Updated growth analysis for Alaska sablefish

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EXECUTIVE SUMMARY

Growth parameters for Alaskan sablefish have not been updated for stock assessment purposes since Hanselman et al. (2007). Meanwhile, there have been several above average year classes of sablefish (Goethel et al. 2020) coupled with extreme warming conditions in both the Gulf of Alaska and Bering Sea (Bond et al. 2015, Di Lorenzo and Mantua 2016), and another evaluation of growth is warranted. In this study we reevaluated estimates of length and weight at age over the time series of 1996-2019. Years prior to 1996 were excluded from this analysis as these data were collected under a different sampling regime and were already corrected for sampling bias, and updated in the 2008 sablefish stock assessment (Hanselman et al. 2007). Specifically, our objectives were to reevaluate estimates of length and weight at age and evaluate any temporal trends. Our analyses showed that there have been temporal changes in both male and female sablefish growth. Fish are growing slower in recent years yet reaching larger maximum sizes, and average length and weight at age have generally shown a declining trend for younger ages. Significant changes in growth were discovered pre- and post-2004 for both sexes. However, because a clear rationale explaining the temporal changes is lacking and due to the need for more data and analysis of growth of large cohorts, we recommend using updated growth information divided into two time periods for both males and females (1981-1993, 1996-2019) for the 2022 sablefish stock assessment. This recommendation incorporates the 1981-1993 bias corrected length-stratified time period that had previously been shown to have significantly different growth and was incorporated into the 2008 stock assessment (Hanselman et al. 2007), and updates post-1996 growth parameters to include all available data. This new information provides the most biologically plausible information to include in the stock assessment that accounts for the changing ecosystem and abundance of sablefish.

INTRODUCTION

Growth parameters for Alaskan sablefish have not been updated since Hanselman et al. (2007). For use in the 2008 sablefish stock assessment, the updated growth information was divided into the two time periods: 1981-1993 and 1996-2004. The choice of where to split growth regimes was not based on a visible shift in growth at that time, but on a change in sampling design on the longline survey (Hanselman et al. 2007). Sampling did not occur in all sablefish management areas during 1994-1995 (Rutecki et al. 2016). Since the last update of sablefish growth, there have been several above average year classes of sablefish (Goethel et al. 2020) coupled with extreme warming conditions in both the Gulf of Alaska (GOA) and Bering Sea (Bond et al. 2015, Di Lorenzo and Mantua 2016). Additionally, significant changes in length at age continue to be seen in other species and have caused substantial changes in stock assessment results, such as with Pacific halibut and northern rock sole (Clark et al. 1999, Walters & Wilderbuer 2000, Clark & Hare 2002, Sullivan 2016, Kapur et al. 2020). To evaluate whether changes to sablefish growth have occurred, we examined all the length and weight at age data that has been collected on the longline survey since 1996. Years prior to 1996 were excluded from this analysis as these data were collected under a different sampling regime and have been included as a separate growth regime in the stock assessment since 2008 (Hanselman et al. 2007).

METHODS

Length at age analysis

Randomly collected age and length data were available from the NMFS domestic longline survey from 1996-2019 (Rutecki et al. 2016, Siwicke et al. 2021). Fish aged 31 years and older were pooled together into a 31+ age category (Goethel et al. 2020). The von Bertalanffy (LVB, Von Bertalanffy 1938) age-length model was fitted to age-length data from 1996-2019 by nonlinear least squares

$$(1)\quad L_a = L_\infty\left(1 - e^{-K(t-t_0)}\right) + \varepsilon_a$$

where ε_a is an additive error term, and L_∞, κ, and t_o are model parameters. L_∞ represents the average maximum length, κ describes the mean growth rate, and t_o describes the mean theoretical age a fish would have been zero length (McDevitt 1990, Quinn & Deriso 1999).

Weight at age analysis

Randomly collected age and weight data were available from the NMFS domestic longline survey from 1996-2019 (Rutecki et al. 2016, Siwicke et al. 2021). Fish aged 31 years and older were pooled together into a 31+ age category (Hanselman et al. 2006). To determine weight at age, first the length-weight relationship was determined using the typical nonlinear allometric relationship:

$$(2)\quad \widehat{W} = \alpha L^{\beta}\varepsilon$$

Here length *L, α,* and *β* are parameters estimated using non-linear least squares procedures. This equation was combined with the LVB length at age model to construct the LVB weight at age model (Quinn and Deriso 1999). A common method to fit weight at age data is with the four-parameter LVB model. However, due to high parameter correlation with only one dependent variable, it is usually difficult to fit all four parameters at once, so a convenient method is to fix the allometric parameter *β*, determined from the length-weight relationship as a fixed parameter (Quinn and Deriso 1999). For this data set, there was a multiplicative error structure, so we log-transform the LVB model to:

$$(3)\qquad \ln\widehat{W}_a = ln\ W_\infty + \beta\ln\left(1 - e^{-K(t-t_0)}\right) + \varepsilon_a$$

where ε_a is a multiplicative error term, and ln W_∞ is exponentiated to obtain the estimate of W_∞. Nonlinear least squares was used to determine the best estimates of W_∞, κ, and t_0, while *β* is fixed at 3.

Cluster Analysis

To determine if temporal changes had occurred in growth, a *k*-means cluster analysis was performed on the yearly growth parameters. *K*-means clustering is used for splitting a dataset into a set of *k* groups (Kaufman and Rousseeuw 1990). Years that are clustered in the same group are similar. This analysis was conducted to determine if and where obvious breaks in the time series had occurred.

Clusters are defined so that the total intra-cluster variation (known as total within-cluster variation) is minimized. The Hartigan-Wong algorithm (1979) was used, which defines the total within-cluster variation as the sum of squared Euclidean distances between items and the corresponding centroid

$$(4)\qquad W(C_k) = \sum_{x_i \in C_k} (x_i - \mu_k)^2$$

where x_i is a data point (standardized annual growth parameters) belonging to the cluster C_k, and μ_k is the mean value of the points assigned to the cluster C_k. Each observation (x_i) is assigned to a given cluster such that the sum of squares distance of the observation to their assigned cluster centers (μ_k) is minimized.

The total within-cluster variation (*Total.with*) is as follows:

$$(5)\qquad \text{Total.with} = \sum_{k=1}^{k} W(C_k) = \sum_{k=1}^{k}\sum_{x_i \in C_k}(x_i - \mu_k)^2$$

The total within-cluster sum of squares measures the compactness of the clustering.

The first step when using k-means clustering is to indicate the number of clusters (k) that will be generated in the final solution. To determine the optimal number of clusters, we used the average silhouette approach with the Cluster package in *R* to measure the quality of a clustering: how well each object lies within its cluster (Kaufman and Rousseeuw 1990). The silhouette value is a measure of how similar an object is to its own cluster (cohesion) compared to other clusters (separation). The average silhouette method computes the average silhouette of observations for different values of k. The optimal number of clusters k is the one that maximizes the average silhouette over a range of possible values for k^2. The silhouette ranges from −1 to +1, where a high value indicates that the object is well matched to its own cluster and poorly matched to neighboring clusters. If most objects have a high value, then the clustering configuration is appropriate. If many points have a low or negative value, then the clustering configuration may have too many or too few clusters.

Using the Cluster package in *R*, the Hartigan-Wong algorithm was then run using the recommended number of clusters as determined in the silhouette optimization procedure. Once the algorithm is run, selected objects are selected as cluster means, or centroids. Next, each of the remaining objects is assigned to its closest centroid, where closest is defined using the Euclidean distance between the object and the cluster mean. This step is called the "cluster assignment step". After this, the algorithm computes the new mean value of each cluster. The cluster assignment and centroid update steps are iteratively repeated until the cluster assignments stop changing (i.e., until convergence is achieved, Kaufman and Rousseeuw 1990).

Growth Model Comparisons

Several models were then tested to compare estimated growth parameters between various time periods, as determined by the cluster analysis, for both length and weight. This was to determine if there were significant differences in growth between the various time periods/clusters (i.e. if multiple growth regimes were supported by the data and should be accounted for in the stock assessment model). The statistical methods for making these comparisons requires the use of indicator variables (i.e. the estimated growth parameters that are allowed to vary over time in each modeling approach) (Galucci and Quinn II 1979, Ritz and Streibig 2008). Essentially, four types of models were fit. The General Model includes separate parameter estimates for all estimated growth parameters in each time period identified by the cluster analysis, the "one parameter in common models" share a common parameter estimate between the time periods, the "two parameters in common models" share two common parameter estimates between the time periods, and the Common Model has the same parameter estimates for all time periods (i.e., no time blocks are implemented). These models are defined as follows, where *Year* indicates that the given parameter is estimated independently over each time period indicated by the associated cluster analysis. For brevity we only present models below that were used for the length at age analysis, however, the same model setup was also used for the weight at age analysis, where L_∞ is replaced by W_∞ and β is fixed at 3.

General Model: Separate parameter estimates for all estimated parameters in each time period.

(6) $$L_a = L_\infty[Year](1 - e^{-K[Year](t - t_0[Year])})$$

One parameter in common between time periods.

Common L_∞ Model:

(7) $$L_a = L_\infty(1 - e^{-K[Year](t - t_0[Year])})$$

Common K model:

(8) $$L_a = L_\infty[Year](1 - e^{-K(t - t_0[Year])})$$

Common t_0 Model:

(9) $$L_a = L_\infty[Year](1 - e^{-K[Year](t - t_0)})$$

Two parameters in common between time periods.

Common L_∞ and K Model:

(10) $L_a = L_\infty(1 - e^{-K(t - t_0[Year])})$

Common L_{inf} and t_0 Model:

(11) $L_a = L_\infty(1 - e^{-K[Year](t - t_0)})$

Common K and t_0 Model:

(12) $L_a = L_\infty[Year](1 - e^{-K(t - t_0)})$

Common Model: Same parameter estimates for all time periods.

(13) $L_a = L_\infty(1 - e^{-K(t - t_0)}$

Each "one parameter in common" model is a subset of the general model, each "two parameters in common" model is a subset of two of the "one parameter in common" models, and the "common model" is a subset of each "two parameters in common" model. The model with the lowest AIC was defined as the "best" model. If the difference in AIC value was less than 2, the more parsimonious model was chosen.

RESULTS

Temporal changes in growth were evident for both males and females. Results of the silhouette optimization of the annual LVB growth parameters for female sablefish recommended that the time series be split into two clusters (silhouette width = 0.507, Fig. 1.1a). The total within cluster sum of squares was 25.9 (between sum of squares/total sum of squares = 62.5%). Cluster analysis shows that a change in growth occurred after 2004 in females. The following were the recommended clusters for the time series of female sablefish growth that were tested for significant differences: 1996-2004 and 2005-2019 (Fig. 1.2a). The General Model was determined to be the best model for estimating growth in females, based on AIC values (Table 1.1). The General Model for female sablefish has separate L_∞, W_∞, k, and t_o parameters for the two time periods: 1996-2004 and 2005-2019 (Fig. 1.3a and 1.4a, Table 1.2 and 1.3).

Results of the silhouette optimization of the annual LVB growth parameters for male sablefish recommended that the time series be split into two clusters (silhouette width = 0.508, Fig. 1.1b). The total within cluster sum of squares was 28.4 (between sum of squares/total sum of squares = 58.9%). A disadvantage of using a cluster analysis with time series data is that a cluster does not necessarily contain consecutive data, unlike the female results. The following years were lumped together into two clusters: cluster 1 includes years 1996, 1997, 1998, 1999, 2001, 2002, 2003, **2010**, **2017**, **2018**, and **2019**, and cluster 2 includes years **2000**, 2004, 2005, 2006, 2007, 2008, 2009, 2011, 2012, 2013, 2014, 2015, and 2016 (Fig. 1.2b). 2000 temporally falls within the time series of the early time period (cluster 1), yet was grouped (most similar growth) with the late time period (cluster 2), and 2010 falls temporally within the time series of the later time period (cluster 2), yet was grouped (most similar growth) with the early time period (cluster 1). Years 2017, 2018, and 2019 shared similar growth with the early time period (cluster 1). For a long lived species such as sablefish, growth is not expected to change drastically from year to year. Due to vagaries in the cluster results and for the simplicity of assessment, we recommend that 2000, 2010, and 2017-2019 remain within their respective time periods when estimating growth. The following are the final recommended clusters (same as females) for the time series of male sablefish growth that were further tested for significant differences: 1996-2004 and 2005-2019 (Fig. 1.2b). The General Model was determined best for estimating growth in terms of length at age, and the Common W_∞ Model was determined best for estimating growth in terms of weight at age, based on AIC values (Table 1.1). Because the AIC values were similar, and to maintain consistency between length and weight estimated growth, it is recommended that the General Model is best for estimating both length and weight at age for male sablefish. The General Model has separate $L_{\infty,}$ W_∞, k, and t_o parameters for the two time periods: 1996-2004 and 2005-2019 (Fig. 1.3b and 1.4b, Tables 1.2 and 1.3).

There have been temporal changes in growth in both male and female sablefish in Alaskan waters. Results from the cluster analysis of annual LVB growth curves during years 1996-2019 show that a significant change in growth occurred after 2004 (Fig. 1.3 and Fig. 1.4, Tables 1.1 and 1.2). A comparison of growth curves fit to these updated time periods show that the slope of the growth curves for both sexes is steeper in the earlier time periods, indicating faster growth at this time. This is especially evident during ages 6-11 in females (Fig. 1.3a and 1.4a), which is when sablefish growth is fastest and fish are reaching maturity. This also indicates that there has been a decrease in size at age over time. In general, the earlier time periods had the fastest growth at young ages and highest t_o parameters.

Current growth estimates used in the 2021 Alaska sablefish stock assessment are split between two time periods: 1981-1993 and 1996-2004 (Goethel et al. 2020). Current maximum lengths and weights during the 1996-2004 time period are as following: 67.7 cm and 3.162 kg for males and 80.2 cm and 5.471 kg for females (Goethel et al. 2020). Refined estimates from this analysis will result in a slighter larger estimated maximum size (Tables 1.2 and 1.3) for females than what is currently used in the stock assessment model.

DISCUSSION

Our analyses show that there have been temporal changes in the growth of both male and female sablefish, and that the recent time series (1996-2019) of data available for estimating growth span multiple sablefish growth regimes. While these changes were not severe, they were significantly different. It appears that in more recent years sablefish are growing to a larger maximum size, but at a slower rate, which translates to smaller sized fish during the critical early ages. Coincidentally, our analysis recommended the time series be divided into two time periods that split where the last update of growth concluded (after 2004; Hanselman et al. 2007).

Concerns regarding increased ocean temperatures and density dependent effects caused by increased abundance were what initiated this reevaluation of growth. While temporal changes were evident in both sexes, there were no clear trends that emerged in relation to years of increased ocean temperatures or high recruitment with females. There was, however, a change in growth seen in 2017-2019 in males that could potentially be due to density dependence. While we analyzed annual growth parameters to determine potential temporal changes in growth, a more robust analysis that tracks cohorts to see if large year classes experience differential growth may prove more beneficial. This type of analysis will require more years of data tracking the cohorts in question than what is available. Additional analysis of potential growth changes in 2004 is warranted and may benefit from a cohort-based analysis during this time stanza and further research into environmental or ecosystem drivers that may help explain why a definitive change in growth occurred. A recent growth analysis of Northeast Pacific sablefish did not detect any changes in 2004, but a change was detected in 2009 in sablefish age 4 and 6 (Kapur et al. 2020). For these reasons, we do not recommend incorporating additional time blocks of growth in the sablefish assessment currently but recommend updating size-at-age parameters with the most recent data to include all post-1996 data. We recommend using the updated growth information divided into two time periods (1981-1993 and 1996-2019) for both males and females in the 2022 Alaska sablefish stock assessment. Incorporating up-to-date biological data will provide the most accurate picture of population size-at-age and spawning biomass.

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Tables

Table 1.1. AIC values of length at age (top table) and weight at age (bottom table) models for sablefish. The df are the degrees of freedom and an asterisk denotes the best fit model for each sex.

Model	df	AIC: Female	AIC: Male
General Model	7	99,457*	77,213*
Common L_∞ Model	6	99,504	77,218
Common t_0 Model	6	99,615	77,265
Common K Model	6	99,668	77,305
Common L_∞ and K Model	5	99,747	77,350
Common L_∞ and t_0 Model	5	99,617	77,268
Common K and t_0 Model	5	99,684	77,375
Common Model	4	100,158	77,739

Model	df	AIC: Female	AIC: Male
General Model	7	44,475*	24,359
Common W_∞ Model	6	44,566	24,358*
Common t_0 Model	6	44,570	24,378
Common K Model	6	44,740	24,445
Common W_∞ and K Model	5	44,820	24,534
Common W_∞ and t_0 Model	5	44,595	24,830
Common K and t_0 Model	5	44,795	24,531
Common Model	4	45,264	24,962

Table 1.2. Estimated length at age growth parameters (and standard errors) for sablefish sampled during specified time periods. *Denotes parameters currently used in the stock assessment (Goethel et al. 2020).

Sex	Parameters	1981-1993*	1996-2004*	1996-2004	2005-2019	1996-2019
Female	L_∞	75.568 (0.460)	80.22 (0.221)	80.2 (0.221)	82.8 (0.29)	81.2 (0.19)
	k	0.208 (0.018)	0.222 (0.005)	0.22 (0.005)	0.14 (0.002)	0.17 (0.003)
	t_o	-3.629 (0.523)	-1.949 (0.119)	-1.9 (0.119)	-4.3 (0.13)	-3.28 (0.09)
	n	31	5,767	5,767	9,591	15.358
Male	Parameters	1981-1993*	1996-2004*	1996-2004	2005-2019	1996-2019
	L_∞	65.269 (0.341)	67.774 (0.127)	67.8 (0.12)	68.3 (0.13)	67.9 (0.09)
	k	0.227 (0.029)	0.290 (0.009)	0.29 (0.008)	0.20 (0.004)	0.23(0.003)
	t_o	-4.092 (0.936)	-2.273 (0.171)	-2.3 (0.16)	-4.1 (0.15)	-3.3 (0.11)
	n	30	4,889	4,889	8,503	13,392

Table 1.3. Estimated weight at age growth parameters (and standard errors) for sablefish sampled during specified time periods.

Sex	Parameters	1996-2004	2005-2019	1996-2019
Female	W_∞	5.6 (0.05)	6.2 (0.08)	5.87 (0.04)
	k	0.24 (0.005)	0.14 (0.003)	0.17 (0.002)
	t_o	-1.34 (0.07)	-4.23 (0.08)	-2.98 (0.06)
	n	5,767	9,591	15,358
	Parameters	1996-2004	2005-2019	1996-2019
Male	W_∞	3.3 (0.02)	3.2 (0.02)	3.2 (0.01)
	k	0.34 (0.01)	0.23 (0.005)	0.27 (0.002)
	t_o	-1.53 (0.09)	-3.25 (0.15)	-2.41 (0.07)
	n	4,889	8,503	13,392

Figures

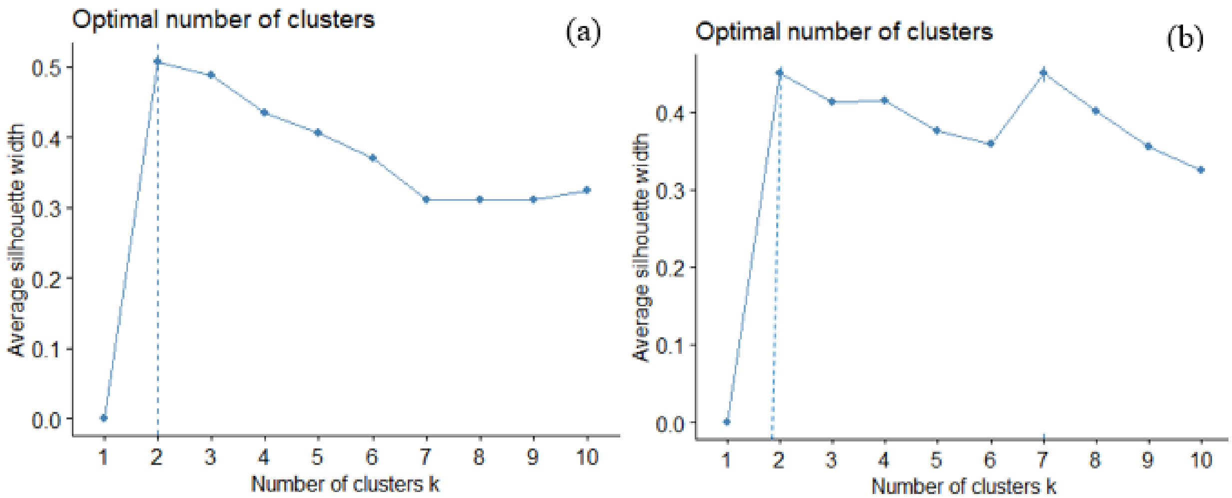

Figure 1.1. Calculated average silhouette width (y axis) per number of clusters (x axis) for females (a) and males (b). Dotted lines represent recommended number of clusters.

Figure 1.2. Final cluster groupings of annual growth curves for female (a) and male (b) sablefish in Alaska waters. 1996 = 1, 1997 = 2, 1998 = 3, etc.

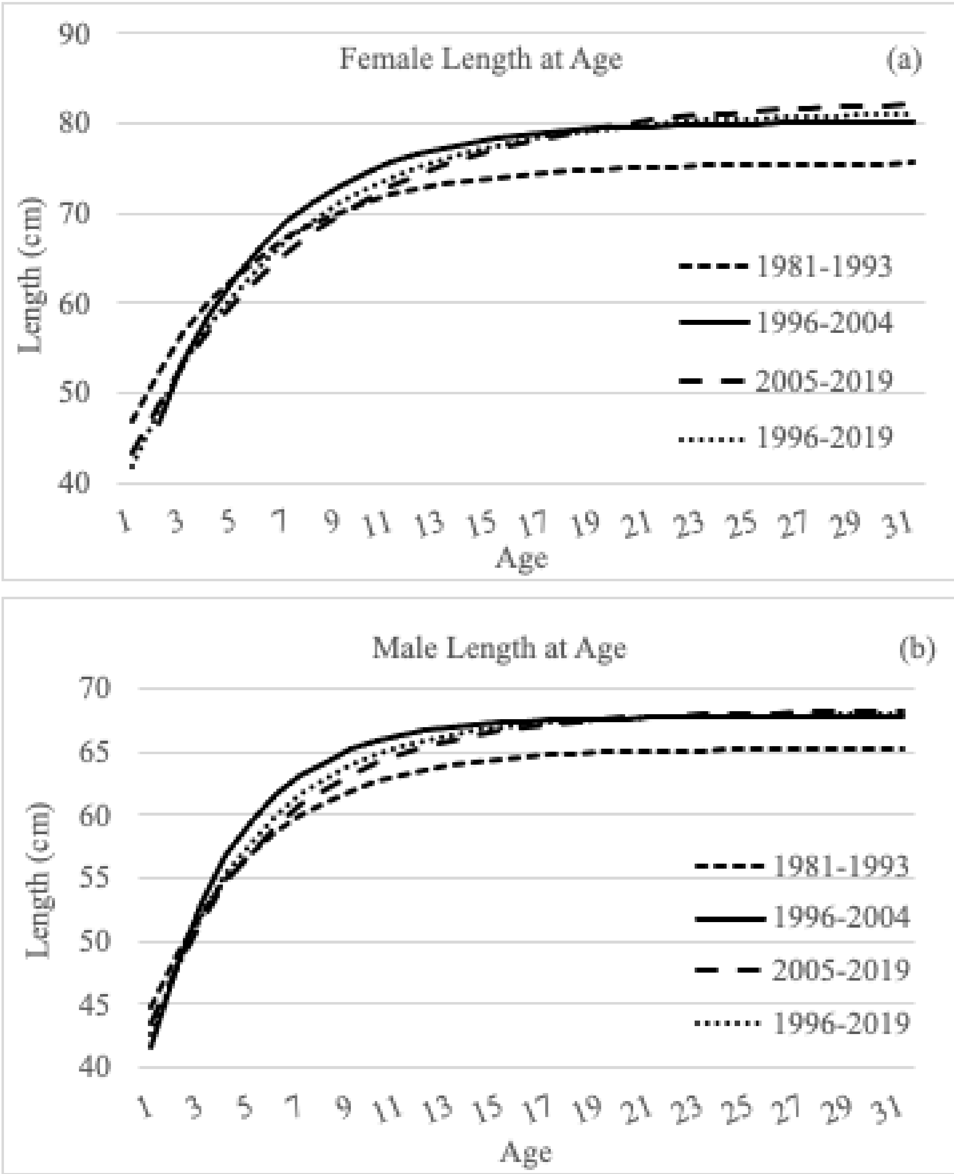

Figure 1.3. Comparison of sablefish LVB fit to age-length data for time periods as determined from the cluster analysis, as well as for lumped 1996-2019 data, for females (a) and males (b). The 1981-1993 growth curve is from the current stock assessment for comparison (Goethel et al. 2020).

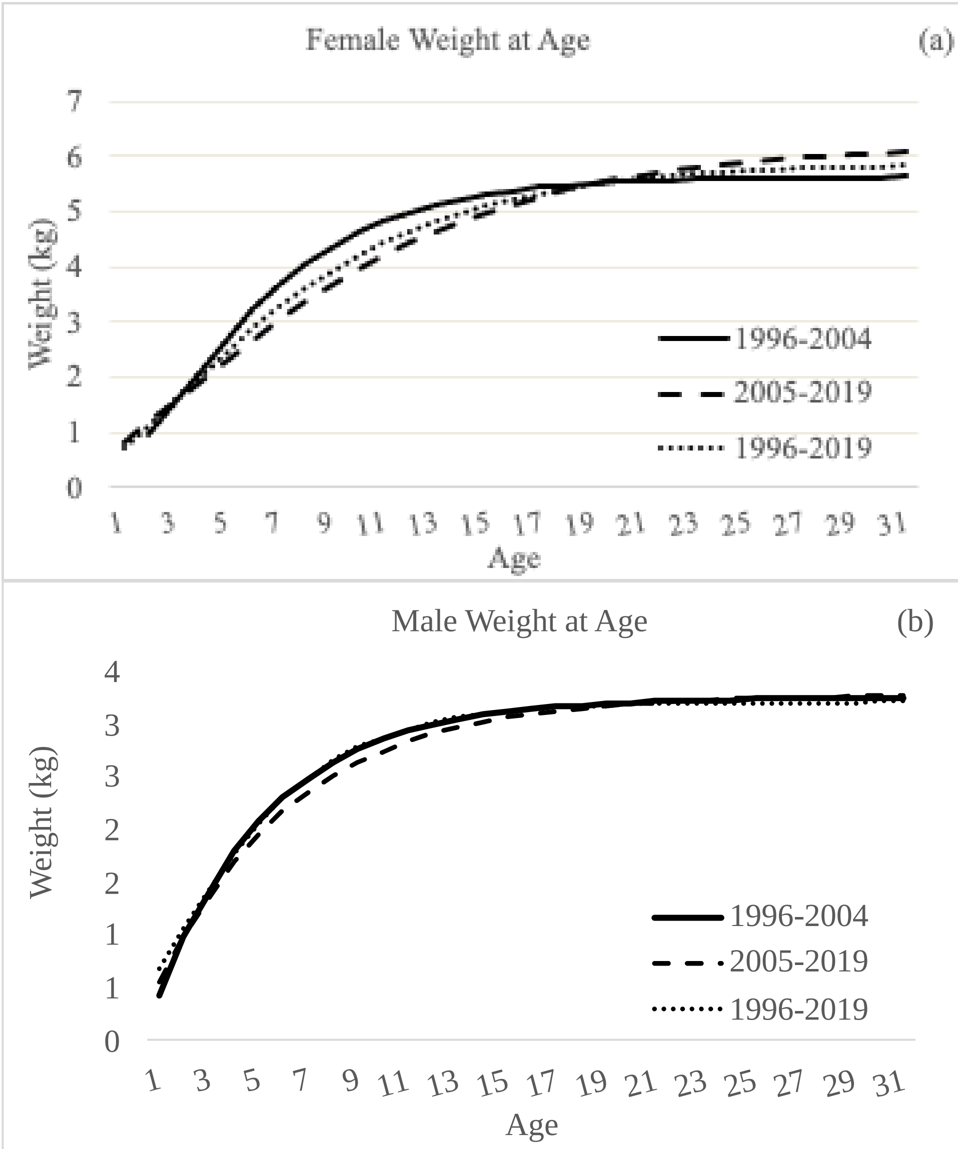

Figure 1.4. Comparison of sablefish LVB fit to age-weight data for time periods as determined from the cluster analysis, as well as for lumped 1996-2019 data, for females (a) and males (b).