Future projections for bigeye tuna in the Indian Ocean

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1. Introduction

In this paper, we carried out the future projections from 2003 to 2023 for bigeye tuna in the Indian Ocean based on the results of stock assessment by ASPM (age-specific production model) (Nishida and Shono, 2004). Our main objective of the stock management is to keep the values of Bmsy (SSB at MSY) and Total Biomass at MSY for the future (short, medium and long term projection i.e. 2008, 2013 and 2023).

2. Material and Methods

We mainly attempted the two types of scenarios, Catch-control and F-control (fishing mortality control). We calculated both point estimation of SSB (spawning stock biomass) & TB (total biomass) and confidence intervals by bootstrap in each scenario. Following biological parameters and selectivity pattern (i.e. F in each fishery), which are the same as used in our ASPM calculation, were also utilized in these calculations (See Table 1.).

Assumptions of each scenario changing the current catch level and the current F level are described in Table 2 and 3, respectively.

Mathematical descriptions of our deterministic projection (i.e. point estimation of the stock trends) are described in the Appendix 1. The selectivity patterns (i.e. F in each fishery at Table 1) are assumed in both catch-control and F-control scenarios. Maximum F at age (in each fishery, LL and PS) are reduced not changing the selectivity in F-control scenarios (See Figure 1 and Figure 2).

We also carried out the stochastic future projection assuming the statistical error about the Stock-Recruitment curve of Beverton-Holt type (Beverton and Holt, 1957) by bootstrap re-sampling (Efron and Tibshirani, 1993) in order to estimate the confidence intervals of the trends of SSB and total-biomass. The procedure of calculation is described in the Appendix 2.

3. Results and Discussions

Figure 1 and 2 shows the trends of SSB and Total-Biomass for 2003 to 2023 when continuing the current catch level and F level, respectively. It is not realistic to keep the large fishing effort in the case that biomass drastically decrease. However, appropriate catch reduction would be necessary.

In this paper, we set the criteria for selecting adequate scenarios in terms of short-term, medium-term and long-term stock recovery. These are as follow:

Criteria from the short-term viewpoint (based on stock biomass in 2008):
- SSB ratio (=(SSB in 2008) / (SSB at MSY: 108825 ton)) is greater than (and equal to) 1.0
- TB ratio (=(Total-Biomass in 2008) / (Total-Biomass at MSY: 395854 ton)) is greater than (and equal to) 1.0
- Annual catch in C-control scenario or average catch (2003-2008) in F-control is greater than 101,605 ton (i.e. MSY level)

Criteria from the medium-term viewpoint (based on stock biomass in 2013):
- SSB ratio (=(SSB in 2013) / (SSB at MSY: 108825 ton)) is greater than (and equal to) 1.0
- TB ratio (=(Total-Biomass in 2013) / (Total-Biomass at MSY: 395854 ton)) is greater than (and equal to) 1.0
- Annual catch in C-control scenario or average catch (2003-2013) in F-control is greater than 101,605 ton (i.e. MSY level)

Criteria from the long-term viewpoint (based on stock biomass in 2023):
- SSB ratio (=(SSB in 2023) / (SSB at MSY: 108825 ton)) is greater than

(and equal to) 1.0
- TB ratio (=(Total-Biomass in 2023) / (Total-Biomass at MSY: 395854 ton)) is greater than (and equal to) 1.0
- Annual catch in C-control scenario or average catch (2003-2023) in F-control is greater than 101,605 ton (i.e. MSY level)

Table 4 – 18 show these SSB ratio, Total-Biomass ratio and catch (tonnage) in each scenario. For instance, LL0_PS15000 (in catch-control) and LL0.0_PS0.05 (in F-control) satisfy above criteria about SSB ratio, TB ratio and catch level. We should also be careful that it is effective to reduce more catch by purse seine fishery when reducing a certain amount of total catch (tonnage). It is obvious that control of PS is more effective than that of LL.

Figure 5 – 8 show the wormplots in 100 times and 90% confidence intervals by bootstrap in LL0_PS15000 and LL0.0_PS0.05 scenarios. In general, the range of confidence intervals in F control scenario is narrower than that in catch-control one. However, the management to control fishing mortality is difficult to monitor since it is a function of various factors. Therefore, it is reasonable to use corresponding catch level (to desirable F).

For instance, if it is agreed to reduce the annual total catch of 15,000 tons, then we can estimate the possibility of stock recovery to compare four catch-control scenarios, LL15000_PS0, LL10000_PS5000, LL5000_PS10000, and LL0_PS15000 in our calculation. Judging from the results in Table 4–10, there is high risk that the stock will be collapsed for the long future. However, SSB at MSY and Total-Biomass at MSY are maintained not only in 2008 (and 2013) but also in 2023 in LL0_PS15000 scenario.

In conclusion, it is necessary to reduce the current bigeye catch level to keep the sustainable yield, especially the catch by purse seine fishery. However, these results of future projection are dependant on the assumed biological parameters, especially the selectivity pattern in longline and purse seine fishery. Therefore, it is necessary to check whether or not these F-at-age are adequate (including whether or not dome-shape selectivity in longline fisheries is appropriate).

References

Beverton, R. J. H. and Holt, S. J. (1957). On the dynamics of exploited fish populations. *Fish. Invest. Ser.* II, **19**, 533p.

Efron, B. and Tibshirani, R. J. (1993). *An Introduction to the Bootstrap,* Chapman & Hall, London, 436p.

Nishida, T and Shono, H. (2004). Updated stock assessment of bigeye tuna (*Thunnus obesus*) resources in the Indian Ocean by the age structured production model (ASPM) analyses. *Submitted to IOTC-WPTT-2004 meeting*, 16p.

Note:

We can promptly/easily calculate these four kinds of future projections (Catch-control and F-control) (deterministic projection and stochastic one) based on the revised ASPM results (and so on) using our Excel-VPA macro programs during IOTC-WPTT-2004 meeting, if necessary.

Table 1. Biological parameters and F in each fishery (longline & purse seine).

Age	0	1	2	3	4	5	6	7	8+
M	0.8	0.8	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Ma	0	0	0	0.5	1	1	1	1	1
Wa	1.2	7.8	24	39	53	66	76	84	89
F(LL)	0	0.0332	0.3143	0.6179	0.6644	0.5827	0.4757	0.3156	0.3156
F(PS)	0.1352	0.2008	0.0972	0.0777	0.0695	0.0494	0.0245	0.0096	0.0005

Table 2. Twenty-five scenarios changing the current catch level (C-control).

Scenario	LL (longline)	PS (purse seine)
LL0_PS0	2002 (current) catch level (95,062 ton)	2002 (current) catch level (29,327 ton)
LL5000_PS0	Reduction of the 5000 ton of the 2002 catch level	2002 catch level
LL10000_PS0	Reduction of the 10000 ton of the 2002 catch level	2002 catch level
LL15000_PS0	Reduction of the 15000 ton of the 2002 catch level	2002 catch level
LL20000_PS0	Reduction of the 20000 ton of the 2002 catch level	2002 catch level
LL0_PS5000	2002 (current) catch level	Reduction of the 5000 ton of the 2002 catch level
LL5000_PS5000	Reduction of the 5000 ton of the 2002 catch level	Reduction of the 5000 ton of the 2002 catch level
LL10000_PS5000	Reduction of the 10000 ton of the 2002 catch level	Reduction of the 5000 ton of the 2002 catch level
LL15000_PS5000	Reduction of the 15000 ton of the 2002 catch level	Reduction of the 5000 ton of the 2002 catch level
LL20000_PS5000	Reduction of the 20000 ton of the 2002 catch level	Reduction of the 5000 ton of the 2002 catch level
LL0_PS10000	2002 (current) catch level	Reduction of the 10000 ton of the 2002 catch level
LL5000_PS10000	Reduction of the 5000 ton of the 2002 catch level	Reduction of the 10000 ton of the 2002 catch level
LL10000_PS10000	Reduction of the 10000 ton of the 2002 catch level	Reduction of the 10000 ton of the 2002 catch level
LL15000_PS10000	Reduction of the 15000 ton of the 2002 catch level	Reduction of the 10000 ton of the 2002 catch level
LL20000_PS10000	Reduction of the 20000 ton of the 2002 catch level	Reduction of the 10000 ton of the 2002 catch level
LL0_PS15000	2002 (current) catch level	Reduction of the 15000 ton of the 2002 catch level
LL5000_PS15000	Reduction of the 5000 ton of the 2002 catch level	Reduction of the 15000 ton of the 2002 catch level
LL10000_PS15000	Reduction of the 10000 ton of the 2002 catch level	Reduction of the 15000 ton of the 2002 catch level
LL15000_PS15000	Reduction of the 15000 ton of the 2002 catch level	Reduction of the 15000 ton of the 2002 catch level
LL20000_PS15000	Reduction of the 20000 ton of the 2002 catch level	Reduction of the 15000 ton of the 2002 catch level
LL0_PS20000	2002 (current) catch level	Reduction of the 20000 ton of the 2002 catch level
LL5000_PS20000	Reduction of the 5000 ton of the 2002 catch level	Reduction of the 20000 ton of the 2002 catch level
LL10000_PS20000	Reduction of the 10000 ton of the 2002 catch level	Reduction of the 20000 ton of the 2002 catch level
LL15000_PS20000	Reduction of the 15000 ton of the 2002 catch level	Reduction of the 20000 ton of the 2002 catch level
LL20000_PS20000	Reduction of the 20000 ton of the 2002 catch level	Reduction of the 20000 ton of the 2002 catch level

Table 3. Twenty-five scenarios changing the current F level (F-control).

Scenario	LL (longline)	PS (purse seine)
LL0.0_PS0.0	2002 (current) F level (F at age 4 is 0.6644)	2002 (current) F level (F at age 1 is 0.2008)
LL0.05_PS0.0	Reduction of the 0.05 of the 2002 F level	2002 F level
LL0.1_PS0.0	Reduction of the 0.1 of the 2002 F level	2002 F level
LL0.15_PS0.0	Reduction of the 0.15 of the 2002 F level	2002 F level
LL0.2_PS0.0	Reduction of the 0.2 of the 2002 F level	2002 F level
LL0.0_PS0.05	2002 (current) F level	Reduction of the 0.05 of the 2002 F level
LL0.05_PS0.05	Reduction of the 0.05 of the 2002 F level	Reduction of the 0.05 of the 2002 F level
LL0.1_PS0.05	Reduction of the 0.1 of the 2002 F level	Reduction of the 0.05 of the 2002 F level
LL0.15_PS0.05	Reduction of the 0.15 of the 2002 F level	Reduction of the 0.05 of the 2002 F level
LL0.2_PS0.05	Reduction of the 0.2 of the 2002 F level	Reduction of the 0.05 of the 2002 F level
LL0.0_PS0.1	2002 (current) F level	Reduction of the 0.1 of the 2002 F level
LL0.05_PS0.1	Reduction of the 0.05 of the 2002 F level	Reduction of the 0.1 of the 2002 F level
LL0.1_PS0.1	Reduction of the 0.1 of the 2002 F level	Reduction of the 0.1 of the 2002 F level
LL0.15_PS0.1	Reduction of the 0.15 of the 2002 F level	Reduction of the 0.1 of the 2002 F level
LL0.2_PS0.1	Reduction of the 0.2 of the 2002 F level	Reduction of the 0.1 of the 2002 F level
LL0.0_PS0.15	2002 (current) F level	Reduction of the 0.15 of the 2002 F level
LL0.05_PS0.15	Reduction of the 0.05 of the 2002 F level	Reduction of the 0.15 of the 2002 F level
LL0.1_PS0.15	Reduction of the 0.1 of the 2002 F level	Reduction of the 0.15 of the 2002 F level
LL0.15_PS0.15	Reduction of the 0.15 of the 2002 F level	Reduction of the 0.15 of the 2002 F level
LL0.2_PS0.15	Reduction of the 0.2 of the 2002 F level	Reduction of the 0.15 of the 2002 F level
LL0.0_PS0.2	2002 (current) F level	Reduction of the 0.2 of the 2002 F level
LL0.05_PS0.2	Reduction of the 0.05 of the 2002 F level	Reduction of the 0.2 of the 2002 F level
LL0.1_PS0.2	Reduction of the 0.1 of the 2002 F level	Reduction of the 0.2 of the 2002 F level
LL0.15_PS0.2	Reduction of the 0.15 of the 2002 F level	Reduction of the 0.2 of the 2002 F level
LL0.2_PS0.2	Reduction of the 0.2 of the 2002 F level	Reduction of the 0.2 of the 2002 F level

Table 4. (SSB in 2008) / (SSB at MSY: 108825 ton) in each C-control scenario.

LL \ PS		±0	-5000	-10000	-15000	-20000
		29,327	24,327	19,327	14,327	9,327
±0	95,062	0.22704	0.44706	0.68947	0.94359	1.20433
-5000	90,062	0.37690	0.61293	0.86274	1.12030	1.38246
-10000	85,062	0.53866	0.78367	1.03771	1.29713	1.55988
-15000	80,062	0.70657	0.95673	1.21314	1.47345	1.73627
-20000	75,062	0.87752	1.13063	1.38829	1.64891	1.91147

Table 5. (TB in 2008) / (TB at MSY: 395854 ton) in each C-control scenario.

LL \ PS		±0	-5000	-10000	-15000	-20000
		29,327	24,327	19,327	14,327	9,327
±0	95,062	0.63458	0.77756	0.91049	1.03625	1.15658
-5000	90,062	0.71388	0.84959	0.97749	1.09950	1.21688
-10000	85,062	0.78760	0.91779	1.04164	1.16053	1.27539
-15000	80,062	0.85713	0.98294	1.10345	1.21969	1.33237
-20000	75,062	0.92337	1.04561	1.16329	1.27724	1.38802

Table 6. (SSB in 2013) / (SSB at MSY: 108825 ton) in each C-control scenario.

LL \ PS		±0	-5000	-10000	-15000	-20000
		29,327	24,327	19,327	14,327	9,327
±0	95,062	0.00000	0.01489	0.51968	1.06595	1.55875
-5000	90,062	0.00000	0.29010	0.84981	1.36144	1.82667
-10000	85,062	0.08149	0.62475	1.15595	1.63728	2.08043
-15000	80,062	0.39321	0.94161	1.44059	1.89742	2.32273
-20000	75,062	0.71806	1.23587	1.70785	2.14494	2.55559

Table 7. (TB in 2013) / (TB at MSY: 395854 ton) in each C-control scenario.

LL \ PS		±0	-5000	-10000	-15000	-20000
		29,327	24,327	19,327	14,327	9,327
±0	95,062	0.00000	0.44659	0.83821	1.08044	1.27397
-5000	90,062	0.03586	0.69453	0.97264	1.18203	1.35947
-10000	85,062	0.51495	0.85331	1.08759	1.27267	1.43859
-15000	80,062	0.71729	0.97747	1.18081	1.35564	1.51288
-20000	75,062	0.86063	1.08278	1.26843	1.43294	1.58336

Table 8. (Annual fixed catch) / (MSY: 101605 ton) in each C-control scenario.

LL \ PS		±0	-5000	-10000	-15000	-20000
		29,327	24,327	19,327	14,327	9,327
±0	95,062	1.22424	1.17503	1.12582	1.07661	1.02740
-5000	90,062	1.17503	1.12582	1.07661	1.02740	0.97819
-10000	85,062	1.12582	1.07661	1.02740	0.97819	0.92897
-15000	80,062	1.07661	1.02740	0.97819	0.92897	0.87976
-20000	75,062	1.02740	0.97819	0.92897	0.87976	0.83055

Remark) MSY, SSB at MSY and TB at MSY are obtained from ASPM results.

Table 9. (SSB in 2023) / (SSB at MSY: 108825 ton) in each C-control scenario.

PS / LL		±0	-5000	-10000	-15000	-20000
		29,327	24,327	19,327	14,327	9,327
±0	95,062	0.00000	0.00000	0.09433	1.20652	1.81961
-5000	90,062	0.00000	0.00000	0.83164	1.56917	2.09851
-10000	85,062	0.00000	0.28456	1.27987	1.87349	2.35442
-15000	80,062	0.00000	0.92296	1.62413	2.14550	2.59464
-20000	75,062	0.42385	1.33807	1.91910	2.39679	2.82336

Table 10. (TB in 2023) / (TB at MSY: 395854ton) in each C-control scenario.

PS / LL		±0	-5000	-10000	-15000	-20000
		29,327	24,327	19,327	14,327	9,327
±0	95,062	0.00000	0.00000	0.57846	1.12938	1.35627
-5000	90,062	0.00000	0.00000	0.96569	1.25006	1.44295
-10000	85,062	0.00000	0.68738	1.12649	1.34723	1.52113
-15000	80,062	0.00000	0.97049	1.24084	1.43190	1.59361
-20000	75,062	0.72946	1.11787	1.33524	1.50905	1.66198

Table 11.(SSB in 2008) / (SSB at MSY: 108825ton) in each F-control scenario.

PS / LL	±0	-0.05	-0.1	-0.15	-0.2
±0	0.89204	1.00365	1.12971	1.27213	1.43307
-0.05	0.96157	1.08189	1.21783	1.37144	1.54508
-0.1	1.03915	1.16915	1.31605	1.48210	1.66984
-0.15	1.12597	1.26675	1.42586	1.60575	1.80918
-0.2	1.22341	1.37622	1.54896	1.74429	1.96522

Table 12. (TB in 2008) / (TB at MSY: 395854ton) in each F-control scenario.

PS / LL	±0	-0.05	-0.1	-0.15	-0.2
±0	0.93826	1.01159	1.09242	1.18159	1.28006
-0.05	0.96123	1.03783	1.12119	1.21386	1.31619
-0.1	0.98646	1.06551	1.15281	1.24932	1.35610
-0.15	1.01427	1.09663	1.18768	1.28843	1.40000
-0.2	1.04505	1.13108	1.22627	1.33171	1.44860

Table 13. Average catch of six years (2003-2008) in each F-control scenario.

PS / LL	±0	-0.05	-0.1	-0.15	-0.2
±0	104,294	104,353	104,265	103,999	103,521
-0.05	102,231	102,065	101,721	101,165	100,360
-0.1	99,918	99,499	98,868	97,987	96,813
-0.15	97,318	96,612	95,658	94,411	92,822
-0.2	94,385	93,357	92,038	90,377	88,319

Table 14.(SSB in 2013) / (SSB at MSY: 108825ton) in each F-control scenario.

PS / LL	±0	-0.05	-0.1	-0.15	-0.2
±0	0.88161	1.00155	1.13793	1.29306	1.46957
-0.05	0.95285	1.08330	1.23179	1.40088	1.59347
-0.1	1.03306	1.17545	1.33770	1.52265	1.73354
-0.15	1.12377	1.27977	1.45772	1.66079	1.89259
-0.2	1.22685	1.39843	1.59437	1.82822	2.07405

Table 15. (TB in 2013) / (TB at MSY: 395854ton) in each F-control scenario.

PS / LL	±0	-0.05	-0.1	-0.15	-0.2
±0	0.93466	1.01098	1.09533	1.18867	1.29208
-0.05	0.95833	1.03785	1.12586	1.22342	1.33169
-0.1	0.98450	1.06761	1.15976	1.26208	1.37583
-0.15	1.01361	1.10077	1.19760	1.30531	1.42528
-0.2	1.04616	1.13793	1.24008	1.35392	1.48097

Table 16. Average catch of 11 years (2003-2013) in each F-control scenario.

PS / LL	±0	-0.05	-0.1	-0.15	-0.2
±0	103,031	104,825	106,618	108,396	110,142
-0.05	101,470	103,050	104,598	106,097	107,521
-0.1	99,669	101,003	102,271	103,446	104,499
-0.15	97,589	98,637	99,579	100,380	101,002
-0.2	95,175	95,895	96,457	96,822	96,943

Table 17.(SSB in 2023) / (SSB at MSY: 108825ton) in each F-control scenario.

PS / LL	±0	-0.05	-0.1	-0.15	-0.2
±0	0.88109	1.00147	1.13836	1.29409	1.47131
-0.05	0.95238	1.08340	1.23255	1.40241	1.59592
-0.1	1.03271	1.17580	1.33893	1.52489	1.73699
-0.15	1.12364	1.28057	1.45964	1.66405	1.89746
-0.2	1.22708	1.39988	1.59731	1.82295	2.08093

Table 18. (TB in 2023) / (TB at MSY: 395854ton) in each F-control scenario.

PS / LL	±0	-0.05	-0.1	-0.15	-0.2
±0	0.93826	1.01096	1.09547	1.18899	1.29263
-0.05	0.95817	1.03788	1.12610	1.22389	1.33245
-0.1	0.98439	1.06770	1.16014	1.26277	1.37687
-0.15	1.01357	1.10102	1.19818	1.30629	1.42672
-0.2	1.04623	1.13837	1.24096	1.35532	1.48298

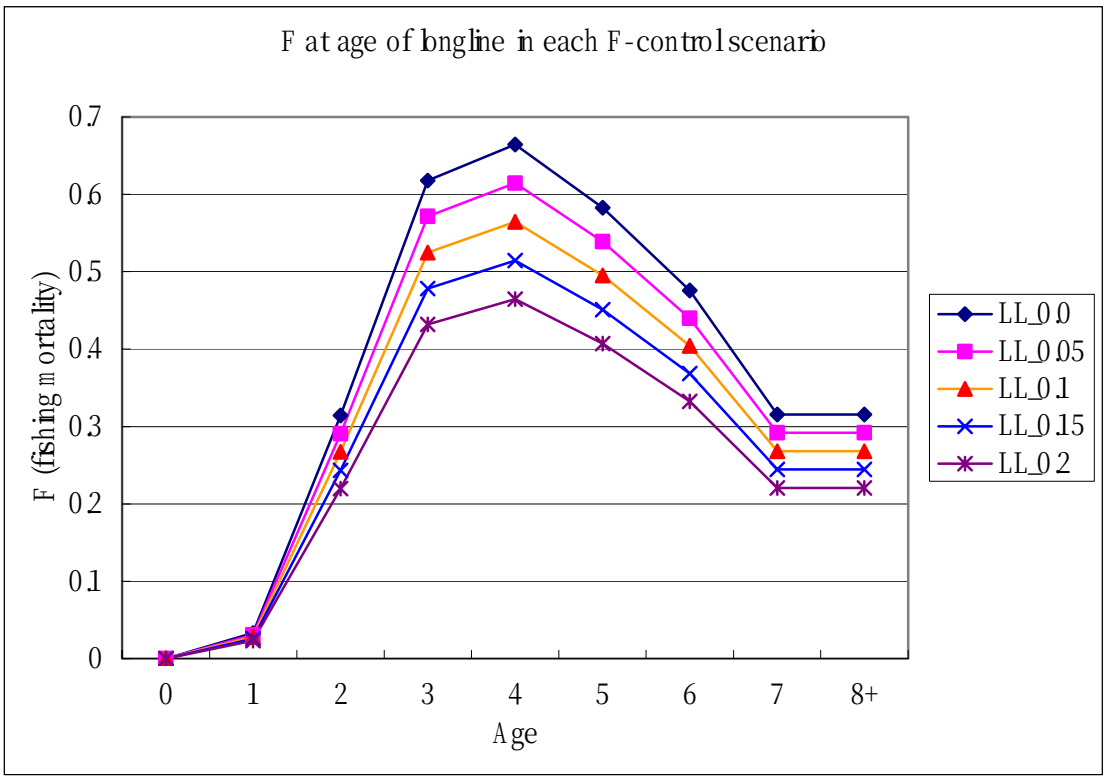

Figure 1. Selectivity pattern of longline fishery in each F-control scenario.

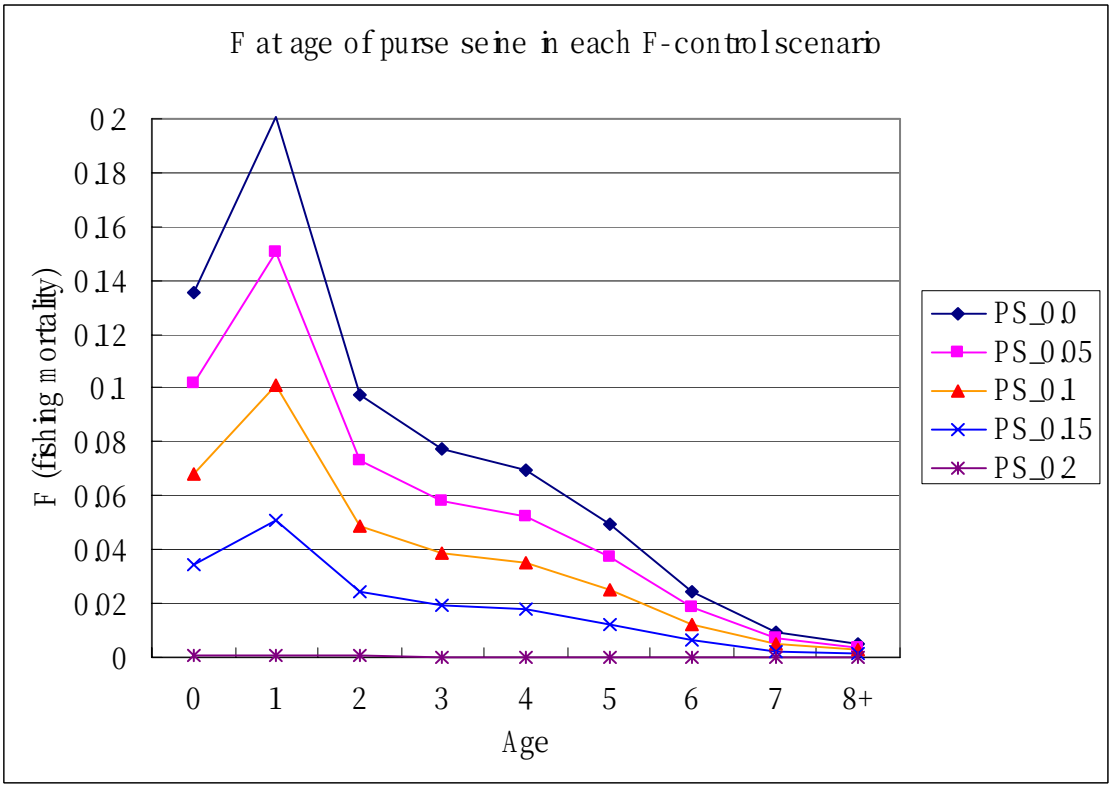

Figure 2. Selectivity pattern of purse seine fishery in each F-control scenario.

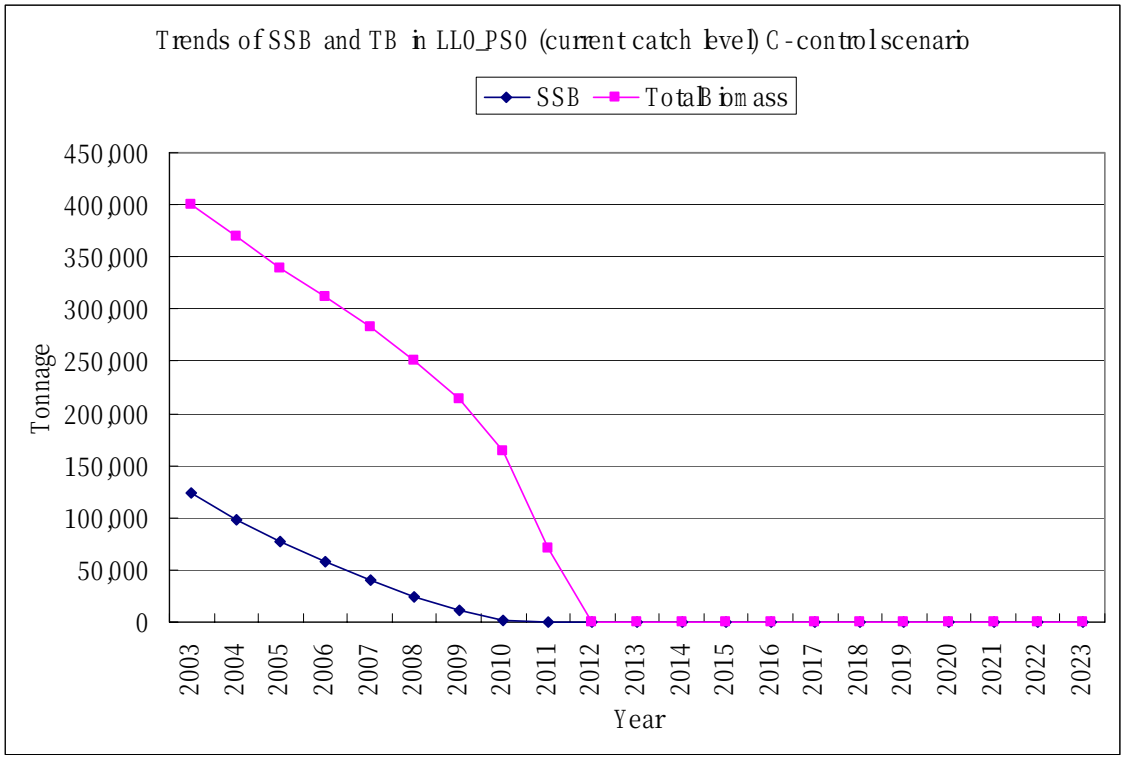

Figure 3. Trends of SSB and TB when continuing the current catch level.

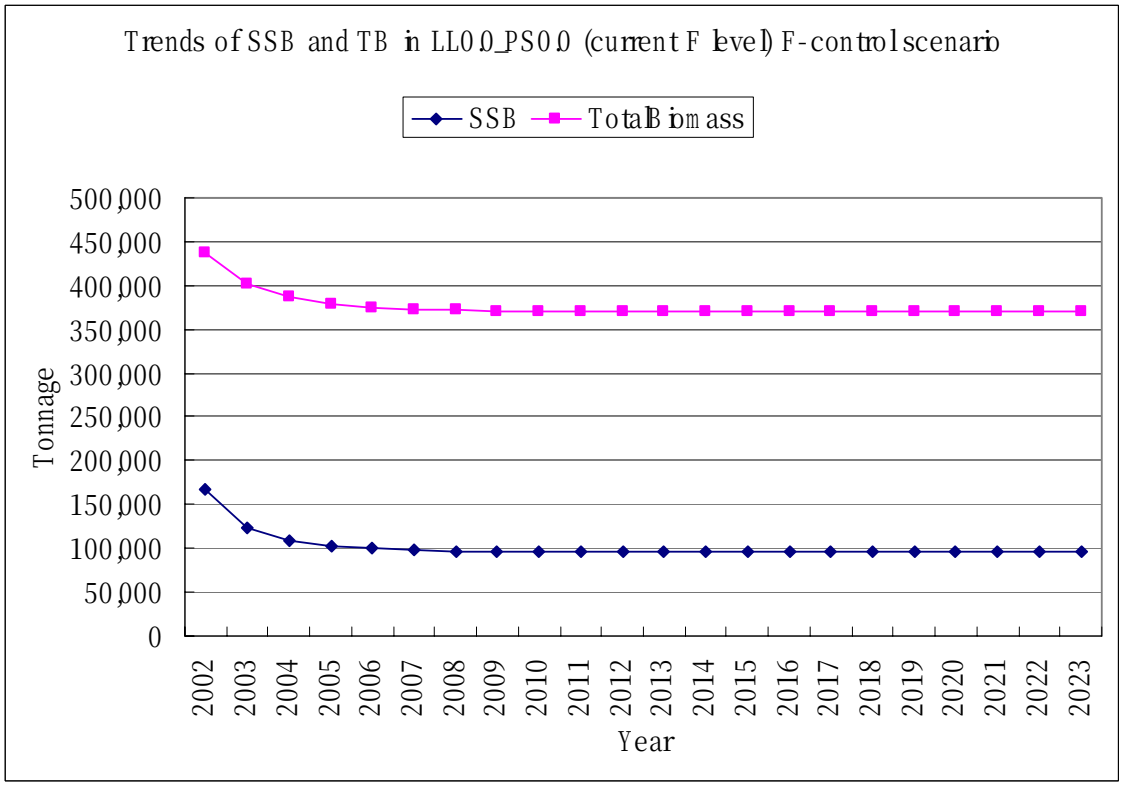

Figure 4. Trends of SSB and TB when continuing the current F level.

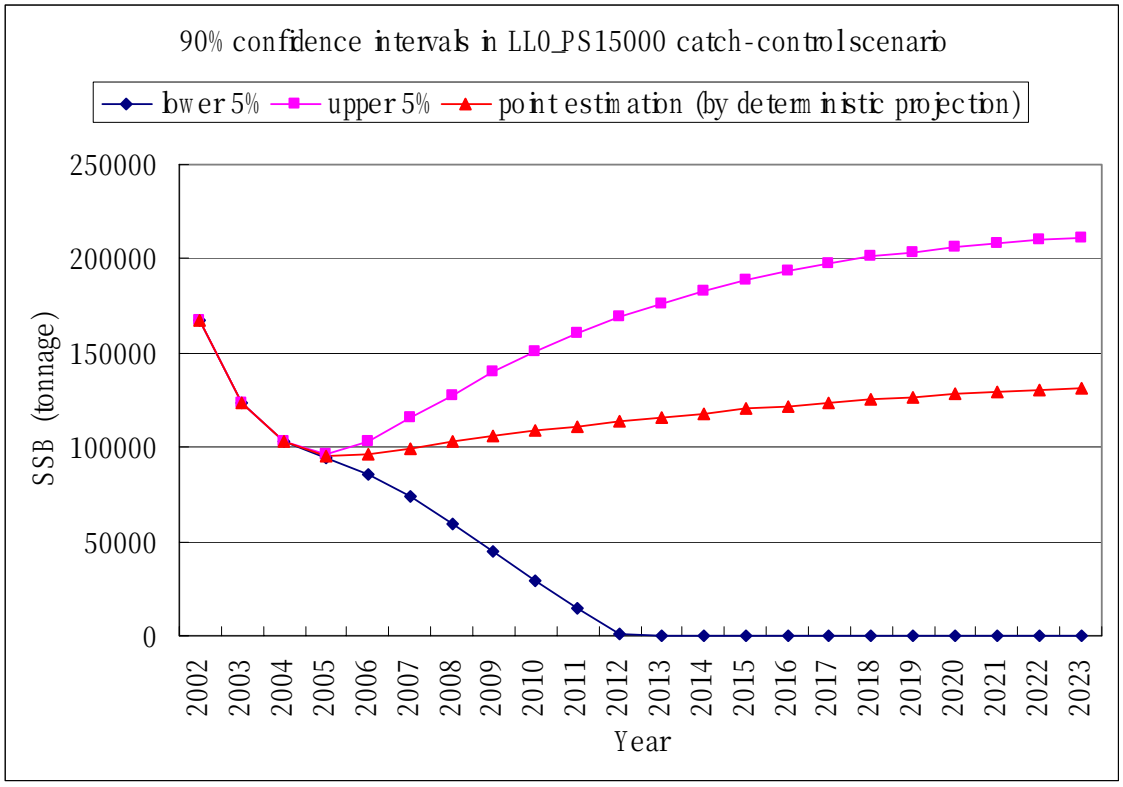

Figure 5. SSB trends (90% confidence intervals) in LL0_PS15000 scenario.

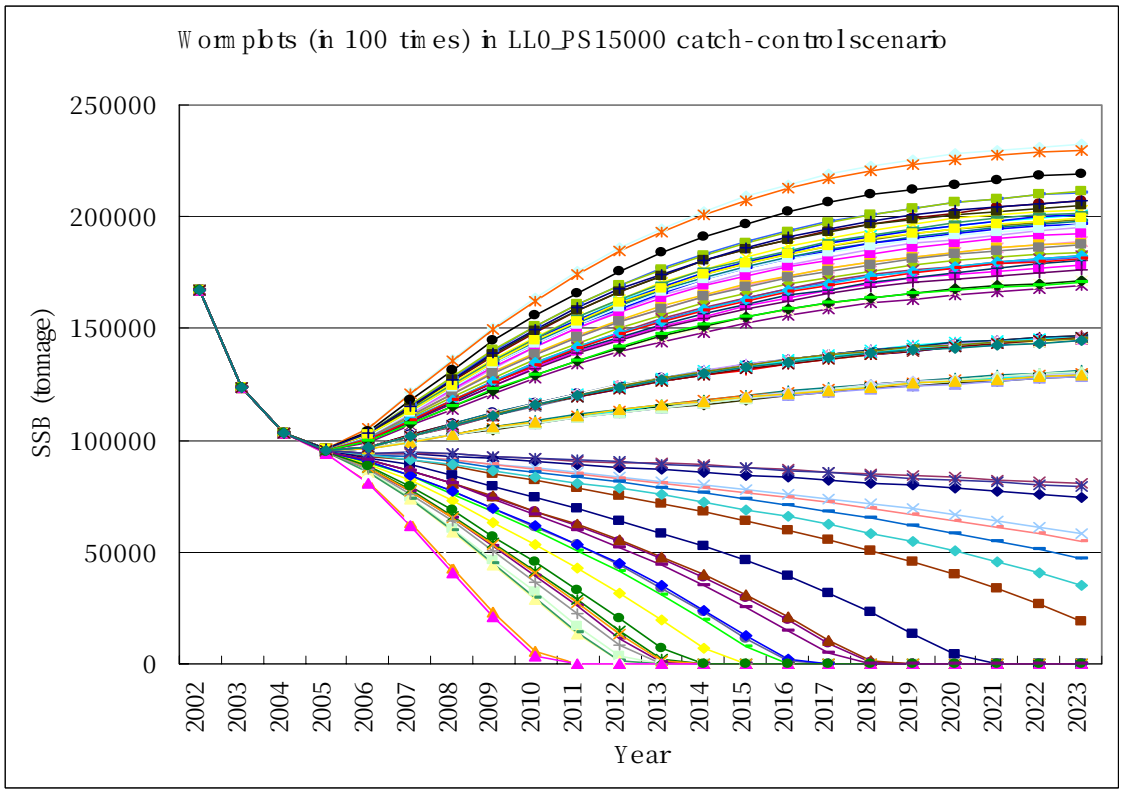

Figure 6. Wormplots in 100 times of SSB trends in LL0_PS15000 scenario.

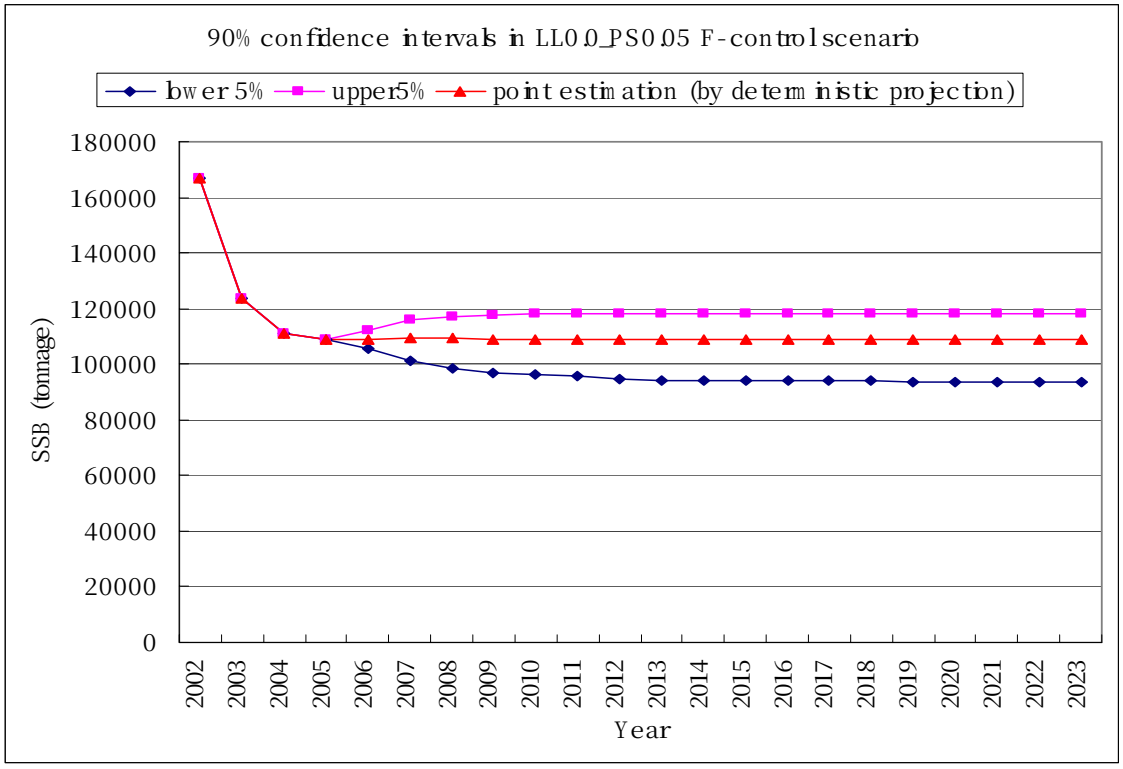

Figure 7. SSB trends (90% confidence intervals) in LL0.0_PS0.05 scenario.

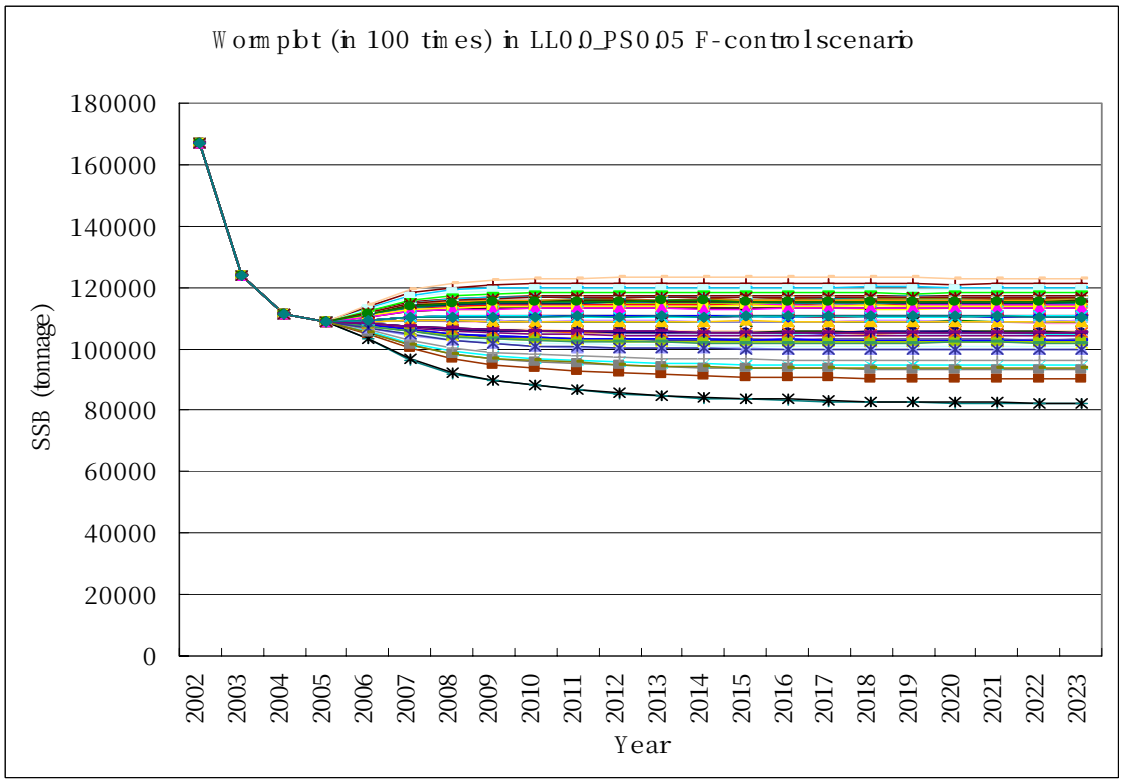

Figure 8. Wormplots in 100 times of SSB trends in LL0.0_PS0.05 scenario.

Appendix 1. Basic framework of future projection based on the ASPM results

$$\left\{\begin{array}{l} N_{a+1,y+1} = N_{a,y}\exp(-Z_{a,y}) \ \ (a=0,...,6) \\ N_{8+,y+1} = N_{7,y}\exp(-Z_{a,y}) + N_{8+,y}\exp(-Z_{8+,y}) \end{array}\right\} \quad \text{(A.1)}$$

$$R_y = N_{0,y} = \frac{\alpha * SSB_y}{\beta + SSB_y} \text{(S-R curve in the deterministic projection)} \quad \text{(A.2)}$$

$$Z_{a,y} = F_{a,y} + M_a \quad \text{(A.3)}$$

$$F_{a,y} = F_{a,y}^{LL} + F_{a,y}^{PS} \quad \text{(A.4)}$$

where
$a-age,\ y-year,\ LL-longline,\ PS-purse\ seine.$

As the parameters of Beverton-Holt curve in equation (A.2), we used the estimated values obtained from the ASPM calculation, $\hat{\alpha}$=31427000 and $\hat{\beta}$=1734.9.

$$F_{a,y}^{LL} = s_a^{LL} f_y^{LL},\ F_{a,y}^{PS} = s_a^{PS} f_y^{PS} \quad \text{(A.5)}$$

We utilized the assumption so-called 'separability' expressed in equation (A.5) in our projections. Thus, catch in each fishery (LL and PS) in the following catch-equations are showed as a function of f_y (unknown parameters).

$$\left\{\begin{array}{l} C_{a,y}^{LL}(f_y^{LL}) = N_{a,y}F_{a,y}^{LL}\{1-\exp(-Z_{a,y})\}/Z_{a,y} \\ C_{a,y}^{PS}(f_y^{PS}) = N_{a,y}F_{a,y}^{PS}\{1-\exp(-Z_{a,y})\}/Z_{a,y} \end{array}\right\} \quad \text{(A.5)}$$

At last, we estimated these parameters through minimizing the following equation (A.6) so as to fit in assumed fishing pattern of LL and PS $C_{a,y}^{LL*}, C_{a,y}^{PS*}$ $(C_{a,y}^{*} = C_{a,y}^{LL*} + C_{a,y}^{LL*})$ with catch in each fishery obtained from the models (i.e. above catch-equations).

$$\left(C_{a,y}^{LL*} - C_{a,y}^{LL}(f_y^{LL})\right)^2 + \left(C_{a,y}^{PS*} - C_{a,y}^{PS}(f_y^{PS})\right)^2 \to 0 \ \ (f_y^{LL}, f_y^{PS}) \quad \text{(A.6)}$$

Appendix 2. Procedure of stochastic projection using bootstrap experiments.

Step-1. Do bootstrap re-sampling for the pair of (SSB_y, R_{y+1}) (y=1977…2002)

Step-2. Estimate the Beverton-Holt stock-recruitment curve (i.e. unknown parameter, α and β).

Step-3. Add log-normal random numbers to the part of future recruitment (2003-2023) using the following S-R curve instead of equation (A.2).

$$R = \frac{\alpha^* * SSB}{\beta^* + SSB} \exp\left(\varepsilon - \frac{\sigma^2}{2}\right),\ \varepsilon \sim N(0, \sigma^2) \quad \text{(stochastic projection)} \qquad \text{(A.7)}$$

In this step, we used the following value, $\hat{\sigma}^2$, as an estimate of σ^2.

$$\hat{\sigma}^2 = \log\{(CV)^2 + 1\} (= 0.045447804...)$$

$$CV = \sqrt{\frac{1}{25} \sum_{y=1978}^{2002} \frac{(R_y - \hat{R}_y)^2}{\hat{R}_y^2}} \qquad \text{(A.8)}$$

where

R_y: past observed number of recruitment (i.e. number at age 0) in year y,

$\hat{R}_y$: number of recruitment (in year y) estimated from the equation (A.2).

Step-4: Make the future projection up to year 2023 by catch-control scenario or F-control one.

Step-5: Replicate these processes (for Step-1 to Step-5) in 100 times.

Step-6: Calculate the 90% confidence intervals of SSB and Total-Biomass using the way for bias correction of bootstrap re-sampling, called 'BC-method' (Efron and Tibshirani, 1993).