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Update on natural mortality estimators for chub mackerel in the Northwest Pacific Ocean

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Summary

The Technical Working Group (TWG) on Chub Mackerel Stock Assessment (CMSA) has determined to update the calculation of natural mortality coefficients (*M*) because age-specific *M* at age 0 was not available in the previous document (NPFC-2019-TWG CMSA02-WP01). Since a recent paper estimated life-history parameters in relation to the individual growth by adding new data to NPFC-2019-TWG CMSA02-WP01, we here updated both age-common and age-specific *M* values obtained from life-history parameters. The growth coefficient (*K*) and asymptotic fork length (L_∞) were estimated to be higher and lower, respectively, than those in the previous estimates because the newly added data had smaller fork lengths for five years of age and older than the previous ones. The updated *M* values obtained from equations such as Pauly and Jensen were necessarily higher than those in the previous document because of the higher growth coefficient; accordingly, the median value of *M* among various estimators changed from 0.41 to 0.53. We also estimated age-specific *M* including age 0 using Gislason estimators. We suggest application of the median of updated estimators and the updated Gislason estimates as the age-common *M* and as the age-specific *M*, respectively, for rerunning candidate stock assessment models under the scenarios of operating models in CMSA.

Introduction

The Technical Working Group on Chub Mackerel Stock Assessment (TWG CMSA) in NPFC has agreed that (1) the candidates of stock assessment models (VPA, ASAP, KAFKA, and SAM) would be compared by an operating model (OM) (NPFC, 2019) and (2) uncertainties regarding natural mortality coefficients (*M*), weight-at-age, and maturity-at-age should be incorporated into scenario settings of OM (NPFC, 2020). The TWG CMSA has determined two sets of natural mortality would be used: the median of various estimators ($M = 0.41$) and age-specific *M* based on Gislason estimator (NPFC, 2020). The age-specific *M* did not include age 0 in the previous document (Takahashi et al., 2019) because they calculated *M*-at-age based on the fork length at the timing of starting age (e.g., 12 months after birth for age 1). Japan was, therefore, requested to provide the updated age-specific *M* including age 0 from recalculation of Japan's data (NPFC 2020). At the same time, a recent paper (Kamimura et al., 2021) estimated the von Bertalanffy growth function by collecting and adding new data to those used in the previous document (Takahashi et al., 2019). In this document, we updated not only age-specific but also age-common *M* estimates using the updated life-history parameters in the von Bertalanffy growth function.

Von Bertalanffy growth function

Kamimura et al. (2021) analyzed a total of 15,415 fish of chub mackerel (*Scomber japonicus*) landed in fishing ports on the Pacific coast of northern Japan between 2006 and 2019. This included new data of 7,570 fish as well as 7,845 fish samples used in the previous analysis (Takahashi et al., 2019). Fishing gear included purse seines, dipnets, setnets, and vertical longlines. Most of the samples were captured by purse seine fisheries. Fork length (FL) was measured to the nearest 1 mm by using digital calipers. Ages were determined by counting annual rings on scales or sectioned sagittal otoliths under electronic microscopes. According to the previous evidence that spawning mainly occurs around April (Kamimura et al., 2015; Kanamori et al., 2019), the hatch date was assumed to be in April and calculated ages as $t = A + m/12$, where *A* is age (in years) estimated from scale and otolith observations and *m* is the number of months between the catch month and the preceding April. These samples encompassed the year classes of 2006 to 2016, collected between 2006 and 2019, although those in the previous analysis has a narrower range of year classes (2006 to 2015), collected between 2006 and 2018 (Table 1). The von Bertalanffy (VB) equation was fitted to the FL-at-age data:

$$L_t = L_\infty[1 - \exp\{-K(t - t_0)\}],$$

where L_t, L_∞, K, and t_0 are FL at age t, asymptotic FL, growth coefficient, and hypothetical age at zero FL, respectively. We used a normal distribution as an observation error (or individual difference):

$$L_{t,i} \sim Normal(\hat{L}_t, \varphi^2),$$

where $L_{t,i}$ is the FL of sample i at age t, $\hat{L}_t$ is the predicted mean FL, and φ is the standard deviation of FL. The maximum likelihood method was used to estimate the parameters of L_∞, K, and t_0. We also analyzed a lognormal distribution or gamma distribution, but found the normal distribution had a much lower AIC (i.e., higher predictability) than these other two probability distribution (normal: 149580.7, lognormal: 149928.2, gamma: 149835.6). Hence, we show the results of normal distribution in this document. We conducted a sensitivity analysis that incorporated the difference of the parameter values among year classes as random effects because the growth parameters could vary among year classes (Kamimura et al., 2021). The results of the sensitivity analysis are show in Appendix.

The estimated growth coefficient and the asymptotic FL were higher and lower, respectively, than those in the previous analysis (Takahashi et al., 2019) (K: 0.20 → 0.39, L_∞: 44.6 → 37.1[cm]). This change is because the recent year classes after 2013 exhibited smaller body sizes due to density dependence, which is shown as lower FL for the ages of five years and older in the added data (Fig. 1). This resulted in steeper increase in FL for age 4 and younger and flatter pattern in FL for age 5 and older (Fig. 1).

Age-common natural mortality

Takahashi et al. (2019) used eight natural mortality estimators, five of which are based on the life-history parameters of L_∞ and/or K (Table 2). In addition to these life-history parameters, we also updated mean environmental temperature (T) and mean fork length (L) by the latest information (Kamimura et al., 2021). As a result, the M estimates obtained using the updated these parameters were necessarily higher than the previous estimates (Pauly, Pauly update, Jensen, Gislasson1, and Gislasson2 in Table 3). These upward shifts were mainly caused by the increase in the growth coefficient *K*. The percentages of increase were 95% for Jensen, 73% for Pauly update, 64% for Pauly, 34% for Gislasson1, 33% for Gislasson2.

Other two estimators (Hoenig and Hoenig update) use the maximum observed age or longevity (A_{max}) for calculating *M* (Table 1). Takahashi et al. (2019) used two values of A_{max} (10 and 11) depending on references (Kamimura in preparation and Iizuka 2002, respectively) and calculated two corresponding estimates of *M*. However, Kamimura et al. (2021) found some individuals with 11 years old in the updated data (Table 1). We, therefore, used the single value of A_{max} (11), resulting in $M = 0.39$ for Hoenig and $M = 0.54$ for Hoenig update (Table 3). We confirmed that the *M* estimate of *S. japonicus* by FishLife, a meta-analytic estimator of various life-history parameters for all fish species globally (Thorson, 2020), did not change since the previous estimate ($M = 0.48$). The median *M* among the various estimators was also shifted upward from 0.41 to 0.53 (Table 3).

Age-specific natural mortality

We recalculated age-specific *M* based on FL at the middle point of age in year (e.g., 6 months after birth for age 0 and 18 months after birth for age1) to fill *M* at age 0. We used the updated von Bertalanffy curve (Fig. 1) to compute FL-at-age and then *M*-at-age. Resulting values of *M* were higher than those in the previous document (Takahashi et al., 2019) for the same reason as the case of age-common *M* (Table 4). The estimators of Gislason1 and Gislason2 were quite similar, and the average value of *M* decreased from age 0 ($M = 0.80$) to age 6 ($M = 0.40$).

Conclusions

We reported the updated estimates in natural mortality coefficients (*M*) obtained from life-history parameters. Many *M* estimators exhibited higher values than in the previous estimators due to a higher growth coefficient of FL. Since the TWG CMSA has determined to use both age-common and age-specific *M* as the OM scenarios (NPFC 2020), we recommend using the median of various updated estimators as the age-common M (0.53) and the mean between Gislason1 and Gislason2 as the age-specific M (0.80 for age 0, 0.60 for age1, 0.51 for age 2, 0.46 for age 3, 0.43 for age 4, 0.41 for age 5, and 0.40 for age 6+) when we analyze candidate stock assessment models under the scenarios of operation models. In the sensitivity analysis that incorporates the difference among year classes as random effects, we found that the growth parameters (K and L_∞) and M estimators were relatively robust against the model change of growth parameter estimation (Appendix). We therefore consider that it will be no problem to use the above M values (age-common median and age-specific values) at least for the inputs to operating models. However, we strongly recommend the M values used to the benchmark stock assessment should be determined thought comprehensive discussion in terms of biological plausibility.

Appendix: Sensitivity Analysis Incorporating the Difference among Year Classes

The parameters of L_∞, K, and t_0 could vary among year classes depending on the stock abundance (i.e., density-dependent effect) (Kamimura et al., 2021). In addition, the sample size and the ranges of age and FL were also different among year classes (Table 1). To resolve these problems, we therefore conducted a sensitivity analysis that estimated the growth parameters specific to each year class as random effects:

$$\log L_{\infty,y} \sim Normal(\log L_\infty, \sigma_L^2),$$
$$\log K_y \sim Normal(\log K, \sigma_K^2),$$
$$t_{0,y} \sim Normal(t_{0,y}, \sigma_t^2).$$

We used a normal distribution as an observation error (or individual difference) in the same manner as the main text. We estimated the parameters of both fixed and random effects by Template Model Builder (TMB), an R package that enables quick implementation of complex nonlinear latent variable models (Kristensen et al., 2016).

The estimated growth parameters of L_∞, K, and t_0 greatly varied among year classes (Table 1, Figure A1). Especially, the values of L_∞ had a decreasing trend (Figure A1), causing smaller predicted values of FL in recent years (Figure A2). A potential reason for this pattern is that the recent increase of stock abundance suppressed the asymptotic size of chub mackerel (Kamimura et al., 2021). This model had a much lower AIC (134911.9) than the model that ignored the difference among year classes (149580.7), highlighting the time-varying growth parameters. However, the average of *K* (0.41), the most influential parameter for *M* estimators, was little different from the updated estimate shown in the main text (0.39), although L_∞ slightly increased from 371mm to 382mm (Table 1).

The age-common *M* estimators obtained using from the outputs of this model (Pauly, Pauly update, Jensen, Gislason1, Gislason2) were only slightly higher than the model that ignores the year class difference (Table A1). Thus, the median value of various *M* estimators slightly changed from 0.53 to 0.55 (Table A1). The age-specific *M* values were also little varied by the model change for the VB growth function, although *M* at age 0 had a relatively large difference between the models (Table A2).

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Table 1: Information on sample data and estimated growth parameters in the previous and updated analyses.

Data	Sample size	Year Class	Sampling Year	FL range (mm)	Age range (years)	L_∞	K	t_0
Analysis ignoring the difference among year classes								
Previous	7845	2006-2015	2006-2018	160-460	0.8-10.2	446	0.2	-3.05
All	15415	2006-2016	2006-2019	121-470	0.2-11.1	371	0.39	-1.96
Analysis incorporating the difference among year classes as random effects								
All	15415	Average	2006-2019	121-470	0.2-11.1	382	0.41	-1.8
-	525	2006	2006-2014	207-426	0.4-8.1	428	0.3	-1.99
-	1548	2007	2007-2017	188-460	0.3-9.8	401	0.49	-1.27
-	659	2008	2008-2019	226-434	0.6-11.1	397	0.48	-1.45
-	1315	2009	2010-2019	212-440	0.8-10.1	401	0.43	-1.63
-	1351	2010	2010-2019	208-470	0.4-9.2	397	0.47	-1.62
-	830	2011	2012-2019	226-455	0.8-8.2	390	0.4	-2.43
-	1865	2012	2012-2019	121-457	0.3-7.2	361	0.54	-1.47
-	4522	2013	2013-2019	160-460	0.5-6.7	355	0.32	-2.34
-	1533	2014	2014-2019	198-430	0.4-5.7	346	0.38	-2.2
-	647	2015	2015-2019	193-420	0.4-4.7	379	0.31	-1.85
-	620	2016	2016-2019	136-358	0.2-3.7	350	0.42	-1.4

Note: The section of “incorporating the difference among year classes as random effects” shows the information of sample data per year class and the growth parameters of the average (estimated by fixed effects) and each year class (estimated by random effects). Details are shown in Appendix.

Table 2: Estimator selected to calculate the natural mortality coefficient (M) for chub mackerel in the Northwest Pacific Ocean.

Estimator identifier	Equation	Reference
"Pauly"	$M = 0.9849 L_{\infty}^{-0.279} K^{0.6543} T^{0.4634}$	Pauly (1980)
"Pauly update"	$M = 4.118 L_{\infty}^{-0.33} K^{0.73}$	Then et al., (2015)
"Jensen"	$M = 1.5K$	Jensen (1996)
"Hoenig"	$M = 4.3/A_{max}$	Hoenig (1983)
"Hoenig update"	$M = 4.899 A_{max}^{-0.916}$	Then et al. (2015)
"Gislason1"	$M = 1.73 L^{-1.61} L_{\infty}^{1.44} K$	Gislason et al. (2010)
"Gislason2"	$M = K(L/L_{\infty})^{-1.5}$	Charnov et al. (2013)
"FishLife"	-	Thorson (2020)

L_{∞}: Asymptotic fork length (cm)

K: Brody growth coefficient of the von Bertalanffy growth curve

T: Mean environmental temperature (°C)

A_{max}: Maximum observed age (longevity)

L: Individual fork length (cm)

Table 3: Updated natural mortality coefficients obtained using the estimators in Table 2 with the life-history parameters. The numbers in the parentheses are those in the previous version (Takahashi et al., 2019).

	***M* value**	L_∞	***K***	***T***	A_{max}	***L***	**Input data source**
"Pauly"	0.72 (0.44)	37.1 (44.6)	0.39 (0.20)	17.0 (16.7)			Kamimura et al. (2021)
"Pauly update"	0.63 (0.36)	37.1 (44.6)	0.39 (0.20)				Kamimura et al. (2021)
"Jensen"	0.59 (0.30)		0.39 (0.20)				Kamimura et al. (2021)
"Hoenig"	0.39 (0.43 & 0.39)				11 (10 & 11)		Iizuka (2002), Kamimura et al. (2021)
"Hoenig update"	0.54 (0.59 & 0.54)				11 (10 & 11)		Iizuka (2002), Kamimura et al. (2021)
"Gislason1"	0.48 (0.36)	37.1 (44.6)	0.39 (0.20)			31.1 (29.0)	Kamimura et al. (2021)
"Gislason2"	0.51 (0.38)	37.1 (44.6)	0.39 (0.20)			31.1 (29.0)	Kamimura et al. (2021)
"FishLife"	0.48 (0.48)						Frose & Pauly (2000)
Median	0.53 (0.41)						

Note: We have updated the life-history parameters of L_∞, K, and T and the mean fork length (L) of catch samples by adding new data (Fig. 1; Kamimura et al. 2021). Although the previous document (Takahashi et al. 2019) used the two values of A_{max} (10 and 11) according to different data sources, the current paper uses the single value of A_{max} (11) because Kamimura et al. (2021) found some individuals of 11 years old in the new added data as the maximum observed age, which is the same as Iizuka (2002). The last row shows the median values among different estimates of natural mortality coefficients.

Table 4: Updated age-specific natural mortality coefficients obtained using the length-based estimators in Table 2. The numbers in the parentheses are those in the previous version (Takahashi et al. 2019).

Age	**Length (cm)**	***M* value**		
		"Gislason1"	**"Gislason2"**	**Mean**
0	22.9	0.79	0.80	0.80
	-	-	-	-
1	27.5	0.59	0.61	0.60
	(24.8)	(0.47)	(0.48)	(0.48)
2	30.6	0.50	0.52	0.51
	(28.4)	(0.38)	(0.39)	(0.39)
3	32.7	0.45	0.47	0.46
	(31.3)	(0.32)	(0.34)	(0.33)
4	34.1	0.42	0.44	0.43
	(33.7)	(0.28)	(0.30)	(0.29)
5	35.1	0.40	0.42	0.41
	(35.7)	(0.26)	(0.28)	(0.27)
6	35.7	0.39	0.41	0.40
	(37.3)	(0.24)	(0.26)	(0.25)

Note: The necessary life-history parameters of L_∞ and K are shown in Tables 1 and 3. The previous document used the timing of age starting (e.g., 12 months after birth for age 1) and, therefore, it is infeasible to calculate natural mortality coefficients at age 0. The present paper uses the middle point of age in year (e.g., 6 months after birth for age 0 and 18 months after birth for age1) to calculate age-specific natural morality coefficients.

Table A1: Natural mortality coefficients (*M*) estimators obtained from the life-history parameters estimated by the model that incorporates the difference of the growth parameters. The numbers in the parentheses are estimates from the model without the growth difference among year classes.

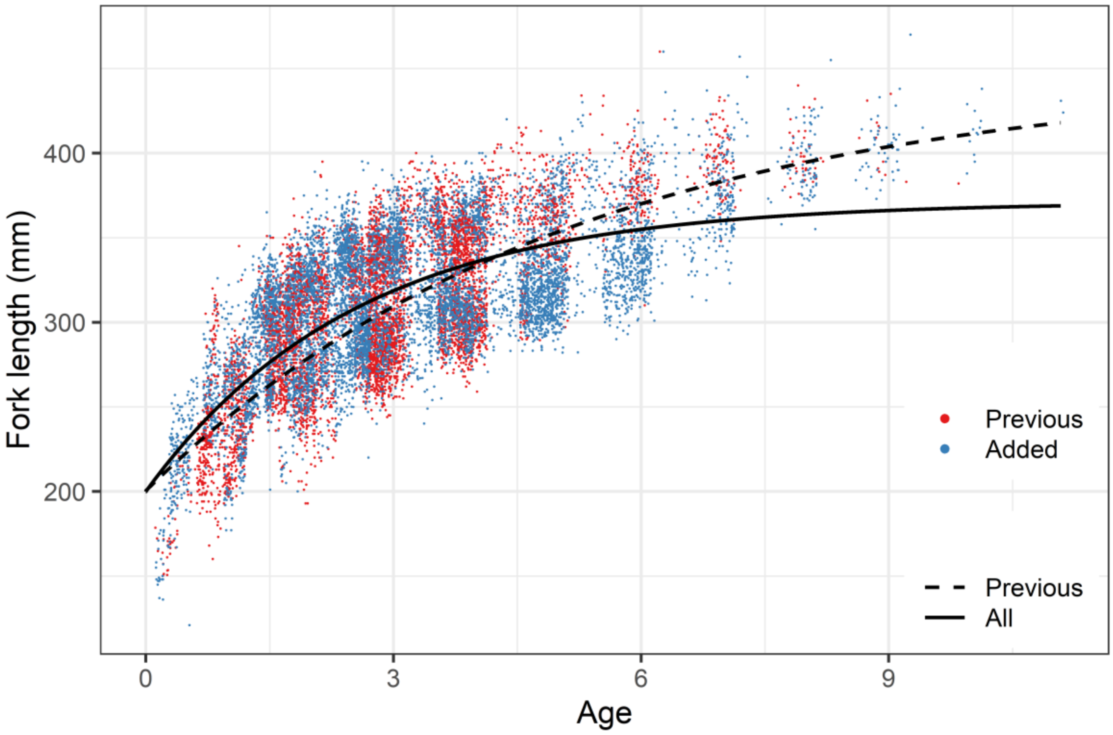
	***M* value**	L_∞	***K***	***T***	A_{max}	***L***	**Data source**
"Pauly"	0.74 (0.72)	38.2 (37.1)	0.41 (0.39)	17.0 (17.0)			Kamimura et al. (2021)
"Pauly update"	0.65 (0.63)	38.2 (37.1)	0.41 (0.39)				Kamimura et al. (2021)
"Jensen"	0.62 (0.59)		0.41 (0.39)				Kamimura et al. (2021)
"Hoenig"	0.39				11		Iizuka (2002) Kamimura et al. (2021)
"Hoenig update"	0.54				11		Iizuka (2002) Kamimura et al. (2021)
"Gislason1"	0.53 (0.48)	38.2 (37.1)	0.41 (0.39)			31.1 (31.1)	Kamimura et al. (2021)
"Gislason2"	0.56 (0.51)	38.2 (37.1)	0.41 (0.39)			31.1 (31.1)	Kamimura et al. (2021)
"FishLife"	0.48						Frose (1990)
Median	0.55 (0.53)						

Table A2: Age-specific natural mortality coefficients obtained from the model that incorporates the difference of the growth parameters. The numbers in the parentheses are estimates from the model without the growth difference among year classes.

Age	**Length (cm)**	***M* value**		
		"Gislason1"	**"Gislason2"**	**Mean**
0	23.3 (22.9)	0.85 (0.79)	0.86 (0.80)	0.85 (0.80)
1	28.3 (27.5)	0.62 (0.59)	0.64 (0.61)	0.63 (0.60)
2	31.6 (30.6)	0.52 (0.50)	0.54 (0.52)	0.53 (0.51)
3	33.9 (32.7)	0.46 (0.45)	0.49 (0.47)	0.48 (0.46)
4	35.3 (34.1)	0.43 (0.42)	0.46 (0.44)	0.45 (0.43)
5	36.3 (35.1)	0.41 (0.40)	0.44 (0.42)	0.43 (0.41)
6	36.9 (35.7)	0.40 (0.39)	0.43 (0.41)	0.42 (0.40)

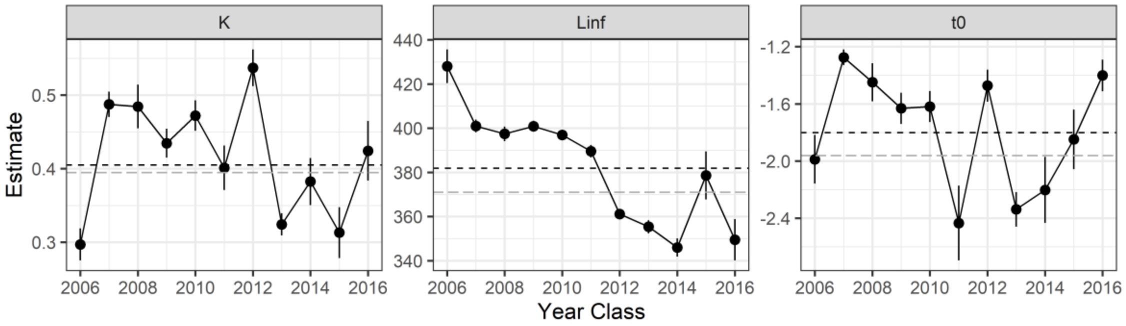
Note: The necessary life-history parameters of L_∞ and K are shown in Tables 1 and A1.

Figure 1:



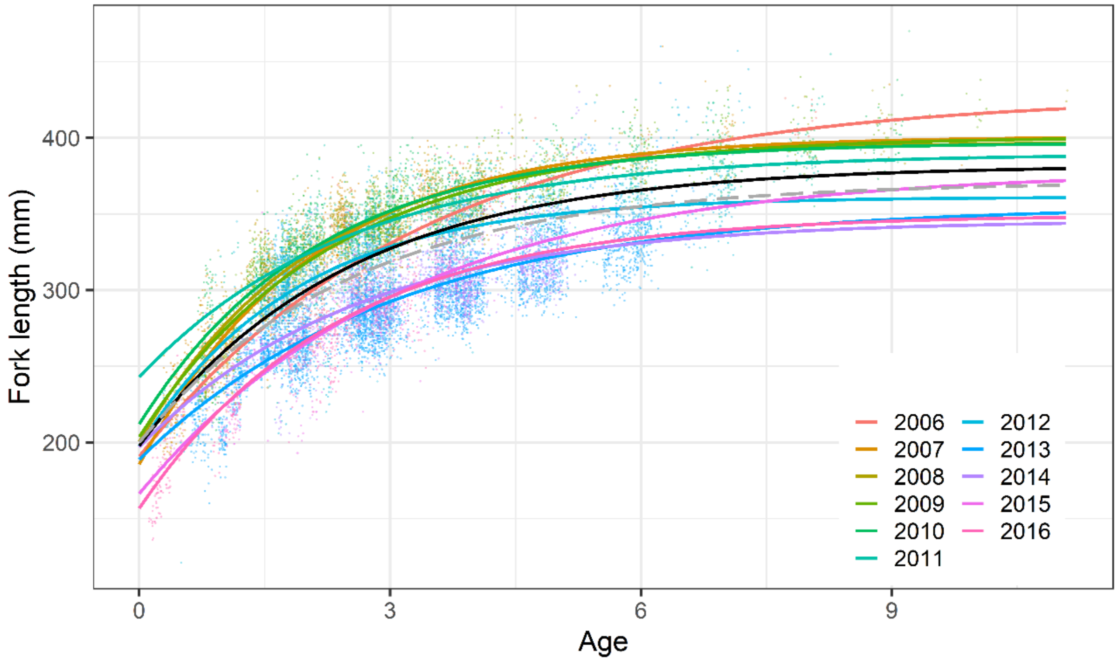
Relationship between age and fork length of chub mackerel in the Northwest Pacific Ocean. The samples used in the previous analysis (Takahashi et al., 2019) are shown in red, while those in the added data are shown in blue. The von Bertalanffy curve is fitted to the previous data (dashed) and all data (solid).

Figure A1:



The estimates (±SD) of growth parameters per year class estimated as random effects. The black dashed lines represent the average of year classes, whereas the gray dashed lines represent the estimates in the analysis that ignores the difference among year classes shown in the main text.

Figure A2:



Relationship between age and fork length by year class. The black line represents the average of year classes, whereas the gray dashed line represents the prediction in the analysis that ignores the difference among year classes shown in the main text.