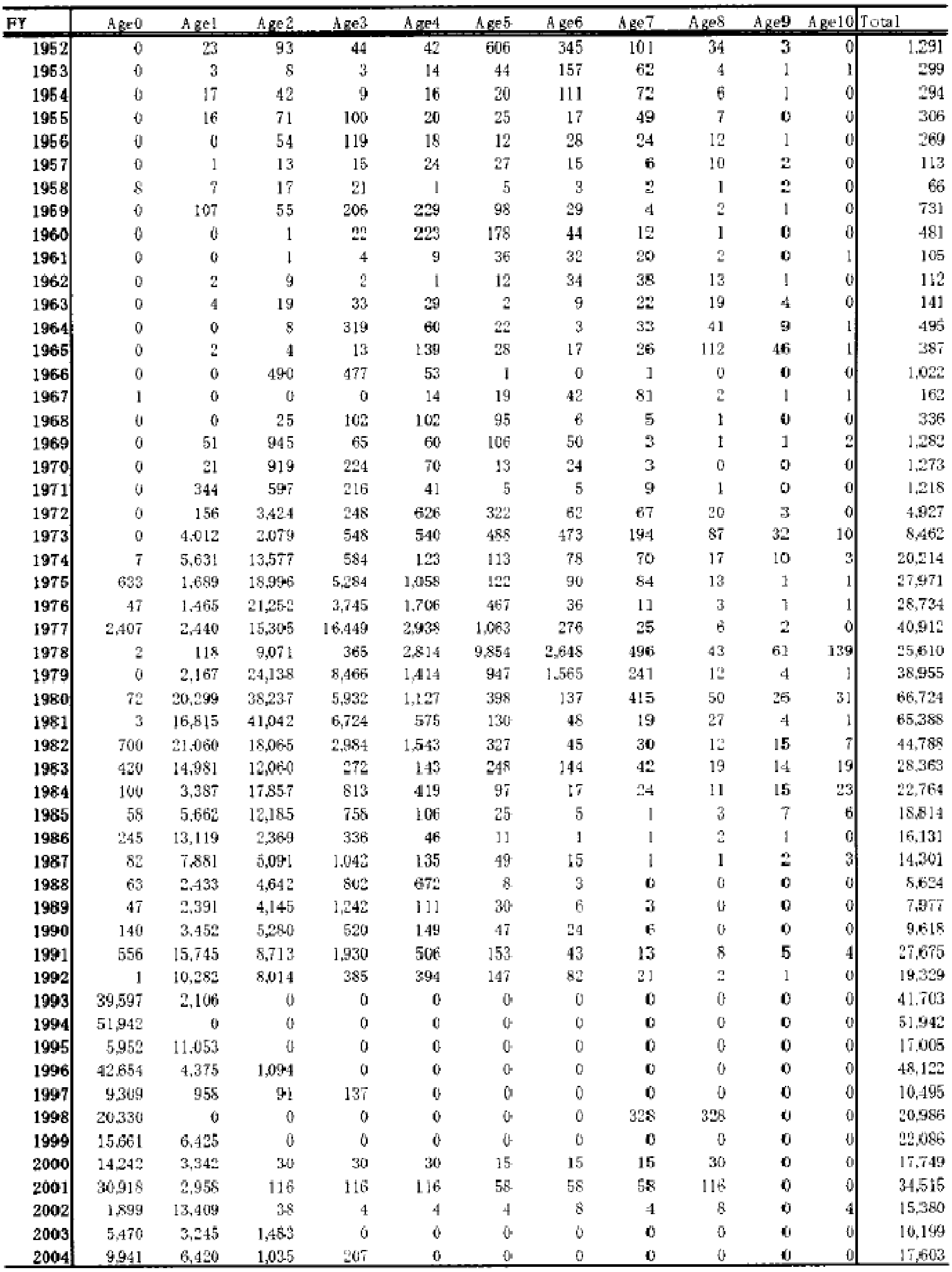
FY	Age0	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10	Total
1952	160,658	39,061	7,112	1,920	448	110	57	52	5	9	13	209,447
1953	291,936	70,980	12,924	3,489	813	201	104	95	10	17	24	380,593
1954	302,385	73,520	13,387	3,613	842	208	108	98	10	18	24	394,215
1955	304,955	74,145	13,501	3,644	850	210	109	99	10	18	25	397,565
1956	381,914	92,856	16,908	4,564	1,064	262	136	124	13	22	31	497,894
1957	386,618	94,000	17,116	4,620	1,077	266	138	125	13	22	31	504,028
1958	248,134	60,330	10,985	2,965	691	171	89	81	8	14	20	323,488
1959	254,563	61,893	11,270	3,042	709	175	91	83	9	15	21	331,870
1960	445,637	108,350	19,729	5,325	1,242	306	159	145	15	26	36	580,969
1961	428,570	104,200	18,973	5,121	1,194	294	153	139	15	25	35	558,720
1962	292,931	71,222	12,968	3,500	816	201	105	95	10	17	24	381,889
1963	480,588	116,848	21,276	5,743	1,339	330	172	156	16	28	39	626,535
1964	419,773	102,061	18,584	5,016	1,170	288	150	136	14	24	34	547,251
1965	276,173	67,147	12,226	3,300	769	190	99	90	9	16	22	360,042
1966	406,340	98,795	17,989	4,856	1,132	279	145	132	14	24	33	529,738
1967	460,885	112,057	20,404	5,508	1,284	317	165	150	16	27	37	600,848
1968	298,937	72,682	13,234	3,572	833	205	107	97	10	17	24	389,719
1969	298,300	72,527	13,206	3,565	831	205	107	97	10	17	24	388,889
1970	299,877	72,910	13,276	3,583	835	206	107	97	10	17	24	390,945
1971	429,356	104,391	19,008	5,131	1,196	295	153	139	15	25	35	559,745
1972	537,399	130,660	23,791	6,422	1,497	369	192	174	18	31	44	700,598
1973	626,885	152,417	27,753	7,491	1,747	431	224	203	21	36	51	817,259
1974	411,952	100,160	18,237	4,923	1,148	283	147	134	14	24	33	537,055
1975	176,621	42,943	7,819	2,111	492	121	63	57	6	10	14	230,258
1976	273,325	66,455	12,100	3,266	762	188	98	89	9	16	22	356,329
1977	613,431	149,146	27,157	7,330	1,709	422	219	199	21	36	50	799,719
1978	742,524	180,533	32,872	8,873	2,069	510	265	241	25	43	60	968,016
1979	415,631	101,054	18,400	4,967	1,158	286	148	135	14	24	34	541,852
1980	302,900	73,645	13,410	3,620	844	208	108	98	10	18	25	394,885
1981	266,008	64,676	11,776	3,179	741	183	95	86	9	15	22	346,791
1982	251,885	61,242	11,151	3,010	702	173	90	82	9	15	20	328,379
1983	373,917	90,912	16,554	4,468	1,042	257	134	121	13	22	30	487,470
1984	362,041	88,025	16,028	4,326	1,009	249	129	118	12	21	29	471,987
1985	336,667	81,855	14,905	4,023	938	231	120	109	12	20	27	438,907
1986	255,653	62,158	11,318	3,055	712	176	91	83	9	15	21	333,291
1987	207,209	50,380	9,173	2,476	577	142	74	67	7	12	17	270,135
1988	212,955	51,777	9,428	2,545	593	146	76	69	7	12	17	277,626
1989	214,215	52,083	9,483	2,560	597	147	77	70	7	12	17	279,269
1990	310,844	75,577	13,761	3,715	866	214	111	101	11	18	25	405,242
1991	315,455	76,698	13,965	3,770	879	217	113	102	11	18	26	411,253
1992	96,091	25,019	9,835	1,898	518	0	0	86	0	0	0	135,446
1993	114,270	5,163	412	1,609	337	224	37	0	0	0	0	122,053
1994	2,386,098	33,852	21,795	1,159	696	0	0	0	0	0	232	2,443,832
1995	168,295	128,498	2,785	4,981	1,339	750	321	214	0	54	54	307,291
1996	800,797	88,882	51,634	5,223	3,083	685	1,456	1,541	257	171	514	954,243
1997	369,440	118,968	18,394	10,310	1,409	74	0	74	0	0	0	518,669
1998	948,965	57,272	14,634	6,017	4,234	149	223	149	74	74	0	1,031,790
1999	822,084	204,275	38,530	10,629	2,491	830	166	0	0	166	0	1,079,172
2000	1,172,551	175,943	10,008	400	200	0	0	0	0	0	0	1,359,102
2001	2,113,247	35,495	1,566	2,349	261	0	261	0	0	0	0	2,153,179
2002	317,979	323,707	279	419	0	140	0	0	0	0	0	642,524
2003	36,686	43,689	15,356	193	43	0	0	0	0	0	0	95,967
2004	681,887	76,241	32,335	24,727	2,853	476	159	0	0	0	0	818,676

Appendix II-8. Estimated catch at age in number for age 0 – age 10+ of bluefin tuna in the North Pacific Ocean by Japanese set net fishery. (Data were adopted from Yamada et al. 2006)



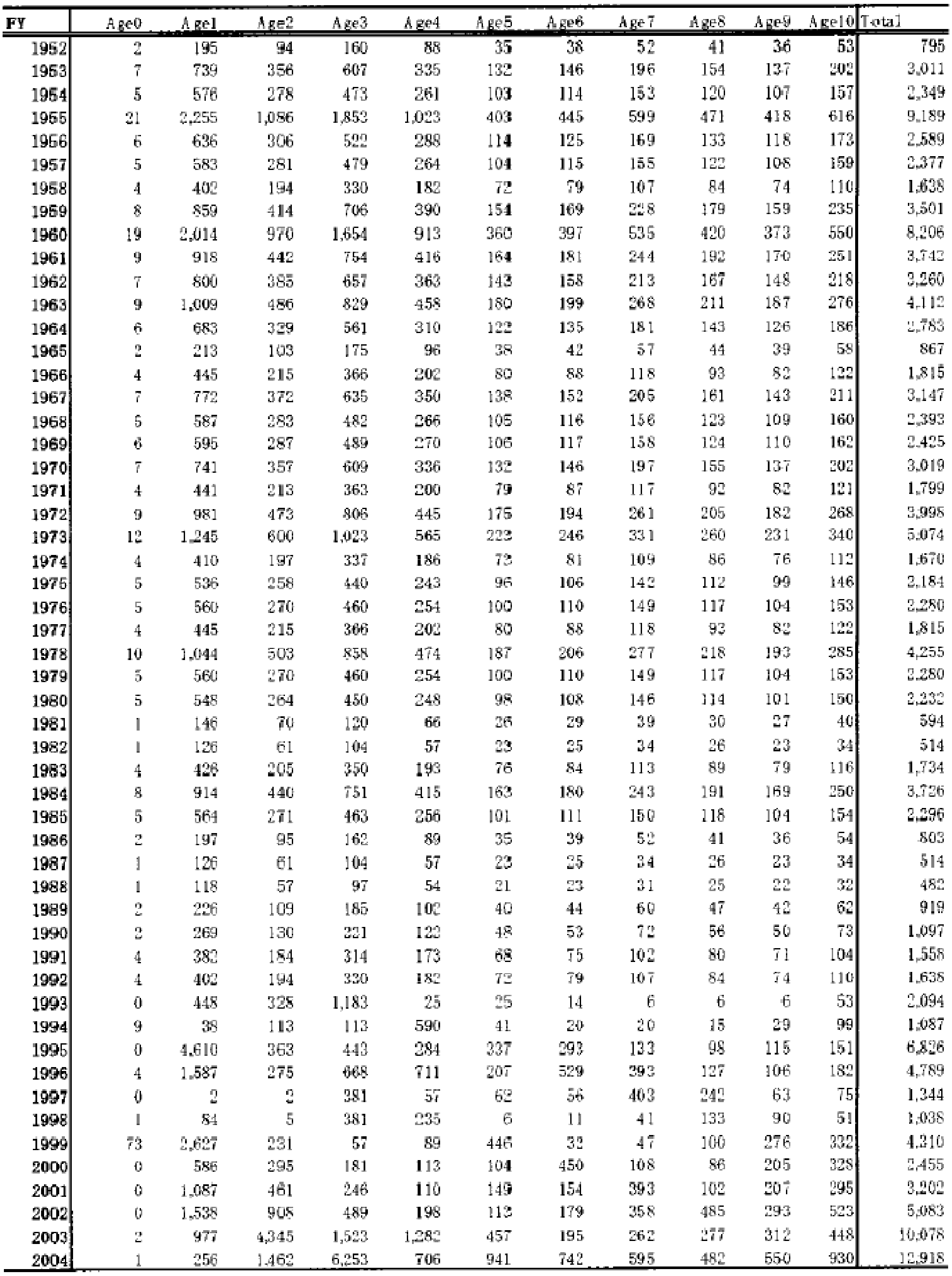
FY	Age0	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10	Total
1952	17,761	67,053	12,710	551	1,883	2,028	2,520	1,772	5,670	1,872	460	114,279
1953	24,395	92,098	17,457	138	965	414	1,792	1,792	9,927	3,447	689	153,114
1954	37,912	143,128	27,130	0	6,007	39,293	7,878	3,644	394	0	0	265,386
1955	29,533	111,497	21,134	860	1,551	7,584	20,202	3,631	2,051	112	28	198,185
1956	31,363	118,403	22,443	17,657	14,778	3,830	10,322	9,599	2,373	1,060	277	232,104
1957	13,877	52,390	9,931	13,965	11,256	2,227	3,010	3,130	993	6,110	963	117,853
1958	8,893	33,572	6,364	15,380	7,669	1,939	1,034	905	215	172	43	76,186
1959	13,701	51,723	9,804	807	4,473	16,814	2,219	67	101	168	0	99,877
1960	30,657	115,738	21,938	0	1,870	6,971	13,431	1,020	170	85	510	192,390
1961	36,161	136,517	25,877	3,716	2,906	3,176	11,082	6,115	439	169	135	226,292
1962	32,362	122,175	23,158	1,422	3,365	2,796	10,236	4,786	1,896	332	142	202,669
1963	40,473	152,796	28,962	18,513	11,601	10,876	1,112	725	2,272	1,015	242	268,586
1964	29,074	109,763	20,805	7,722	5,199	5,776	1,551	912	2,341	669	182	183,995
1965	31,483	118,857	22,529	0	5,611	12,435	227	0	152	227	0	191,521
1966	27,442	103,601	19,637	3,775	8,123	6,101	270	236	236	169	67	169,656
1967	54,428	205,482	38,949	4,910	10,565	7,935	351	307	307	219	88	323,540
1968	44,756	168,967	32,028	5,707	12,280	9,223	408	357	357	255	102	274,439
1969	26,370	99,552	18,870	13,883	20,320	1,388	631	252	0	126	126	181,518
1970	19,459	73,464	13,925	14,604	7,444	2,127	3,048	2,127	496	425	425	137,545
1971	17,238	65,079	12,336	15,847	6,726	1,351	460	314	204	88	22	119,666
1972	24,565	92,741	17,579	6,258	6,885	5,139	1,412	134	150	67	100	155,030
1973	54,818	206,953	39,228	5,007	7,461	10,225	9,182	649	254	268	338	334,383
1974	79,096	298,610	56,601	9,493	3,651	6,235	10,391	4,943	758	730	927	471,436
1975	28,217	106,528	20,192	5,692	8,607	2,400	2,383	3,241	2,126	600	463	180,450
1976	28,906	109,127	20,685	12,046	10,005	9,150	2,222	1,530	1,432	658	197	195,959
1977	27,920	105,405	19,980	6,755	10,340	7,142	2,175	1,207	710	571	203	182,408
1978	48,348	182,526	34,598	2,219	3,672	10,048	4,731	1,505	905	1,135	714	290,400
1979	56,463	213,165	40,405	1,946	2,127	1,571	6,237	8,376	2,309	1,003	1,257	334,860
1980	29,093	109,835	20,819	1,475	2,840	4,453	2,551	3,612	1,682	662	813	177,837
1981	21,077	79,573	15,083	2,338	678	1,660	1,989	2,138	1,576	1,485	1,098	128,694
1982	12,480	47,116	8,931	369	1,798	5,763	842	923	497	861	956	80,535
1983	22,968	86,712	16,436	154	145	425	706	932	787	507	1,221	130,993
1984	45,813	172,957	32,784	932	58	699	524	699	757	757	2,797	258,779
1985	41,173	155,438	29,463	3,135	3,304	4,060	2,799	1,816	1,342	705	700	243,936
1986	41,431	156,414	29,648	2,894	3,050	3,748	2,584	1,677	1,239	651	646	243,981
1987	23,315	88,022	16,684	2,164	2,280	2,802	1,932	1,254	927	486	483	140,349
1988	11,969	45,185	8,565	1,039	1,095	1,346	928	602	445	234	232	71,640
1989	14,818	55,940	10,603	711	749	920	634	412	304	160	159	85,411
1990	25,146	94,935	17,995	484	510	627	432	280	207	109	108	140,833
1991	38,802	146,487	27,767	630	664	816	562	365	270	142	141	216,644
1992	22,695	85,679	16,240	893	941	1,157	797	517	382	201	199	129,703
1993	12,679	21,156	5,488	11,176	398	471	272	181	36	36	127	52,022
1994	102,662	15,744	5,592	874	4,623	461	222	254	48	79	64	130,623
1995	11,228	224,253	2,442	1,013	445	994	710	19	28	19	9	241,160
1996	27,636	83,917	15,498	938	140	154	560	336	42	0	84	129,306
1997	55,791	41,555	9,857	2,829	144	36	54	126	90	18	18	110,519
1998	123,561	45,292	7,726	1,638	1,545	62	108	139	124	46	31	180,273
1999	74,815	52,421	5,048	1,162	538	954	104	52	35	69	69	135,267
2000	100,744	126,913	12,139	986	493	151	329	55	69	27	41	241,947
2001	25,754	86,762	11,952	1,076	194	54	75	161	22	11	22	126,082
2002	8,645	76,549	12,164	2,528	182	79	71	190	127	32	24	100,591
2003	2,924	11,573	22,147	3,365	397	69	47	15	7	10	2	40,557
2004	9,315	11,248	7,788	6,687	1,970	449	414	165	99	87	272	38,495

Appendix II-9. Estimated catch at age in number for age 0 – age 10+ of bluefin tuna in the North Pacific Ocean by Japanese drift net fishery. (Data were adopted from Yamada et al. 2006)



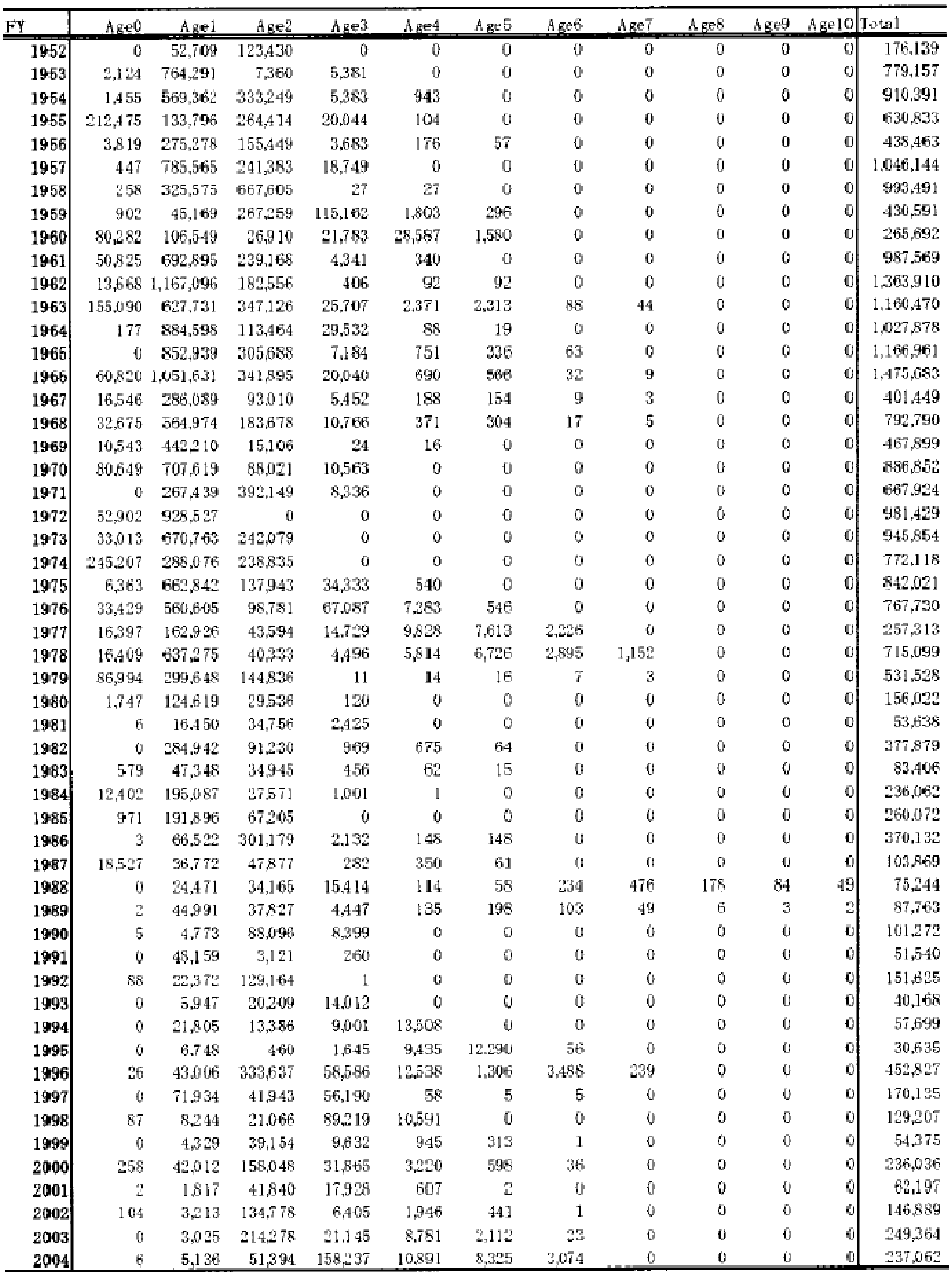
FY	Age0	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10	Total
1952	0	23	93	44	42	606	345	101	34	3	0	1,291
1953	0	3	8	3	14	44	157	62	4	1	1	299
1954	0	17	42	9	16	20	111	72	6	1	0	294
1955	0	16	71	100	20	25	17	49	7	0	0	306
1956	0	0	54	119	18	12	28	24	12	1	0	269
1957	0	1	13	15	24	27	15	6	10	2	0	113
1958	8	7	17	21	1	5	3	2	1	2	0	66
1959	0	107	55	206	229	98	29	4	2	1	0	731
1960	0	0	1	22	223	178	44	12	1	0	0	481
1961	0	0	1	4	9	36	32	20	2	0	1	105
1962	0	2	9	2	1	12	34	38	13	1	0	112
1963	0	4	19	33	29	2	9	22	19	4	0	141
1964	0	0	8	319	60	22	3	33	41	9	1	495
1965	0	2	4	13	139	28	17	26	112	46	1	387
1966	0	0	490	477	53	1	0	1	0	0	0	1,022
1967	1	0	0	0	14	19	42	81	2	1	1	162
1968	0	0	25	102	102	95	6	5	1	0	0	336
1969	0	51	945	65	60	106	50	3	1	1	2	1,282
1970	0	21	919	224	70	13	24	3	0	0	0	1,273
1971	0	344	597	216	41	5	5	9	1	0	0	1,218
1972	0	156	3,424	248	626	322	62	67	20	3	0	4,927
1973	0	4,012	2,079	548	540	488	473	194	87	32	10	8,462
1974	7	5,631	13,577	584	123	113	78	70	17	10	3	20,214
1975	633	1,689	18,996	5,284	1,058	122	90	84	13	1	1	27,971
1976	47	1,465	21,252	3,745	1,706	467	36	11	3	1	1	28,734
1977	2,407	2,440	15,305	16,449	2,938	1,063	276	25	6	2	0	40,912
1978	2	118	9,071	365	2,814	9,854	2,648	496	43	61	139	25,610
1979	0	2,167	24,138	8,466	1,414	947	1,565	241	12	4	1	38,955
1980	72	20,299	38,237	5,932	1,127	398	137	415	50	26	31	66,724
1981	3	16,815	41,042	6,724	575	130	48	19	27	4	1	65,388
1982	700	21,060	18,065	2,984	1,543	327	45	30	12	15	7	44,788
1983	420	14,981	12,060	272	143	248	144	42	19	14	19	28,363
1984	100	3,387	17,857	813	419	97	17	24	11	15	23	22,764
1985	58	5,662	12,185	756	106	25	5	1	3	7	6	18,814
1986	245	13,119	2,369	336	46	11	1	1	2	1	0	16,131
1987	82	7,881	5,091	1,042	135	49	15	1	1	2	3	14,301
1988	63	2,433	4,642	802	672	8	3	0	0	0	0	8,624
1989	47	2,391	4,145	1,242	111	30	6	3	0	0	0	7,977
1990	140	3,452	5,280	520	149	47	24	6	0	0	0	9,618
1991	556	15,745	8,713	1,930	506	153	43	13	8	5	4	27,675
1992	1	10,282	8,014	385	394	147	82	21	2	1	0	19,329
1993	39,597	2,106	0	0	0	0	0	0	0	0	0	41,703
1994	51,942	0	0	0	0	0	0	0	0	0	0	51,942
1995	5,952	11,053	0	0	0	0	0	0	0	0	0	17,005
1996	42,654	4,375	1,094	0	0	0	0	0	0	0	0	48,122
1997	9,309	958	91	137	0	0	0	0	0	0	0	10,495
1998	20,330	0	0	0	0	0	0	328	328	0	0	20,986
1999	15,661	6,425	0	0	0	0	0	0	0	0	0	22,086
2000	14,242	3,342	30	30	30	15	15	15	30	0	0	17,749
2001	30,918	2,958	116	116	116	58	58	58	116	0	0	34,515
2002	1,899	13,409	38	4	4	4	8	4	8	0	4	15,380
2003	5,470	3,245	1,483	0	0	0	0	0	0	0	0	10,199
2004	9,941	6,420	1,035	207	0	0	0	0	0	0	0	17,603

Appendix II-10. Estimated catch at age in number for age 0 – age 10+ of bluefin tuna in the Tsugaru Strait by Japanese handline fishery. (Data were adopted from Yamada et al. 2006)



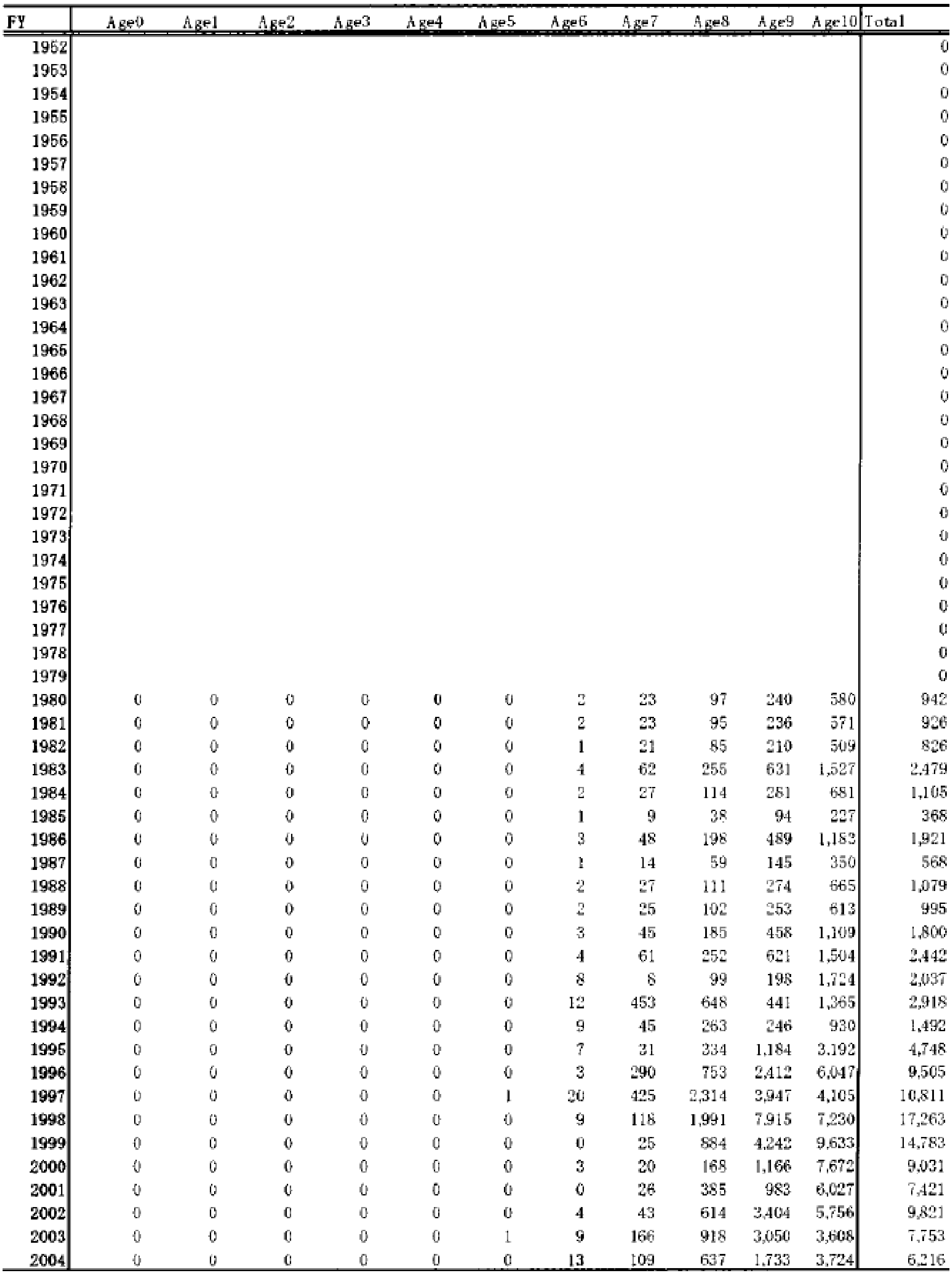
FY	Age0	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10	Total
1952	2	195	94	160	88	35	38	52	41	36	53	795
1953	7	739	356	607	335	132	146	196	154	137	202	3,011
1954	5	576	278	473	261	103	114	153	120	107	157	2,349
1955	21	2,255	1,086	1,853	1,023	403	445	599	471	418	616	9,189
1956	6	636	306	522	288	114	125	169	133	118	173	2,589
1957	5	583	281	479	264	104	115	155	122	108	159	2,377
1958	4	402	194	330	182	72	79	107	84	74	110	1,638
1959	8	859	414	706	390	154	169	228	179	159	235	3,501
1960	19	2,014	970	1,654	913	360	397	535	420	373	550	8,206
1961	9	918	442	754	416	164	181	244	192	170	251	3,742
1962	7	800	385	657	363	143	158	213	167	148	218	3,260
1963	9	1,009	486	829	458	180	199	268	211	187	276	4,112
1964	6	683	329	561	310	122	135	181	143	126	186	2,783
1965	2	213	103	175	96	38	42	57	44	39	58	867
1966	4	445	215	366	202	80	88	118	93	82	122	1,815
1967	7	772	372	635	350	138	152	205	161	143	211	3,147
1968	5	587	283	482	266	105	116	156	123	109	160	2,393
1969	6	595	287	489	270	106	117	158	124	110	162	2,425
1970	7	741	357	609	336	132	146	197	155	137	202	3,019
1971	4	441	213	363	200	79	87	117	92	82	121	1,799
1972	9	981	473	806	445	175	194	261	205	182	268	3,998
1973	12	1,245	600	1,023	565	222	246	331	260	231	340	5,074
1974	4	410	197	337	186	73	81	109	86	76	112	1,670
1975	5	536	258	440	243	96	106	142	112	99	146	2,184
1976	5	560	270	460	254	100	110	149	117	104	153	2,280
1977	4	445	215	366	202	80	88	118	93	82	122	1,815
1978	10	1,044	503	858	474	187	206	277	218	193	285	4,255
1979	5	560	270	460	254	100	110	149	117	104	153	2,280
1980	5	548	264	450	248	98	108	146	114	101	150	2,232
1981	1	146	70	120	66	26	29	39	30	27	40	594
1982	1	126	61	104	57	23	25	34	26	23	34	514
1983	4	426	205	350	193	76	84	113	89	79	116	1,734
1984	8	914	440	751	415	163	180	243	191	169	250	3,726
1985	5	564	271	463	256	101	111	150	118	104	154	2,296
1986	2	197	95	162	89	35	39	52	41	36	54	803
1987	1	126	61	104	57	23	25	34	26	23	34	514
1988	1	118	57	97	54	21	23	31	25	22	32	482
1989	2	226	109	185	102	40	44	60	47	42	62	919
1990	2	269	130	221	122	48	53	72	56	50	73	1,097
1991	4	382	184	314	173	68	75	102	80	71	104	1,558
1992	4	402	194	330	182	72	79	107	84	74	110	1,638
1993	0	448	328	1,183	25	25	14	6	6	6	53	2,094
1994	9	38	113	113	590	41	20	20	15	29	99	1,087
1995	0	4,610	363	443	284	337	293	133	98	115	151	6,826
1996	4	1,587	275	668	711	207	529	293	127	106	182	4,789
1997	0	2	2	381	57	62	56	403	242	63	75	1,344
1998	1	84	5	381	235	6	11	41	133	90	51	1,038
1999	73	2,627	231	57	89	446	32	47	100	276	332	4,310
2000	0	586	295	181	113	104	450	108	86	205	328	2,455
2001	0	1,087	461	246	110	149	154	393	102	207	295	3,202
2002	0	1,538	908	489	198	112	179	358	485	293	523	5,083
2003	2	977	4,345	1,523	1,282	457	195	262	277	312	448	10,078
2004	1	256	1,462	6,253	706	941	742	595	482	550	930	12,918

Appendix II-11. Estimated catch at age in number for age 0 – age 10+ of bluefin tuna in the Eastern North Pacific Ocean by purse seine fishery. (Data were adopted from Yamada et al. 2006)



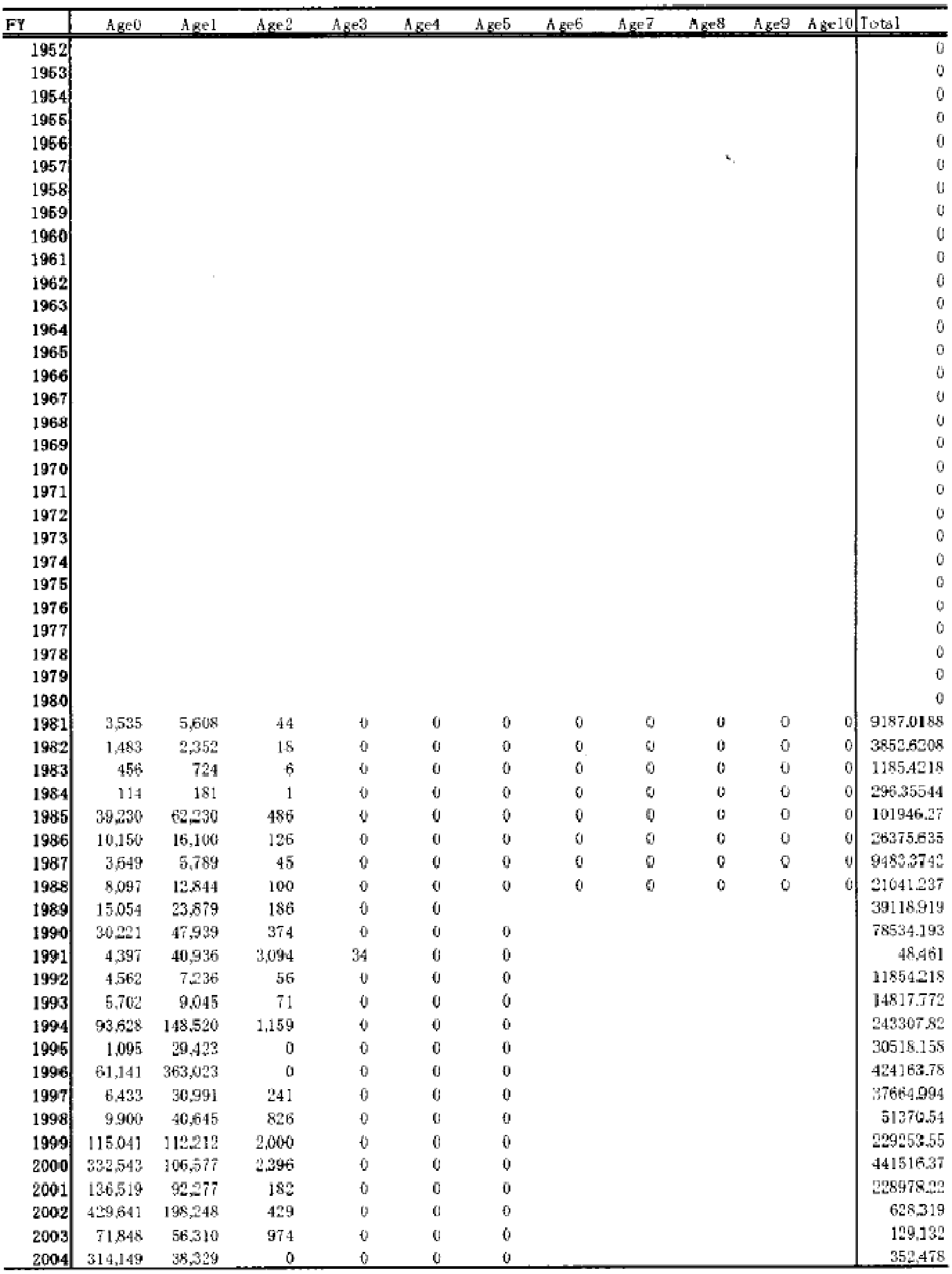
FY	Age0	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10	Total
1952	0	52,709	123,430	0	0	0	0	0	0	0	0	176,139
1953	2,124	764,291	7,360	5,381	0	0	0	0	0	0	0	779,157
1954	1,455	569,362	333,249	5,383	943	0	0	0	0	0	0	910,391
1955	212,475	133,796	264,414	20,044	104	0	0	0	0	0	0	630,833
1956	3,819	275,278	155,449	3,683	176	57	0	0	0	0	0	438,463
1957	447	785,565	241,383	18,749	0	0	0	0	0	0	0	1,046,144
1958	258	325,575	667,605	27	27	0	0	0	0	0	0	993,491
1959	902	45,169	267,259	115,162	1,803	296	0	0	0	0	0	430,591
1960	80,282	106,549	26,910	21,783	28,587	1,580	0	0	0	0	0	265,692
1961	50,825	692,895	239,168	4,341	340	0	0	0	0	0	0	987,569
1962	13,668	1,167,096	182,556	406	92	92	0	0	0	0	0	1,363,910
1963	155,090	627,731	347,126	25,707	2,371	2,313	88	44	0	0	0	1,160,470
1964	177	884,598	113,464	29,532	88	19	0	0	0	0	0	1,027,878
1965	0	852,939	305,688	7,184	751	336	63	0	0	0	0	1,166,961
1966	60,820	1,051,631	341,895	20,040	690	566	32	9	0	0	0	1,475,683
1967	16,546	286,089	93,010	5,452	188	154	9	3	0	0	0	401,449
1968	32,675	564,974	183,678	10,766	371	304	17	5	0	0	0	792,790
1969	10,543	442,210	15,106	24	16	0	0	0	0	0	0	467,899
1970	80,649	707,619	88,021	10,563	0	0	0	0	0	0	0	886,852
1971	0	267,439	392,149	8,336	0	0	0	0	0	0	0	667,924
1972	52,902	928,527	0	0	0	0	0	0	0	0	0	981,429
1973	33,013	670,763	242,079	0	0	0	0	0	0	0	0	945,854
1974	245,207	288,076	238,835	0	0	0	0	0	0	0	0	772,118
1975	6,363	662,842	137,943	34,333	540	0	0	0	0	0	0	842,021
1976	33,429	560,605	98,781	67,087	7,283	546	0	0	0	0	0	767,730
1977	16,397	162,926	43,594	14,729	9,828	7,613	2,226	0	0	0	0	257,313
1978	16,409	637,275	40,333	4,496	5,814	6,726	2,895	1,152	0	0	0	715,099
1979	86,994	299,648	144,836	11	14	16	7	3	0	0	0	531,528
1980	1,747	124,619	29,538	120	0	0	0	0	0	0	0	156,022
1981	6	16,450	34,756	2,425	0	0	0	0	0	0	0	53,638
1982	0	284,942	91,230	969	675	64	0	0	0	0	0	377,879
1983	579	47,348	34,945	456	62	15	0	0	0	0	0	83,406
1984	12,402	195,087	27,571	1,001	1	0	0	0	0	0	0	236,062
1985	971	191,896	67,205	0	0	0	0	0	0	0	0	260,072
1986	3	66,522	301,179	2,132	148	148	0	0	0	0	0	370,132
1987	18,527	36,772	47,877	282	350	61	0	0	0	0	0	103,869
1988	0	24,471	34,165	15,414	114	58	234	476	178	84	49	75,244
1989	2	44,991	37,827	4,447	135	198	103	49	6	3	2	87,763
1990	5	4,773	88,096	8,399	0	0	0	0	0	0	0	101,272
1991	0	48,159	3,121	260	0	0	0	0	0	0	0	51,540
1992	88	22,372	129,164	1	0	0	0	0	0	0	0	151,625
1993	0	5,947	20,209	14,012	0	0	0	0	0	0	0	40,168
1994	0	21,805	13,386	9,001	13,508	0	0	0	0	0	0	57,699
1995	0	6,748	460	1,645	9,435	12,290	56	0	0	0	0	30,635
1996	26	43,006	333,637	58,586	12,538	1,306	3,488	239	0	0	0	452,827
1997	0	71,934	41,943	56,190	58	5	5	0	0	0	0	170,135
1998	87	8,244	21,066	89,219	10,591	0	0	0	0	0	0	129,207
1999	0	4,329	39,154	9,632	945	313	1	0	0	0	0	54,375
2000	258	42,012	158,048	31,865	3,220	598	36	0	0	0	0	236,036
2001	2	1,817	41,840	17,928	607	2	0	0	0	0	0	62,197
2002	104	3,213	134,778	6,405	1,946	441	1	0	0	0	0	146,889
2003	0	3,025	214,278	21,145	8,781	2,112	23	0	0	0	0	249,364
2004	6	5,136	51,394	158,237	10,891	8,325	3,074	0	0	0	0	237,062

Appendix II-12. Estimated catch at age in number for age 0 – age 10+ of bluefin tuna in the North Pacific Ocean by Taiwanese longline fishery. (Data were adopted from Yamada et al. 2006)



FY	Age0	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10	Total
1952												0
1953												0
1954												0
1955												0
1956												0
1957												0
1958												0
1959												0
1960												0
1961												0
1962												0
1963												0
1964												0
1965												0
1966												0
1967												0
1968												0
1969												0
1970												0
1971												0
1972												0
1973												0
1974												0
1975												0
1976												0
1977												0
1978												0
1979												0
1980	0	0	0	0	0	0	2	23	97	240	580	942
1981	0	0	0	0	0	0	2	23	95	236	571	926
1982	0	0	0	0	0	0	1	21	85	210	509	826
1983	0	0	0	0	0	0	4	62	255	631	1,527	2,479
1984	0	0	0	0	0	0	2	27	114	281	681	1,105
1985	0	0	0	0	0	0	1	9	38	94	227	368
1986	0	0	0	0	0	0	3	48	198	489	1,183	1,921
1987	0	0	0	0	0	0	1	14	59	145	350	568
1988	0	0	0	0	0	0	2	27	111	274	665	1,079
1989	0	0	0	0	0	0	2	25	102	253	613	995
1990	0	0	0	0	0	0	3	45	185	458	1,109	1,800
1991	0	0	0	0	0	0	4	61	252	621	1,504	2,442
1992	0	0	0	0	0	0	8	8	99	198	1,724	2,037
1993	0	0	0	0	0	0	12	453	648	441	1,365	2,918
1994	0	0	0	0	0	0	9	45	263	246	930	1,492
1995	0	0	0	0	0	0	7	31	334	1,184	3.192	4,748
1996	0	0	0	0	0	0	3	290	753	2,412	6,047	9,505
1997	0	0	0	0	0	1	20	425	2,314	3,947	4,105	10,811
1998	0	0	0	0	0	0	9	118	1,991	7.915	7,230	17,263
1999	0	0	0	0	0	0	0	25	884	4,242	9,633	14,783
2000	0	0	0	0	0	0	3	20	168	1,166	7,672	9,031
2001	0	0	0	0	0	0	0	26	385	983	6,027	7,421
2002	0	0	0	0	0	0	4	43	614	3,404	5,756	9,821
2003	0	0	0	0	0	1	9	166	918	3,050	3,608	7,753
2004	0	0	0	0	0	0	13	109	637	1.733	3,724	6,216

Appendix II-13. Estimated catch at age in number for age 0 – age 10+ of bluefin tuna in the North Pacific Ocean by Korean purse seine fishery. (Data were adopted from Yamada et al. 2006)



FY	Age0	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9	Age10	Total
1952												0
1953												0
1954												0
1955												0
1956												0
1957												0
1958												0
1959												0
1960												0
1961												0
1962												0
1963												0
1964												0
1965												0
1966												0
1967												0
1968												0
1969												0
1970												0
1971												0
1972												0
1973												0
1974												0
1975												0
1976												0
1977												0
1978												0
1979												0
1980												0
1981	3,535	5,608	44	0	0	0	0	0	0	0	0	9187.0188
1982	1,483	2,352	18	0	0	0	0	0	0	0	0	3852.6208
1983	456	724	6	0	0	0	0	0	0	0	0	1185.4218
1984	114	181	1	0	0	0	0	0	0	0	0	296.35544
1985	39,230	62,230	486	0	0	0	0	0	0	0	0	101946.27
1986	10,150	16,100	126	0	0	0	0	0	0	0	0	26375.635
1987	3,649	5,789	45	0	0	0	0	0	0	0	0	9483.3742
1988	8,097	12,844	100	0	0	0	0	0	0	0	0	21041.237
1989	15.054	23,879	186	0	0							39118.919
1990	30,221	47,939	374	0	0	0						78534.193
1991	4,397	40,936	3,094	34	0	0						48,461
1992	4.562	7,236	56	0	0	0						11854.218
1993	5.702	9,045	71	0	0	0						14817.772
1994	93,628	148,520	1,159	0	0	0						243307.82
1995	1,095	29,423	0	0	0	0						30518.158
1996	61,141	363,023	0	0	0	0						424163.78
1997	6,433	30,991	241	0	0	0						37664.994
1998	9.900	40,645	826	0	0	0						51370.54
1999	115.041	112,212	2,000	0	0	0						229253.55
2000	332,543	106,577	2,296	0	0	0						441516.37
2001	136,519	92,277	182	0	0	0						228978.22
2002	429,641	198,248	429	0	0	0						628,319
2003	71,848	56,310	974	0	0	0						129,132
2004	314,149	38,329	0	0	0	0						352,478

5. Reproductive potential analysis of bluefin tuna in the North Pacific Ocean

Title: Reproductive potential analysis of bluefin tuna, *Thunnus orientalis*, in the North Pacific Ocean

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Running title: reproductive potential of Pacific bluefin tuna

Keyword: Reproductive value, Leslie model, intrinsic rate of population growth; population reproductive potential

Introduction

The spawning stock biomass (SSB) is generally used to decide whether a fish stock has sufficient productivity. Although a large number of studies have examined the sustainable level of SSB (Mace 1993; Zheng and Quinn II 1993; Myers et al. 1994; Machal and Horwood 1995). For a fish stock sustainable use in a long term fishery, using stock abundance to represent a long-term stock productivity is needed. Katsukawa (5) developed the unit stock abundance called population reproductive potential (PRP), which is defined as the expected total reproductive value of the standing stock, to evaluate stock productivity by considering both immediate and future spawning. However, the effectiveness of PRP for stock assessment and fisheries management has not yet been presented. Also it is doubtful whether SSB is an appropriate index of stock sustainability. For example, SSB ignores the value of immature fish, which are indispensible for long-term sustainability. Under the circumstance, decision-making that depends on SSB to be shortsighted. Therefore, in order to evaluate the sustainability of a fish stock, we should consider both immediate and future spawning of the standing stock.

Materials and Methods

The estimated abundance in number by ages and fishing mortality by ages from the results of the virtual population analysis were adopted here in the present study. Also the maturity oogive was used.

In biology, Fishers' reproductive value is widely used as an index of the reproductive contribution of an individual. The value is defined as:

$$\mathrm{R_i} = \sum_{\mathrm{x=i}}^{\mathrm{t_\lambda}} \mathrm{e}^{-\mathrm{r(x-i)}} \cdot \mathrm{m_x} \cdot \mathrm{l_x}$$

where $\mathrm{R_i}$ is Fishers' reproductive value (6) for an age i individual, r is the instantaneous growth rate of the population, in which conservatively, the r was set to 0; $\mathrm{m_x}$ is the average number of offspring which an individual at age x contributed, $\mathrm{l_x}$ is the survival rate of an individual until the spawning season at age x, and $\mathrm{t_\lambda}$is the maximum age of an individual with capability of spawning. Where the first term on the right-hand side, $\mathrm{e}^{-\mathrm{r(x-i)}}$ represents the discount rate of egg value, because the intrinsic growth rate of population r was assumed to be 0 without loss generality, the term is equal to unit to simplify the estimation of reproductive value (Katsukawa et al. 2002). However, an estimation of r can be calculated from Leslie matrix (Leslie 1945; 1947) with the application of annual age abundance in number estimated from virtual population analysis. For the case, R_i is equivalent to the total spawning in the rest of the individual's lifetime. If the reproductive value can be estimated from equation (1), the total reproductive value for the entire stock can be summed up the reproductive value for all the ages, that is

$$R = \sum_{i=1}^{t_\lambda} R_i \times N_i$$

where N_i is the number of individuals at age i for the study stock.

The stock reproductive value is to evaluate the stock productivity, unlike the spawning stock biomass it can be not only due to immediate spawning, but due to future spawning. The value of immature cohort is also evaluated for future reproduction, in which the part was almost ignored in estimating spawning stock biomass (Katsukawa et al. 2002).

Table 1 shows the life history parameters of PBF (Anon. 2007). The fecundity m_x was approximated as the product of the maturation schedule f_x and body weight w_x for the age x at June, which is since the spawning season of PBF is from May to August each year (Chen et al. 2006). Then, the reproductive value at the beginning of the year can be expressed by the fishing mortality at age i as $F_{i+0.5}$ and the natural mortality at age i as $M_{i+0.5}$. The natural mortality used in previous report (Yamada et al. 2007) for age 1, 2, 3, 4 and 5 over are 1.6, 0.8, 0.4, 0.25 and 0.25, respectively.

$$R_i = \sum_{x=i}^{t_\lambda} (m_x \cdot l_x) = \sum_{x=i}^{t_\lambda} \left[f_x \cdot w_x \cdot e^{-\left(0.5F_x + 0.5M_x + \sum_{y=i}^{x-1}(F_y + M_y)\right)} \right]$$

For reproductive value of the plus group, i.e., R_{10+}, is affected by the average age of 10+ ($\bar{a}_y$) and is empirically approximated by a extrapolation of the relationship between age and fishing mortality in Table 1.

Thus, using data shown in Table 1, the reproductive Value at age was calculated and shown in last two columns of Table 1.

Reproductive values increase with age indicates that the old individuals contribute more to spawning than the young individuals. Thus, the abundance index in number was used may result in overestimated immature individuals, the productivity may be underestimated. In contrast, reproductive values per body weight decreases with age means that biomass underestimates the reproductive contribution of young individuals, and spawning stock biomass ignores individuals with a high reproductive value per body weight.

Table 2 shows the trend in PBF abundance expressed by spawning stock biomass, biomass and total number of age 0-10+ fish (N) of PBF. And the annual SSB, abundance in number were also shown in Fig. 1. Spawning stock biomass fluctuated increasingly; the spawning stock biomass reached its historical highest in 1994, while recent N peaked in 1995. This inconsistency is also found then after, and there are simultaneously in the recent peak in 2001, but the spawning stock biomass was the lowest in the same time. This is may be due to the newly introduced fishery made by Taiwan small scale longliners to take the giant spawner from 1993, the trend can be found as the Taiwan fishery employed, the spawning stock biomass showed declined tendency. Fishing pressure on giant spawning cohorts declined drastically after 1999, and this change in the fishing pattern caused the spawning stock biomass increasing again (Fig. 1). Abundance in number and spawning stock biomass also showed opposite reactions to the age-composition fluctuation (Table 3). The trend in total reproductive biomass is intermediate between the trends in N and spawning stock biomass. If age composition is unstable, we must be sensitive to the choice of stock abundance index. The population abundance was projected under various yearly fishing mortalities at age (Table 4). In Table 5, the annual abundance at age in number was shown.

Results and Discussion

Reproductive values and population reproductive potential

Under the assumption that the population is stationary, that is the intrinsic rate of population growth is equal to unit, $r = 1$, the age-specific reproductive values estimated as in Table 2, indicating that the averaged reproductive values at age from 1960 to 2004 increase with age. Then, the reproductive value for all ages from 1960 to 2004 was shown in Fig. 2. The total annual reproductive value is the performance of population reproductive potential (PRP).

The annual total reproductive values of bluefin tuna in the North Pacific Ocean (Fig. 2) indicate that in 1990s the stock has higher relatively reproductive value than others in the study time series, particularly, the reproductive values in 1992 has the historical high value, and ranks the second position in 2003.

Computer simulation can be used to evaluate the trend of a stock with an unstable age composition. The projection of the PBF population stock under constant fishing mortality, starting from the numbers-at-age in 1982-1995 may be pursued in the near future. It is rational to assume that the stock with the higher level in the future has the higher long-term productivity as the estimation within the study. The stock level after a long projection, therefore, can represent the long-term productivity of the initial stock.

However, a plus age group may decline the accuracy of stock abundance projection. As the situation, the projection model used for projection, Katuskawa et al. (2002) proposed a plus age group modeling, that was letting $N_{i,j}$ be the number of age i individuals at the beginning of year j. The dynamics can be expressed as, for age i is $1 \leq i \leq 10$:

$$N_{i+1,j+1} = N_{i,j}e^{-Z_i}$$

where $Z_i = F_i + M_i$. Individuals older than 10-year-old are grouped as a 10+. Thus, the number of age 10+ can be expressed as:

$$N_{15+,y+1} = N_{15+,j}e^{-Z_{15+}} + N_{9,j}e^{-Z_9}$$

The average age of mid-year 15+ fish in year j $\left(\bar{a}_j\right)$ is:

$$\bar{a}_{j+1} = \frac{\left(\bar{a}_j + 1\right)N_{15+,j}e^{-Z_{15+}} + 10.5N_{14,j}e^{-Z_{14}}}{N_{15+,j}e^{-Z_{15+}} + N_{14,j}e^{-Z_{14}}}$$

The weight at age was estimated from the von Bertalanffy growth equation and length-weight relationship (Hsu et al. 2000). This may be different with the current method used herein that the average from age 10 to 12 was used in the present study.

As usual, fish population dynamics can be expressed as a matrix model, e.g. Leslie matrix model. The estimation of intrinsic growth rate of population was used the Leslie matrix with the consecutive annual abundance at age in number, i.e.,

$$\underline{N}_x = \underline{AN}_{x-1}$$

where $\underline{A}$ is the Leslie matrix and it largest real positive eigenvalue, λhas a relationship with the intrinsic growth rate of population,

$$\lambda = e^r$$

Further, the intrinsic growth rate of population can be estimated as:

$$r = \ln \lambda$$

The annual abundance at age in number was as shown in Table 5. And Leslie matrix $\underline{A}$ can be constructed as:

$$\begin{bmatrix} s_0 \times f_0 & s_1 \times f_1 & s_2 \times f_2 & & s_{10+} \times f_{10+} \\ S_0 & 0 & 0 & \cdots & 0 \\ 0 & s_1 & 0 & & 0 \\ & \vdots & & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 0 \end{bmatrix}$$

where s_i and f_i are the survival rate and fertility for age i, and $s_i = e^{-(M_i+F_i)}$. Then the first eigenvalue can be adopted to estimated the intrinsic rate of population growth as above mentioned. We assumed the intrinsic growth rate as a constant one, this may be not appropriate, as this is so, the estimation of the parameter through Leslie matrix model and its eigenvalue seems necessary for accurate computation of PRP in the present study.

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Table 1 Life history parameters of the Pacific bluefin tuna, abstracted from Yamada et al. (2004; 2006) and the present study in the section of the adaptive virtual population analysis.

Age (year)	Weight (kg)	Natural mortality	Fishing mortality*1	Maturity	Reproductive value	Reproductive value/weight
0	1.0	1.6	0.683	0.0	1.23	1.23
1	5.7	0.8	0.528	0.0	12.02	2.11
2	15.5	0.4	0.363	0.0	45.35	2.92
3	25.6	0.25	0.045	0.2	61.99	2.42
4	42.2	0.25	0.069	0.5	78.72	1.87
5	62.2	0.25	0.113	1.0	93.96	1.51
6	84.9	0.25	0.209	1.0	91.81	1.09
7	109.6	0.25	0.369	1.0	91.64	0.84
8	135.7	0.25	0.243	1.0	88.76	0.65
9	162.5	0.25	0.478	1.0	62.43	0.38
10+	218.0	0.25	0.478	1.0	105.27	0.48

*1: data from estimation for 2002 in the present study of adaptive virtual population analysis..

Table 2 The estimated spawning stock biomass of bluefin tuna in the North Pacific Ocean from 1960 to 2005 by the adaptive virtual population analysis.

year	age 0	age 1	age 2	age 3	age 4	age 5	age 6	age 7	age 8	age 9	age 10 plus
1960	0	0	0	1905382	8603762	17047751	10967200	2337014	535427.9	273996.7	470122
1961	0	0	0	863328.2	5577273	16257158	13144066	6122898	874571.6	173942.3	222219.4
1962	0	0	0	704865.5	2512998	11760192	13760988	7961429	2391197	322335.4	108889.5
1963	0	0	0	1140163	1853762	4940271.3	11188837	9900771	2781070	549994.7	97639.96
1964	0	0	0	854723.6	2948165	3156054.1	4400715	8921215	5315333	556094.8	103187.6
1965	0	0	0	586256.4	1901400	5565475.6	2656754	3313365	2995004	1120409	83113.76
1966	0	0	0	1189301	1334506	3386966.2	5034216	2111334	1992374	868324.8	272755.3
1967	0	0	0	867201.8	2481309	1735696.5	2172428	1993016	1336377	1037323	538117
1968	0	0	0	638132.2	2082839	3216028.2	1101358	1064195	602536.4	676664.8	698118.6
1969	0	0	0	511569.7	1406297	3125644.2	1531353	735009.6	630066.4	334937.9	650912.4
1970	0	0	0	991118.6	1259630	2354116.5	2130717	835127	510484.1	418032.6	527298.2
1971	0	0	0	1077237	2622118	2331907.3	2066741	1305952	494607.9	341806.1	546590.6
1972	0	0	0	632180.4	2776945	4963753.4	2034848	1571249	785358.7	304610.1	490038
1973	0	0	0	557780.8	1665378	5109381.9	3735192	1402897	981402.1	439659.5	395394.8
1974	0	0	0	990554	1485336	2860891.6	3760552	2113133	704252.4	456741.8	337539.3
1975	0	0	0	1887525	2677510	2894705.9	2234821	2533201	1166364	355607.1	349873.9
1976	0	0	0	3045837	4972646	4952554.3	2645649	1783345	1888705	771187	421436.2
1977	0	0	0	1349448	8052162	9075098	3992407	2242497	1425409	1485158	835152.6
1978	0	0	0	879855.4	2801103	13228384	6647744	2799182	1784086	974002.5	1485506
1979	0	0	0	1042169	2393498	5007232.4	9020816	4138330	1837059	1306158	1415147
1980	0	0	0	1294763	2591685	4425356.2	4245732	6043156	2710398	1181988	1626562
1981	0	0	0	1610326	3144537	4858218.8	3655434	3314811	4126891	1878007	1641697
1982	0	0	0	824815.6	2593268	4983963.7	4099059	2506827	2369652	2829824	2161784
1983	0	0	0	615764.4	1690248	3749953.1	3669479	3253500	1620520	1619902	3080159
1984	0	0	0	705766.4	1682057	3439883.9	3402388	2963171	2560152	1052507	2687844
1985	0	0	0	811479.1	1831396	3267388.1	3146862	2943833	2343386	1924822	2184846
1986	0	0	0	663143.2	2021516	3593124.7	2960482	2716212	2378076	1782969	2735514
1987	0	0	0	900939.4	1586632	4013440.8	3248866	2587016	2276383	1879303	3125921
1988	0	0	0	752202.9	2031238	3138538	3716654	2784944	2178536	1858137	3604938
1989	0	0	0	1079583	1852839	3664175.7	2938239	3328263	2363971	1804982	3989405
1990	0	0	0	1421240	2807391	3756702.6	3428796	2600585	2908529	1978197	4240260
1991	0	0	0	1744724	4001139	5763486.7	3472729	3022606	2172000	2420225	4469693
1992	0	0	0	1782508	4982438	8217782.7	5264538	2917729	2545636	1732791	4896975
1993	0	0	0	2378818	5366469	10147513	6624866	4166229	2281667	2089742	4700679
1994	0	0	0	938617.7	6577480	11254757	8724582	4274382	3217102	1804649	4950283
1995	0	0	0	754265.4	2613712	12360013	10326174	6664822	2885414	2525999	4710063
1996	0	0	0	853600.1	2050277	5305212.8	10204087	8801361	5172219	1984422	4546209
1997	0	0	0	1841406	2083280	3947028.3	5028937	7870258	7235627	3907736	3955416
1998	0	0	0	1270174	4647852	4188799.8	3316357	4126691	5808524	5256043	4920705
1999	0	0	0	1232550	2831380	8140574.8	3658721	2271039	2961910	3905010	5978876
2000	0	0	0	915244.2	3247380	5112516.7	6173041	3012469	1514582	1960088	5599747
2001	0	0	0	1192668	2368286	6640233.4	4313904	4599075	2462164	1008375	4275124
2002	0	0	0	1539113	3394523	4888091.6	5902740	3296322	3387010	1639063	2734136
2003	0	0	0	1189223	4537961	7061213.4	4543989	4898503	2353918	2166412	2205267
2004	0	0	0	3037495	3230637	9033179.9	6312013	3686241	3930294	1203280	1845912

Table 3 The estimated age composition of North Pacific bigeye tuna from 1960 to 2004.

year	age 0	age 1	age 2	age 3	age 4	age 5	age 6	age 7	age 8	age 9	age 10 plus
1960	0.534863	0.170342	0.055279	0.070038	0.079233	0.054579	0.027573	0.006015	0.001031	0.000424	0.000623
1961	0.536535	0.248722	0.068929	0.026328	0.039553	0.040585	0.026053	0.011311	0.001401	0.000279	0.000305
1962	0.398285	0.376781	0.095165	0.024264	0.020606	0.032565	0.030391	0.016395	0.004875	0.000522	0.000151
1963	0.59567	0.193726	0.100838	0.038519	0.015211	0.012951	0.020236	0.015724	0.005806	0.001145	0.000174
1964	0.527973	0.328305	0.048177	0.032233	0.022657	0.008624	0.008107	0.014104	0.008457	0.001175	0.000187
1965	0.461899	0.335542	0.126908	0.020004	0.016574	0.015963	0.005417	0.005933	0.008347	0.003209	0.000204
1966	0.429012	0.333787	0.129513	0.061308	0.015324	0.01107	0.011105	0.003947	0.003336	0.001259	0.000339
1967	0.557591	0.270979	0.075118	0.039028	0.027178	0.007791	0.007832	0.009134	0.002689	0.001841	0.000818
1968	0.513769	0.313967	0.08423	0.032773	0.027151	0.01817	0.003497	0.002887	0.001239	0.00123	0.001087
1969	0.586214	0.275873	0.076655	0.023292	0.016746	0.012259	0.004921	0.001588	0.00107	0.000519	0.000864
1970	0.390835	0.412617	0.108868	0.050749	0.015728	0.009405	0.007152	0.002264	0.000963	0.000682	0.000737
1971	0.630421	0.165489	0.117246	0.045166	0.024823	0.007363	0.004845	0.002768	0.000798	0.000456	0.000625
1972	0.604821	0.299842	0.033696	0.019843	0.020897	0.012818	0.003853	0.002437	0.001014	0.000327	0.000451
1973	0.537154	0.333229	0.079244	0.01589	0.011466	0.011952	0.007017	0.002076	0.001165	0.000455	0.00035
1974	0.477078	0.32485	0.139266	0.028543	0.010251	0.007205	0.007338	0.003537	0.001003	0.000568	0.00036
1975	0.392311	0.316986	0.182393	0.06688	0.022184	0.007899	0.004701	0.004226	0.001647	0.000419	0.000353
1976	0.411388	0.267114	0.128405	0.118706	0.04568	0.015777	0.005835	0.003096	0.002633	0.00093	0.000436
1977	0.579355	0.198749	0.063481	0.055061	0.063246	0.02493	0.008066	0.003298	0.001681	0.001439	0.000693
1978	0.523871	0.301938	0.065511	0.026588	0.021538	0.038001	0.013788	0.004373	0.002006	0.001034	0.001351
1979	0.494285	0.299714	0.106631	0.036397	0.018723	0.013334	0.018997	0.007005	0.00233	0.00134	0.001244
1980	0.385352	0.336527	0.157641	0.053744	0.024012	0.014	0.009703	0.01171	0.003977	0.00153	0.001804
1981	0.383795	0.252006	0.204388	0.084686	0.032121	0.016395	0.009242	0.006501	0.006495	0.002498	0.001871
1982	0.390103	0.291211	0.162642	0.057931	0.042082	0.024068	0.012688	0.00675	0.004695	0.004732	0.003098
1983	0.557063	0.241708	0.0972	0.034215	0.021591	0.016728	0.012172	0.008272	0.00346	0.002887	0.004704
1984	0.551184	0.266588	0.095405	0.03319	0.017727	0.012048	0.008621	0.006011	0.004138	0.001596	0.003491
1985	0.448217	0.33922	0.117337	0.040633	0.019509	0.011802	0.008186	0.005926	0.003838	0.002703	0.002628
1986	0.420329	0.297455	0.176915	0.039325	0.024749	0.014938	0.008855	0.006274	0.004517	0.00287	0.003773
1987	0.464379	0.279772	0.120937	0.060618	0.02317	0.019479	0.011488	0.006966	0.004928	0.003407	0.004855
1988	0.499243	0.25452	0.124056	0.047438	0.029775	0.013739	0.011794	0.006941	0.004318	0.003071	0.005105
1989	0.441208	0.293985	0.137553	0.061045	0.022671	0.014991	0.008744	0.007562	0.004297	0.002746	0.005199
1990	0.576254	0.194624	0.121788	0.051883	0.023726	0.010711	0.00714	0.00417	0.003681	0.002123	0.0039
1991	0.394601	0.366561	0.105744	0.062049	0.033339	0.016194	0.007234	0.00479	0.002809	0.002586	0.004092
1992	0.275026	0.200935	0.266715	0.104528	0.070294	0.039174	0.018859	0.00812	0.005525	0.003163	0.007659
1993	0.398414	0.136801	0.098548	0.163723	0.084148	0.055622	0.030599	0.013807	0.005865	0.004261	0.008212
1994	0.81037	0.068876	0.026103	0.019911	0.033452	0.018844	0.011488	0.004716	0.00246	0.001128	0.002652
1995	0.395787	0.470583	0.038398	0.019317	0.01634	0.02716	0.015915	0.00831	0.002891	0.00204	0.003259
1996	0.551593	0.210796	0.140187	0.029296	0.01497	0.012088	0.018322	0.011562	0.005493	0.001921	0.003771
1997	0.377806	0.345072	0.117233	0.080113	0.019721	0.012682	0.011842	0.015311	0.010745	0.005075	0.004401
1998	0.61594	0.159247	0.082677	0.054318	0.041448	0.012261	0.007711	0.007105	0.008005	0.006265	0.005025
1999	0.623809	0.217285	0.056887	0.03836	0.02077	0.02074	0.006421	0.00339	0.003388	0.003871	0.005078
2000	0.592417	0.255205	0.069825	0.027915	0.02082	0.011545	0.010773	0.003721	0.001617	0.001787	0.004374
2001	0.761519	0.115109	0.055539	0.027171	0.012329	0.011851	0.005968	0.00494	0.002026	0.000766	0.002782
2002	0.417315	0.40802	0.069972	0.044911	0.023914	0.011817	0.010897	0.004837	0.003955	0.001795	0.002565
2003	0.212608	0.279247	0.318919	0.064467	0.056893	0.029584	0.013981	0.011715	0.004896	0.004107	0.003582
2004	0.666381	0.037388	0.072561	0.132514	0.030331	0.02847	0.014942	0.006934	0.005722	0.002056	0.002702

Table 4 The estimated fishing mortality at age of bluefin tuna in the North Pacific Ocean from 1960 to 2004 by the adaptive virtual population analysis.

year	age 0	age 1	age 2	age 3	age 4	age 5	age 6	age 7	age 8	age 9	age 10 p
1960	0.276	0.415	0.253	0.082	0.18	0.25	0.402	0.968	0.818	0.743	0.743
1961	0.195	0.802	0.886	0.087	0.036	0.131	0.305	0.683	0.829	1.194	1.194
1962	0.299	0.897	0.483	0.046	0.043	0.055	0.238	0.617	1.028	0.931	0.931
1963	0.316	1.112	0.861	0.251	0.287	0.188	0.081	0.34	1.318	1.675	1.675
1964	0.219	0.716	0.645	0.431	0.116	0.231	0.078	0.291	0.735	1.665	1.665
1965	0.157	0.785	0.56	0.099	0.236	0.196	0.149	0.408	1.724	2.142	2.142
1966	0.305	1.337	1.045	0.659	0.522	0.192	0.041	0.229	0.44	0.515	0.515
1967	0.308	0.902	0.563	0.096	0.136	0.535	0.732	1.731	0.516	0.628	0.628
1968	0.244	1.032	0.907	0.293	0.417	0.928	0.411	0.615	0.493	0.609	0.609
1969	0.166	0.745	0.227	0.208	0.392	0.354	0.591	0.316	0.265	0.444	0.444
1970	0.358	0.756	0.378	0.213	0.257	0.161	0.448	0.54	0.245	0.318	0.318
1971	0.19	1.038	1.223	0.217	0.107	0.094	0.134	0.451	0.338	0.32	0.32
1972	0.192	0.927	0.348	0.145	0.155	0.199	0.214	0.334	0.398	0.394	0.394
1973	0.224	0.593	0.742	0.159	0.185	0.209	0.406	0.448	0.438	0.526	0.526
1974	0.297	0.465	0.621	0.14	0.148	0.315	0.44	0.652	0.761	0.854	0.854
1975	0.181	0.7	0.226	0.178	0.138	0.1	0.215	0.27	0.368	0.37	0.37
1976	0.273	0.982	0.392	0.175	0.151	0.216	0.116	0.156	0.149	0.223	0.223
1977	0.289	0.747	0.507	0.576	0.147	0.229	0.25	0.134	0.123	0.094	0.094
1978	0.309	0.792	0.338	0.101	0.23	0.444	0.428	0.38	0.154	0.401	0.401
1979	0.257	0.515	0.558	0.289	0.163	0.191	0.357	0.439	0.293	0.232	0.232
1980	0.199	0.273	0.396	0.289	0.156	0.19	0.175	0.364	0.239	0.352	0.352
1981	0.189	0.351	1.174	0.613	0.202	0.17	0.228	0.239	0.23	0.257	0.257
1982	0.257	0.875	1.337	0.765	0.701	0.46	0.206	0.446	0.264	0.288	0.288
1983	0.22	0.412	0.557	0.14	0.066	0.145	0.188	0.175	0.257	0.259	0.259
1984	0.195	0.53	0.563	0.241	0.116	0.096	0.084	0.158	0.135	0.37	0.37
1985	0.262	0.503	0.945	0.348	0.119	0.139	0.118	0.124	0.143	0.198	0.198
1986	0.26	0.753	0.924	0.382	0.093	0.116	0.093	0.095	0.135	0.167	0.167
1987	0.218	0.43	0.553	0.328	0.139	0.119	0.121	0.095	0.09	0.098	0.098
1988	0.156	0.242	0.336	0.365	0.313	0.079	0.071	0.107	0.08	0.08	0.08
1989	0.167	0.23	0.323	0.293	0.098	0.09	0.089	0.068	0.053	0.06	0.06
1990	0.131	0.289	0.353	0.121	0.061	0.071	0.078	0.074	0.032	0.066	0.066
1991	0.911	0.554	0.248	0.111	0.075	0.084	0.121	0.093	0.118	0.099	0.099
1992	0.52	0.534	0.31	0.039	0.056	0.069	0.133	0.147	0.081	0.098	0.098
1993	0.283	0.184	0.127	0.116	0.024	0.105	0.398	0.253	0.176	0.076	0.076
1994	0.452	0.493	0.21	0.107	0.117	0.078	0.233	0.398	0.096	0.057	0.057
1995	0.441	1.022	0.081	0.066	0.112	0.204	0.13	0.225	0.219	0.151	0.151
1996	0.504	0.621	0.594	0.43	0.201	0.055	0.214	0.108	0.114	0.292	0.292
1997	0.44	1.005	0.345	0.235	0.051	0.073	0.087	0.224	0.115	0.21	0.21
1998	0.53	0.517	0.256	0.449	0.18	0.135	0.31	0.228	0.214	0.287	0.287
1999	0.521	0.762	0.339	0.238	0.214	0.282	0.172	0.367	0.266	0.343	0.343
2000	1.166	1.052	0.471	0.344	0.091	0.187	0.307	0.135	0.274	0.322	0.322
2001	0.602	0.476	0.19	0.106	0.02	0.062	0.188	0.201	0.099	0.302	0.302
2002	0.683	0.528	0.363	0.045	0.069	0.113	0.209	0.269	0.243	0.478	0.478
2003	1.105	0.714	0.245	0.121	0.059	0.05	0.068	0.083	0.235	0.413	0.413
2004	0.79	1.581	0.283	0.353	0.147	0.147	0.21	0.269	0.188	0.871	0.871

Table 5 The estimated abundance at age in number of bluefin tuna in the North Pacific Ocean from 1960 to 2005 by the adaptive virtual population analysis.

year	age 0	age 1	age 2	age 3	age 4	age 5	age 6	age 7	age 8	age 9	age 10 plus
1960	3523862	1122273	364200	461434	522014	359587	181659	39632	6790	2791	4103
1961	4271396	1980096	548748	209599	314881	323103	207409	90044	11152	2220	2430
1962	2751985	2603402	657547	167655	142376	225013	209990	113281	33681	3607	1044
1963	4646434	1511134	786569	300464	118654	101024	157849	122655	45285	8928	1358
1964	4036959	2510265	368371	246455	173240	65941	61991	107845	64666	8982	1428
1965	3306268	2401807	908403	143188	118639	114265	38777	42467	59745	22971	1460
1966	2689475	2092510	811915	384338	96068	69399	69615	24744	20915	7892	2124
1967	3021503	1468395	407055	211489	147272	42218	42439	49497	14572	9976	4434
1968	2692167	1645198	441366	171734	142270	95210	18325	15127	6495	6446	5698
1969	3320823	1562783	434239	131945	94865	69448	27879	8997	6060	2938	4892
1970	1973625	2083623	549760	256271	79425	47494	36114	11434	4861	3443	3721
1971	3895607	1022619	724507	279096	153389	45496	29940	17102	4934	2818	3861
1972	4815792	2387447	268297	157997	166392	102064	30681	19407	8073	2606	3592
1973	4745424	2943874	700071	140382	101296	105585	61993	18344	10292	4018	3096
1974	4127543	2810513	1204892	246945	88689	62338	63484	30598	8680	4918	3114
1975	2813208	2273061	1307915	479586	159076	56646	33713	30303	11811	3006	2534
1976	2677978	1738811	835866	772732	297361	102703	37983	20151	17142	6057	2836
1977	4402042	1510132	482340	418364	480552	189421	61290	25062	12770	10936	5269
1978	4238364	2442821	530016	215112	174253	307447	111553	35378	16233	8362	10927
1979	3801252	2304922	820033	279908	143991	102547	146095	53869	17918	10305	9566
1980	2493411	2177487	1020010	347750	155369	90585	62780	75769	25732	9902	11675
1981	2304809	1513377	1227416	508565	192898	98456	55503	39043	39004	15003	11237
1982	1892608	1412826	789070	281058	204162	116765	61558	32746	22780	22960	15028
1983	2499335	1084453	436101	153510	96870	75052	54613	37114	15524	12954	21104
1984	3073312	1486450	531964	185061	98841	67180	48072	33516	23074	8897	19467
1985	2476132	1873990	648217	224474	107778	65198	45224	32736	21205	14930	14520
1986	1994364	1411354	839423	186586	117430	70878	42017	29770	21433	13617	17900
1987	1890211	1138786	492263	246741	94312	79288	46760	28354	20060	13866	19761
1988	2208513	1125927	548788	209853	131715	60776	52172	30707	19102	13587	22585
1989	2099886	1399194	654669	290537	107901	71346	41618	35989	20450	13067	24745
1990	3898063	1316531	823830	350965	160493	72456	48300	28205	24898	14364	26380
1991	2726318	2532583	730591	428698	230344	111886	49982	33095	19410	17866	28270
1992	1111635	812166	1078044	422495	284125	158339	76227	32821	22332	12785	30957
1993	1425924	489610	352705	585965	301167	199072	109514	49416	20990	15250	29391
1994	9367833	796206	301752	230168	386699	217833	132803	54511	28435	13045	30659
1995	3712803	4414453	360207	181208	153280	254781	149292	77953	27121	19138	30575
1996	4631946	1770137	1177208	246008	125709	101507	153855	97093	46129	16133	31667
1997	2270218	2073521	704450	481394	118503	76203	71160	92006	64564	30493	26445
1998	4190649	1083460	562508	369559	281998	83417	52462	48339	54460	42624	34190
1999	5247848	1827930	478569	322706	174733	174478	54019	28517	28502	32567	42722
2000	5362185	2309958	632012	252672	188452	104494	97506	33684	14633	16176	39595
2001	8192729	1238385	597513	292320	132643	127496	64204	53150	21795	8239	29928
2002	3399961	3324233	570081	365901	194836	96278	88778	39412	32220	14624	20901
2003	968512	1272077	1452796	293670	259167	134768	63690	53367	22303	18711	16319
2004	4235942	237662	461244	842345	192804	180972	94981	44074	36374	13067	17175
2005	4235942	388138	36245	257553	438260	123300	115733	57031	24960	22328	9379

Table 6 The reproductive values by age from 1960 to 2004.

year	age 0	age 1	age 2	age 3	age 4	age 5	age 6	age 7	age 8	age 9	age 10+
1960	1.226015	8.002621	26.97119	28.86029	36.4916	42.46191	32.28165	17.72749	27.50435	33.38595	80.76107
1961	0.646908	3.894046	19.32595	42.13343	55.33399	57.84126	42.17134	24.72125	19.73094	11.914	51.44406
1962	0.906393	6.053988	33.03994	50.0107	63.36627	69.28283	48.14174	26.30943	16.55511	21.61859	66.91981
1963	0.319373	2.169734	14.68174	31.57343	49.00013	71.50899	70.67141	37.42441	6.758937	4.134672	31.80091
1964	0.655329	4.040555	18.40058	32.02	60.66359	72.85847	79.41265	49.08094	20.50213	4.225137	32.12052
1965	0.792009	4.589712	22.39454	35.60762	46.8667	63.21896	58.93184	30.86099	2.830002	1.525612	19.93536
1966	0.14196	0.953887	8.083218	20.34986	48.05638	95.08303	107.9526	80.95114	62.8058	57.15303	101.4428
1967	0.381089	2.568388	14.08737	19.03182	23.2475	19.89952	15.25721	8.933307	49.64912	43.71972	90.6037
1968	0.16108	1.018308	6.360728	10.76228	15.47997	19.46574	44.07123	41.51716	52.45627	45.72487	92.34163
1969	0.786265	4.597619	21.55351	21.53904	30.52138	47.4489	52.80423	85.82077	88.91823	67.73614	108.9071
1970	0.738499	5.23237	24.80051	31.35528	46.04073	64.65465	56.28246	70.86802	106.4089	91.84492	123.5314
1971	0.412377	2.469913	15.52083	49.89923	75.45508	94.39842	89.06101	72.92646	92.63143	91.39933	123.2845
1972	1.008165	6.050447	34.02624	43.55781	60.57954	77.69503	82.02811	77.07737	77.09501	76.40014	114.4909
1973	0.742976	4.603922	18.53959	33.21764	46.31443	58.34049	53.01816	58.11308	62.25685	55.67432	100.333
1974	0.762586	5.083296	18.01059	27.22779	36.69121	40.54054	35.97697	29.14403	27.35526	25.80666	72.27621
1975	1.595463	9.470331	42.44308	49.85048	72.31122	93.49994	88.85113	88.12358	83.06685	80.96157	117.2719
1976	1.020902	6.643816	39.47575	57.20817	82.40817	111.5446	138.7273	141.1602	138.826	115.8437	135.8424
1977	0.729594	4.824623	22.66297	36.61091	79.04092	106.8604	133.995	169.4259	174.0899	159.3413	154.5465
1978	0.7665	5.171072	25.4084	29.6924	38.134	49.28096	67.57253	90.01552	110.642	75.12077	113.6922
1979	0.934655	5.985993	22.29633	34.65553	55.53843	71.3136	70.8209	83.68149	111.6426	113.313	134.6253
1980	1.687755	10.20012	29.82656	40.6841	65.9087	86.13108	93.67729	87.78282	102.8923	84.56827	119.4019
1981	0.530307	3.173075	10.03121	29.8989	67.5152	94.54439	103.0246	113.5229	117.909	106.5809	131.3013
1982	0.098583	0.631376	3.370787	9.796886	24.78098	57.01519	85.38813	80.91036	107.6391	98.807	127.2935
1983	1.75067	10.80489	36.30656	61.55321	85.94199	104.5609	113.3057	120.7909	113.1075	106.0606	131.039
1984	1.552158	9.343174	35.32695	61.69788	96.30417	126.214	134.3839	126.8799	117.9212	80.96157	117.2719
1985	0.9092	5.852154	21.53781	55.48062	95.89464	127.2552	145.6106	151.6236	144.9882	123.1869	139.2812
1986	0.76525	4.915764	23.23006	59.92179	107.3401	140.0544	158.8163	163.5506	153.3109	132.9708	143.6666
1987	1.638915	10.09494	34.53711	62.21491	104.839	145.0894	166.8343	183.1887	181.0397	157.7641	153.9296
1988	2.292756	13.2733	37.62822	54.8708	95.63957	161.3364	179.4276	185.7536	188.7534	164.9921	156.7254
1989	3.127357	18.30526	51.27423	76.02005	123.6543	166.1923	189.2193	205.0878	202.1225	173.4287	159.8914
1990	3.753917	21.19573	62.97891	97.4895	133.2547	172.5355	192.7198	206.3727	206.0725	170.8516	158.935
1991	1.326288	16.3362	63.26826	85.24673	115.3247	149.095	163.679	178.6161	173.9239	157.3723	153.7757
1992	2.038963	16.98688	64.48556	92.62238	116.3813	147.1817	157.2738	172.784	183.3036	157.7641	153.9296
1993	3.186537	20.94573	56.03266	62.88497	84.82779	98.54717	96.93307	140.8979	166.7226	166.6446	157.3535
1994	1.838074	14.30656	52.12883	64.57738	86.18276	113.4119	112.6306	130.1889	191.5532	174.7324	160.3718
1995	1.267292	9.756	60.3332	64.20786	82.3758	106.4327	128.0865	129.2391	139.6597	138.3337	145.9837
1996	0.7678	6.295114	26.0697	46.51413	87.65354	126.6232	125.9312	146.9018	133.5196	97.84782	126.7853
1997	1.040078	7.99883	48.63266	69.94858	108.1484	133.634	139.5529	134.8663	148.4234	119.6035	137.6198
1998	0.94539	7.955329	29.69094	35.43993	67.65846	91.96204	92.82471	114.01	115.9261	99.04832	127.4208
1999	0.7301	6.088649	29.0328	36.37207	55.37838	75.97041	92.7889	85.83204	99.94179	86.43399	120.4814
2000	0.278636	4.428894	28.22336	42.10963	72.38492	88.28335	96.48815	119.7718	101.441	90.956	123.0382
2001	1.925346	17.41106	62.37133	75.7191	102.7941	120.798	119.4996	130.3889	134.881	95.49205	125.5238
2002	1.225674	12.01903	45.35367	61.9858	78.71706	93.95641	91.80962	91.63827	88.7594	62.43433	105.2665
2003	0.89257	13.34778	60.66397	78.68914	109.1757	135.0193	136.1781	125.3865	96.37467	72.97923	112.3361
2004	0.265697	2.899679	31.3621	38.2636	66.91816	85.65816	85.585	81.97699	72.5251	24.81455	71.0579

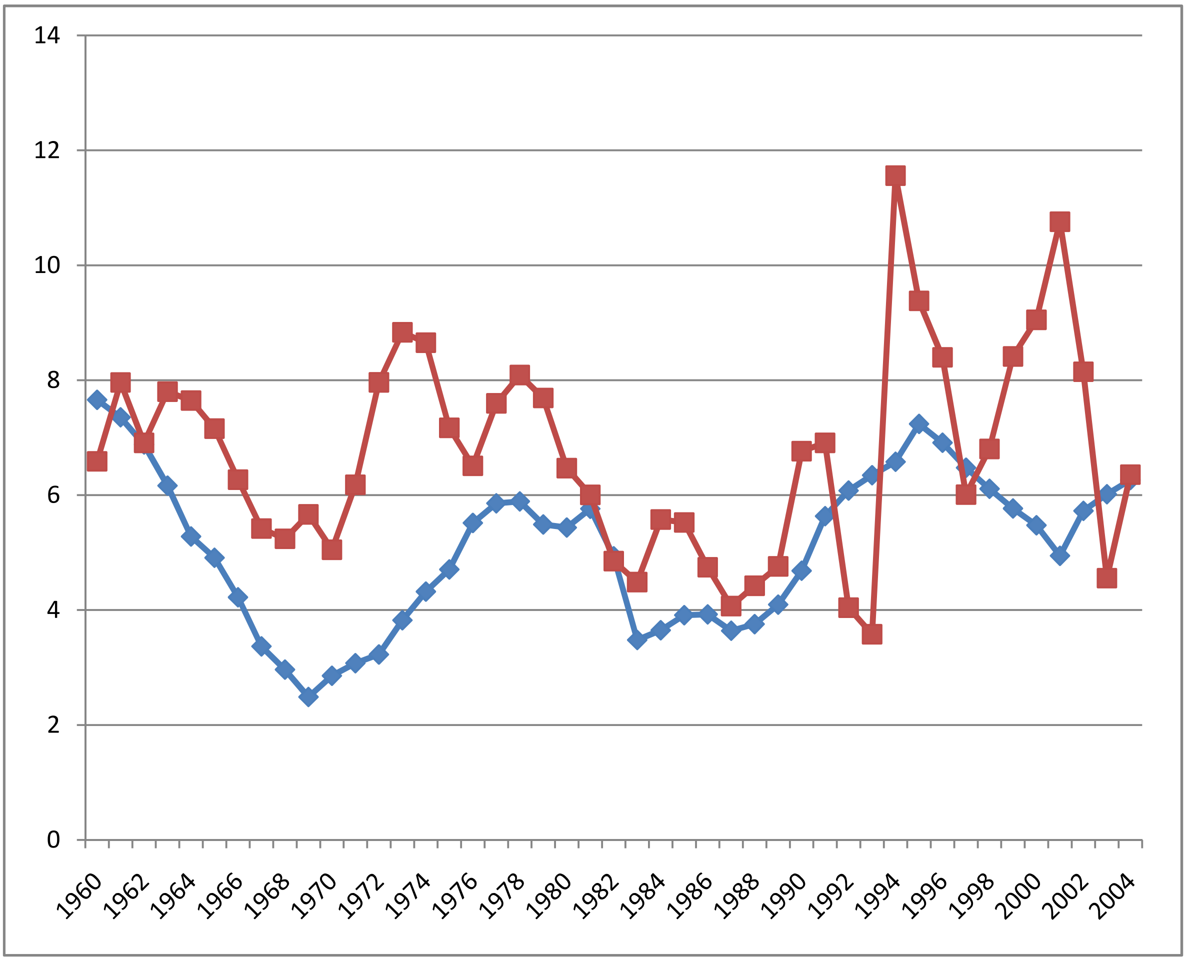

Fig. 1 The estimated total abundance in number (red, in 1,000,000) and spawning stock biomass (blue, in 10,000,000 t) by the adaptive virtual population analysis.

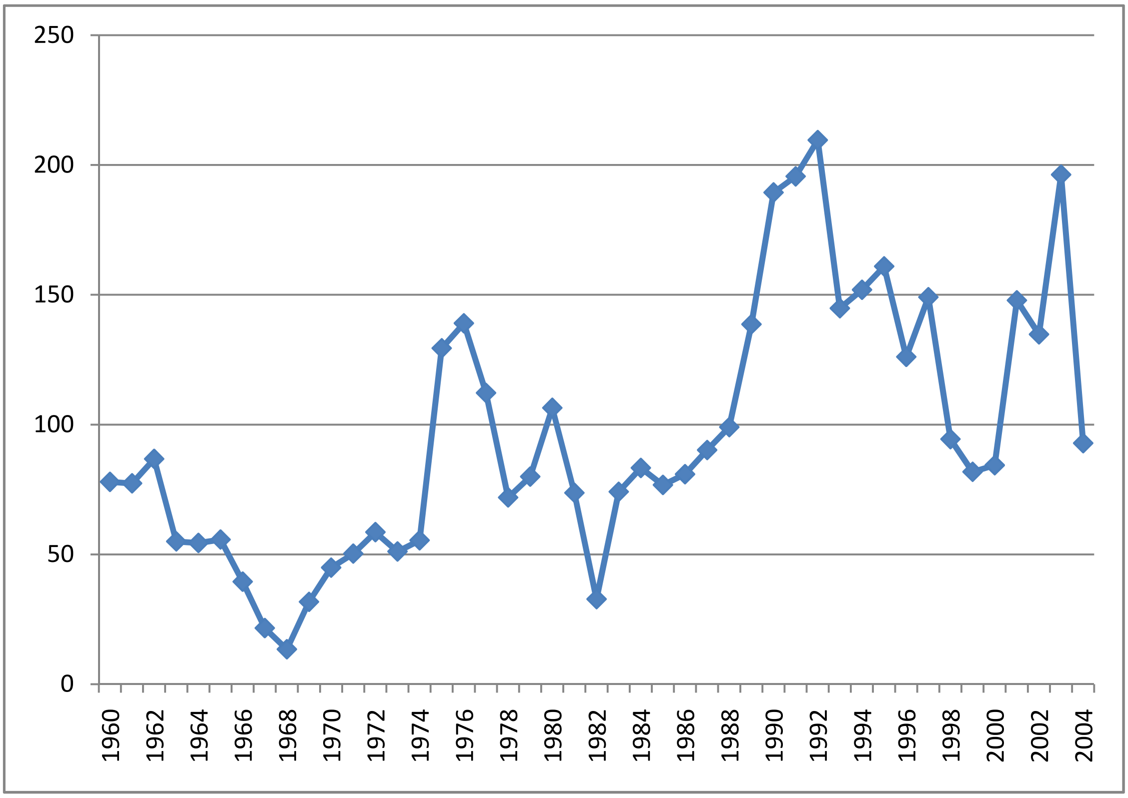

Fig. 2 The annual reproductive values (10,000,000) of North Pacific bluefin tuna from 1960 to 2004.

自評：

本研究之目的有三：其一，估計台灣小釣船捕獲太平洋黑鮪之標準化單位努力漁獲量，以做爲代表台灣利用該北太平洋黑鮪資源的豐度指標；其二，採用貝氏途徑(Bayesian Approach)將機率誤差用在生產量模式分析；和其三，有別於剃刀型之估計產卵群生物量，用生殖價(reproductive value)和族群升值潛能(population reproductive potential)來表現族群的永續更新生產力(sustainable renewal productivity)。以上之計畫目標，都已達成。並已將第一項目標所得結果，投稿日本 Fisheries Science (IF: 0.98)，現已被接受，預計 2008 年 2 月之 vol. 74, no. 5 期刊出。第二項目標，已作爲博士班助理之畢業論文，將於 96 學年度第 1 學期畢業，同時投送日本 Fisheries Science 發表，預計 2008 年刊出。。第三項目標將投 Fisheries Research (IF:1.21)。預計 2008 年刊出。