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Evaluating productivity parameter uncertainty using the age-structured production model diagnostic with recruitment

Huihua Lee[a], Desiree Tommasi[a,b], Fukuda Hiromu[c], Kevin Piner[d]

a: NOAA Fisheries, Southwest Fisheries Science Center,
La Jolla, CA, USA
b: Institute of Marine Sciences, University of California Santa Cruz,
Santa Cruz, CA, USA
c: Fisheries Stock Assessment Center, Fisheries Resources Institute, Japan Fisheries
Research and Education Agency, Japan
d: NOAA Fisheries (retired),
WY, USA

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Summary

Management strategy evaluation (MSE) evaluates how robust a feedback-control management strategy is to uncertainties using forward simulation. These uncertainties include process uncertainty, parameter uncertainty, model uncertainty, data and observation systems error, and implementation uncertainty. Among these uncertainties, the productivity parameters, length at age 3, natural mortality for age 2 and older, and steepness of the stock-recruitment relationship, greatly impacted the historical trajectory of Pacific bluefin tuna spawning stock biomass in the 2022 assessment. Potential combinations for the values of these parameters are enormous, and some combinations may not be plausible for the stock, given the fishing history and life-history traits. A plausible uncertainty grid for productivity parameters was selected based on the following steps. We first selected the range of productivity parameters based on the data and life-history information. We then showed that the age-structured production model diagnostic with recruitment (ASPM-R) is a valuable tool for selecting productivity combinations. The PBF model prefers larger length at age 3 and higher natural mortality for age 2 and older than the base values. The larger the length at age 3 and natural mortality for age 2 and older are, the broader range of potential steepness parameters selected. Last, we eliminated low productivity assumption that created low depletion levels not consistent with the history of the PBF fishery. The final combinations were candidates for the uncertainty grid for the MSE operating model(s).

Introduction

Fishery managers and decision-makers today sometimes rely on management strategy evaluation (MSE) outcomes to decide what management strategies will be implemented in the future. MSE uses a forward simulation approach to determine how robust feedback-control management strategies are to uncertainties (Smith 1994). MSE takes account of the collection and use of future data and uncertainties in the managed system.

One notable benefit of an MSE is the ability to assess management strategies under a range of uncertainties in the system. Uncertainties are five folds in MSE: (1) process uncertainty, (2) parameter uncertainty, (3) model uncertainty, (4) errors in data and observation systems when conducting assessments, and (5) implementation uncertainty, as outlined in Punt et al. 2016. Process uncertainty is the random variation in parameters such as future recruitment and time-varying selectivity. Parameter uncertainty is the uncertainty in the parameter values fixed in the operating models (e.g., steepness, natural mortality). Model uncertainty is the uncertainty in the form of the biological relationship (e.g., whether the stock-recruitment relationship is Beverton-Holt or Ricker, whether fishery selectivity is asymptotic or dome-shaped). Errors in data and observation systems related to collecting data, such as catches, size compositions, or surveys. Implementation uncertainty may arise from imperfectly implemented management actions.

The ISC Pacific bluefin tuna (PBF) working group is tasked to develop an MSE to help inform a long-term management strategy for PBF once the stock is rebuilt to the second rebuilding target of 20%SSB_0 (JWG 2022). Tommasi and Lee 2022 outlined the general MSE framework for PBF and addressed process uncertainty, data and observation systems errors, and implementation uncertainty. In this working paper, we aim to evaluate the parameter uncertainties that greatly impact the historical trajectory of the stock.

Methods

In the 2022 stock assessment, the ISCPBF working group identified productivity parameters as the most influential and uncertain among the uncertainties examined (including model uncertainty and errors in data and observation systems; ISC 2022). These productivity parameters are length at age 3 (L_2), natural mortality for age 2 and older (M_{2+}), and steepness of the stock-recruitment relationship (h). Length at age 3 (L_2) was estimated externally from otolith data and specified in the assessment model as a fixed value. Parameters M_2 and h were estimated externally based on direct data from tagging and indirect information (e.g., through empirical relationships). They were specified in the assessment model.

The uncertainty associated with these productivity parameters was examined via changing parameter value(s) for each parameter (i.e., sensitivity analysis) in the assessment model. The combinations of the values of these parameters have yet to be explored and can be enormous. A decision must be made to select the plausible combination of the productivity parameters for the stock, given its fishing history and life-history traits. We first reviewed the direct data and indirect information to select the range of these parameters. We then fit the fishery data into the assessment model under these alternative productivity assumptions.

Determining the range of the productivity parameters

A suit of empirical estimators of M was used to explore the range of the natural mortality for mature fish. These estimators were based on the maximum age, von Bertalanffy growth function, and age at maturity (Table 1). A meta-analysis was then used to synthesize all methods giving equal weight to each method for each estimator.

The length-at-age data from otoliths collected by Japanese and Taiwanese scientists between 1992 and 2014 (Fukuda et al. 2015) were used to explore the range of the length-at-age 3 in the first quarter. A total of 1,782 pairs of length-at-age were summarized, ranging from 1 to 27 years old and from 70.5 cm to 271 cm in fork length.

There is less information to guide the choice of a range for parameter h than M or length-at-age due to the lack of early life history data. Independent estimates of steepness that incorporated biological and ecological characteristics of the stock (Iwata 2012; Iwata et al. 2012b) reported that the mean of h was around 0.999. We initially explore a broad range of h values from 0.6 to 1.

Age-structured production model with recruitment (ASPM-R)

Lee et al. (2022) used the age-structured production model diagnostic (ASPM; Maunder and Piner 2015) to select a plausible uncertainty grid for the productivity parameters based on the improvement of the fits of the adult indices from the short time series model (ISC 2022). However, this approach did not account for the cohort growth influencing stock productivity. We therefore used here the age-structured production model diagnostic with recruitment (ASPM-R). First, the short-time model was fit to catch, size compositions, and abundance indices (adult and recruitment indices) just like the assessment model, but alternative productivity assumptions were specified. The ASPM-R model was then conducted with recruitment deviations and selectivities specified at the estimates from the short-time model. The ASPM-R model estimated scaling parameters (ln(R0) and R1) and the initial F and fit to catch and adult abundance indices. This ASPM-R model with the alternative assumption was compared to the ASPM-R model with the base-case assumption. A statistical degradation of more than 2 likelihood units of the total likelihood in the ASPM-R model with the alternative assumption as compared to the total likelihood from the ASPM-R model with the base-case assumption was considered an implausible productivity combination for the stock.

Results

The plausible range of the length-at-age 3 in the first quarter

The length-at-age 3 in the first quarter (L_2 = 3.0 years old) was specified at 118.57 cm fork length, with the CV of the length-at-age 3 at 4.4% in the 2022 stock assessment model. The fish grows from the previous quarter (2.75 years old) at 112.25 cm to 124.6 cm in the second quarter of age 3 (3.25 years old) based on the growth assumptions in the assessment. From the aging data, 32 out of 1,782 pairs of length-at-age were in the first quarter of age 3 if the aging error is ignored. The first quantile, median, and third quantile of the 32 pairs were 117, 120, and 125 cm, respectively. After synthesizing the model-based estimates and aging data, we therefore selected the range of L_2 used in the following analyses from 116 to 126 cm.

The plausible range of natural mortality for mature fish

A suite of empirical estimates of M are shown in Table 1. Four methods (Then_nls, Then_lm, Hamel_Amax, and ZM_CA_pel) using maximum age estimated M from 0.16 to 0.26 with an average of 0.19 for the maximum age of 25 years old and from 0.13 to 0.23 with an average of 0.21 for the maximum age of 28 years old, respectively. Four methods (Then_VBGF, Hamel_k, Jensen_k1, and Jensen_k2) using the von Bertalanffy growth function (Linf= 249.917, k=0.188, t0=-0.42174) estimated M from 0.20 to 0.30 with an average of 0.28. Three methods (Roff, Jensen_Amat, and Ri_Ef_Amat) using age at full maturity as 5 years old estimated M from 0.32 to 0.36 with an average of 0.34. The synthesized M estimate from each estimator given equal weight was 0.27 and 0.28 for the maximum age of 28 and 25 years old, respectively. We therefore selected the range of the mature M used in the following analyses from 0.20 to 0.30. We limit the M at a maximum of 0.3, given that an M higher than 0.3 seems biologically implausible (there was no fish left at age 19 and above without fishing).

Age-structured production model with recruitment (ASPM-R)

Table 2 shows the total likelihood values from the ASPM-R models with alternative length at age 3 (L_2), natural mortality for age 2 and older (M_{2+}), and steepness (h) (Table 2). The total likelihood values generally degraded when the steepness value was smaller regardless of M_{2+} or L_2 values. The degradation was defined as the difference in total likelihood between the alternative ASPM-R model and the base ASPM-R model, where this difference is greater and equal to two likelihood units. If this difference is smaller than two or positive, the alternative ASPM-R model is considered not statistically different or better than the base ASPM-R model.

The model preferred larger L_2 than the base value regardless of M_{2+}. In other words, none of the combinations of h and M_{2+} were selected when L_2 was 116 cm. The selected range of h expanded when L_2 was larger. In the case of M_{2+}=0.25, the selected values of h were 0.95- 0.999 when L_2 was 118.57, whereas the selected h expanded to 0.87 when L_2 was 124. The exceptions happened when M_{2+} was 0.2, where the models with h values between 0.93 and 0.97 did not converge when L_2 was 124 or 126 cm. For each L_2 from 116 to 126 cm, the best fit was at a higher steepness value (0.99 - 0.999).

The stock also preferred higher M_{2+}. The selected range of h expanded when M_{2+} was higher. In the case of L_2=118.57, the selected h was at 0.999 when M_{2+} was 0.2, whereas the selected h expanded to 0.87 when M_{2+} was 0.3.

These selected grids were further examined by the absolute scale of the model (i.e., unfished spawning stock biomass, SSB0) and the relative scale of the model (i.e., spawning stock biomass ratio, SSBratio1983 = SSB1983/SSB0 and SSBratio2020 = SSB2020/SSB0). The depletion level at the starting year against the depletion level in the terminal year showed two depletion patterns (Figure 1). The distinct pattern was related to the productivity associated with low h (low productivity) (Figure 2). These grids had steepness smaller than 0.83 when M_{2+} was 0.3 or steepness smaller than 0.87 when M_{2+} was 0.25 (Figures 1 and 2, Table 2). We then eliminated these relatively low-productivity (low steepness) grids. The uncertainty of the model scale is shown in Table 3.

The uncertainty of the model due to productivity parameters

We selected the largest and smallest model scales for each M_{2+}. The uncertainty range for the short-time model with the alternative productivity assumptions are shown in Figure 3.

Discussion

MSE should consider influential uncertainties, if not all the uncertainties. However, not all parameters' values are plausible given the fishing history and life-history of the stock. We first selected a range of productivity parameters based on data and life history information. We then showed that ASPM-R is a valuable tool for further refining the productivity combinations. The PBF model prefers larger length at age 3 and higher natural mortality for age 2 and older than the base values. The larger the length at age 3 and natural mortality for age 2 and older are, the broader range of potential steepness parameters selected. However, not all the selected combinations have similar depletion levels given the PBF fishery history. The low productivity assumption created lower depletion levels, which are less plausible for PBF given the fishing history. The decision where to break the depletion level may be subjective given the various combination of steepness and natural mortality.

The ASPM-R has an advantage over the ASPM when selecting the productivity combinations. The ASPM-R accounts for recruitment index and the cohort growth in size compositions influencing stock productivity resulting broader range of steepness selected (Lee et al. 2022). This work could be the basis of the ISCPBF working group to select the uncertainty range in productivity for the MSE operating model(s) (i.e., ‘conditioning’ the operating model(s) to data).

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Table 1. The methods used to estimate natural mortality.

Method	M1	M2	Parameters input	Reference
Then_nls	0.256	0.231	maximum age	Then et al. (2015)
Then_lm	0.216	0.192	maximum age	Then et al. (2015)
Hamel_Amax	0.216	0.193	maximum age	Hamel (2015)
ZM_CA_pel	0.162	0.131	maximum age, k, t0	Alverson and Carney (1975) Zhang and Megrey (2006)
Then_VBGF	0.196		Linf, k	Then et al. (2015)
Hamel_k	0.33		k	Hamel (2015)
Jensen_k1	0.282		k	Jensen (1996, 1997)
Jensen_k2	0.301		k	Jensen (1996, 1997)
Gislason	0.262		Linf, k, length	Gislason et al. (2010)
Charnov	0.368		Linf, k, length	Charnov et al. (2013)
Roff	0.362		k, age at maturity	Roff (1984)
Jensen_Amat	0.33		age at maturity	Jensen (1996, 1997)
Ri_Ef_Amat	0.317		age at maturity	Rikhter and Efanov (1976)

Table 2. The total likelihood values from ASPM-R models that varied the values of length at age 3 and steepness when natural mortality for age 2 and older is at (a) 0.2, (b) 0.25, and (c) 0.3. The bold value is the total likelihood value from the base ASPM-R model (M_{2+}=0.25, L_2 = 118.57, and h=0.999). The yellow highlights are the total likelihood values that are either not statistically different (not more than 2 likelihood unit degradation) or improved from the base ASPM-R model (smaller likelihood value). The underlined values are associated with the open circles in Figure 1.

a. M_{2+}=0.2

		Length at age 3 (asymptotic length)					
		116	118.57	120	122	124	126
		(244.2)	(249.9)	(253.2)	(257.9)	(262.5)	(267.2)
Steepness	0.93	3.7	2.4	1.5	-0.4	117.6	175.7
	0.95	1.5	-0.1	-1.9	143.9	198.7	279.5
	0.97	-0.8	-3.0	-4.2	-7.6	209.5	267.2
	0.99	-0.6	-3.7	-6.6	-12.2	-16.7	-15.8
	0.999	-0.9	-4.4	-6.4	-10.4	-15.1	-19.6

b. M_{2+}=0.25

		Length at age 3					
		116	118.57	120	122	124	126
Steepness	0.83	7.5	3.3	1.9	-0.5	-2.9	-3.9
	0.85	5.6	2.3	0.2	-1.6	-3.4	-4.8
	0.87	4.3	1.0	-1.0	-3.1	-4.6	-6.2
	0.89	2.5	-0.9	-2.3	-4.2	-6.6	-8.9
	0.91	0.7	-2.4	-4.0	-6.2	-9.0	-11.2
	0.93	-0.6	-3.9	-5.6	-8.0	-11.9	-14.3
	0.95	-1.7	-5.0	-6.7	-10.4	-14.7	-18.8
	0.97	-2.0	-5.9	-7.6	-12.8	-18.6	-22.0
	0.99	-2.7	-6.6	-8.9	-12.7	-19.4	-22.7
	0.999	-2.4	**-6.2**	-8.8	-12.9	-18.7	-21.6

c. M$_{2+}$=0.3

		Length at age 3					
		116	118.57	120	122	124	126
Steepness	0.61	16.6	275.4	6.3	2.4	-1.2	-4.3
	0.63	15.3	8.8	5.5	1.7	-2.6	-5.3
	0.65	13.5	7.7	4.5	0.7	-2.8	-6.0
	0.67	12.6	7.1	3.6	-0.3	-4.0	-6.7
	0.69	12.0	5.3	2.3	-1.4	-4.8	-7.4
	0.71	10.7	4.9	1.8	-2.2	-5.2	-8.0
	0.73	9.1	3.7	1.0	-3.2	-5.9	-8.6
	0.75	8.2	2.2	-0.1	-4.1	-7.3	-9.3
	0.77	6.9	1.4	-0.5	-4.9	-7.7	-10.1
	0.79	5.3	0.1	-1.7	-5.4	-8.5	-10.6
	0.81	3.8	-1.1	-3.2	-6.2	-9.2	-11.1
	0.83	3.0	-2.2	-4.0	-7.2	-10.5	-12.1
	0.85	1.7	-3.3	-5.3	-8.1	-11.2	-13.2
	0.87	0.2	-4.7	-6.4	-9.1	-12.8	-14.1
	0.89	-1.0	-5.8	-7.7	-10.3	-14.1	-15.6
	0.91	-1.6	-6.5	-8.6	-11.6	-15.5	-18.4
	0.93	-2.1	-7.6	-9.0	-12.9	-17.8	-20.1
	0.95	-2.3	-7.9	-10.3	-14.3	-19.8	-22.7
	0.97	-2.7	-8.3	-10.7	-14.8	-20.8	-24.7
	0.99	-2.7	-8.2	-11.1	-15.7	-21.0	-25.2
	0.999	-2.3	-7.9	-10.5	-15.0	-20.4	-24.3

Table 3. The heatmap of the unfished spawning stock biomass (SSB0) estimated from plausible ASPM-R models that varied the values of length at age 3 and steepness when natural mortality for age 2 and older is at (a) 0.2, (b) 0.25, and (c) 0.3. Red squares showed larger SSB0, whereas green squares showed smaller SSB0.

a. M_{2+}=0.2

	116	118.57	120	122	124	126
0.97				1,367,650		
0.99			931,769	997,322	1,059,490	1,101,550
0.999		787,598	805,318	834,904	865,041	899,664

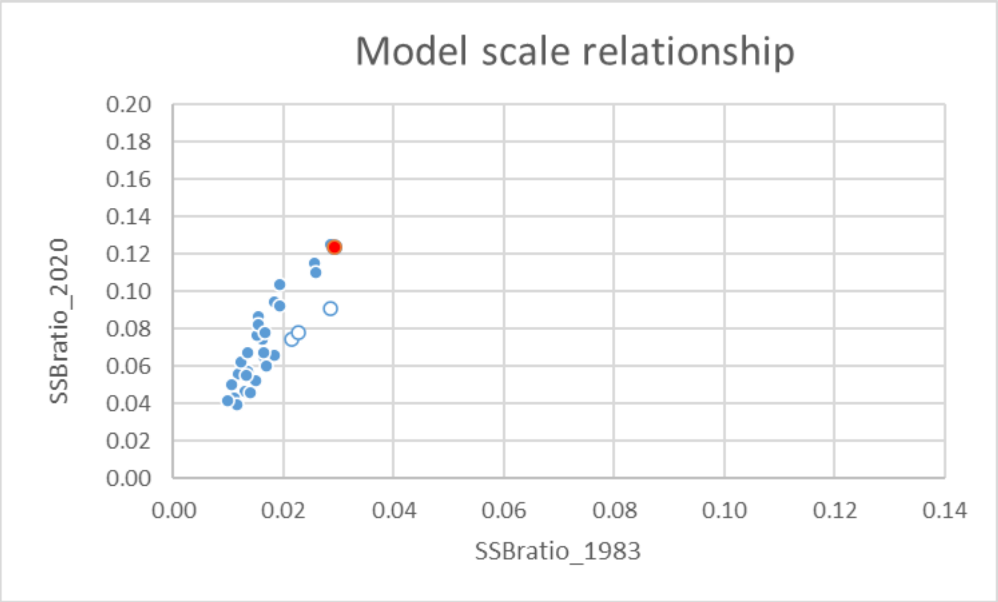
b. M_{2+}=0.25

	116	118.57	120	122	124	126
0.89					1,173,410	1,228,610
0.91				1,071,690	1,179,680	1,248,000
0.93			912,466	1,033,930	1,117,600	1,201,190
0.95		753,808	815,626	937,430	1,037,830	832,155
0.97		657,684	702,782	780,199	850,395	915,501
0.99		565,976	580,459	617,891	652,284	688,311
0.999		536,151	543,985	558,435	576,812	595,772

c. M_{2+}=0.3

	116	118.57	120	122	124	126
0.85			759,398	823,762	860,435	907,451
0.87		675,725	715,875	780,175	845,038	913,192
0.89		632,452	669,107	742,346	818,153	887,002
0.91		580,893	622,675	698,360	779,367	842,259
0.93		532,769	564,658	636,822	706,582	773,025
0.95		481,773	507,980	558,395	612,977	678,483
0.97		439,012	454,761	487,319	524,597	566,100
0.99		404,934	411,056	422,023	436,768	458,231
0.999		391,433	394,654	400,845	410,351	423,054

a. M_{2+}=0.25



b. M_{2+}=0.3

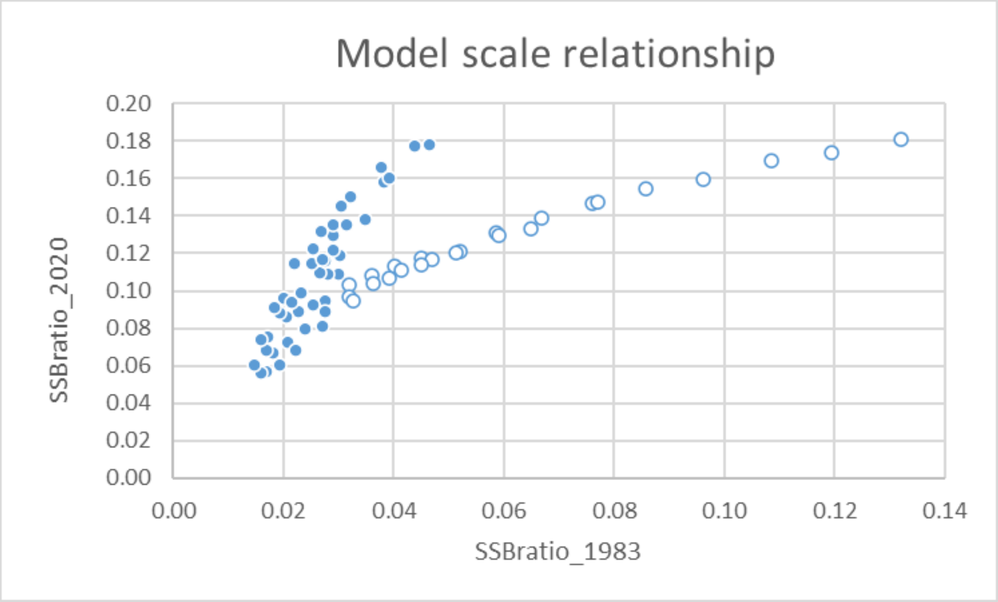


Figure 1. The plot of the estimated 1983 spawning stock biomass (SSBratio1983 = SSB1983/SSB0) against the estimated 2020 spawning stock biomass ratio (SSBratio2020 = SSB2020/SSB0) from the ASPM-R models with the alternative combination of L_2, h, and M_2. The red dot indicated the base ASPM-R model (M_{2+}=0.25, L_2 = 118.57, and h=0.999). The open circles are from the ASPM-R models with steepness smaller than 0.87 when M_{2+} was 0.25 (a) and smaller than 0.83 when M_{2+} was 0.3 (b).

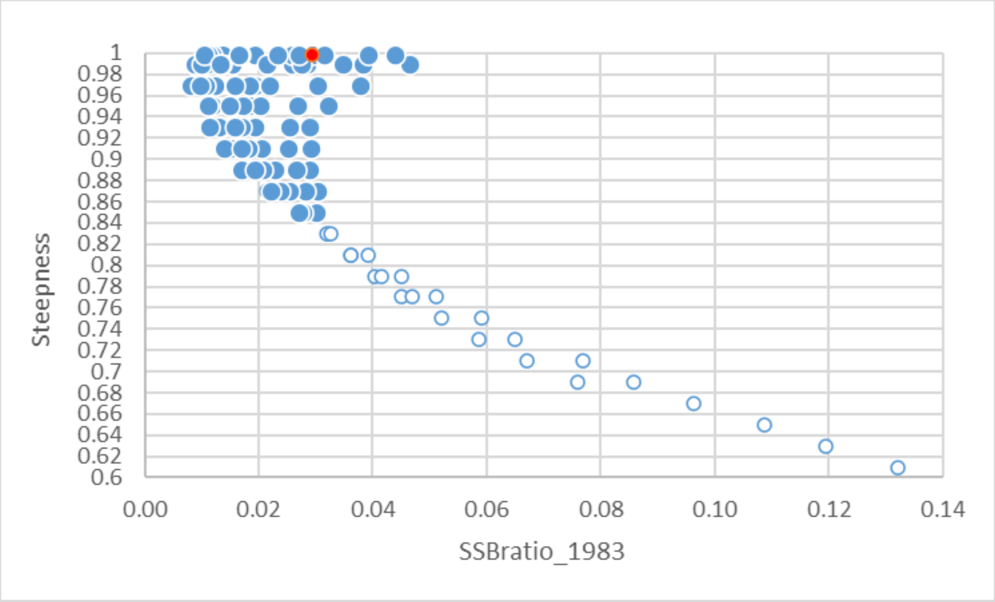


Figure 2. The plot of the estimated 1983 spawning stock biomass (SSBratio1983 = SSB1983/SSB0) against steepness values from the ASPM-R models with the alternative combination of L_2, h, and M_2. The red dot indicated the base ASPM-R model (M_{2+}=0.25, L_2 = 118.57, and h=0.999). The open circles are from the ASPM-R models with steepness smaller than 0.87 when M_{2+} was 0.25 and smaller than 0.83 when M_{2+} was 0.3.

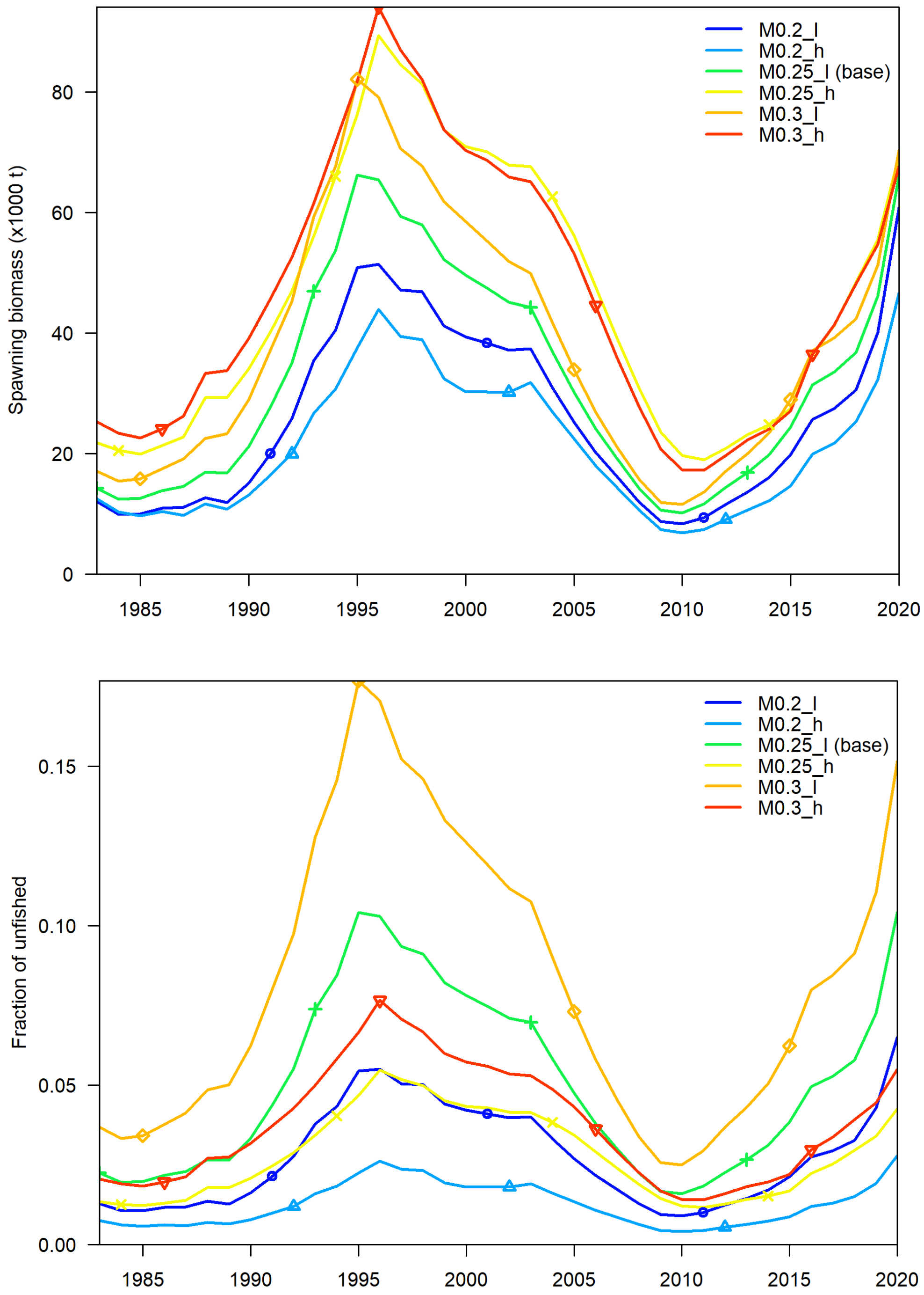


Figure 3. The trajectory of the spawning biomass (upper panel) and spawning stock biomass ratio (lower panel) estimated from the full models with largest and smallest model scales for each M_{2+} (referred to Table 3).