Preliminary results for an age-structured model for sablefish (*Anoplopoma fimbria*) in the Northern Southeast Inside management area

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Introduction

Sablefish have been commercially fished in Southeast Alaska inside waters since at least the early 1900s (Carlile et al. 2002). There is a long history of sablefish management in the Northern Southeast Inside (NSEI) management area, with seasonal closures beginning in 1945 and tagging experiments occurring as early as 1951 (Figure 1; Carlile et al. 2002). Attempts to develop an age-structured model for NSEI sablefish date back to 1995 (Carlile et al. 2002, Dressel 2009, Mueter 2010, Williams and Kirk 2017).

Currently the Alaska Department of Fish and Game (ADFG) conducts an annual mark-recapture pot survey in May (Stahl and Holum 2010). Tags are recaptured in the ADFG longline survey in July and the longline fishery in August (Beder and Stahl 2016). A time-stratified modified Petersen model is used to estimate abundance in the Bayesian open source software JAGS 4.3.0 (Sullivan and Williams 2018, Depaoli 2016). The abundance estimate is then partitioned into age classes and biomass estimates using age composition and weight-at-age data collected during the longline survey and fishery. A yield-per-recruit model is used to estimate F50% using the optim() function in the statistical software R (R Core Team 2018). ADFG has defined Acceptable Biological Catch (ABC) as FABC=F50% for the NSEI sablefish stock (Dressel 2009).

Several factors have motivated an effort to develop an age-structured model. The current ADFG framework relies on Federal estimates of selectivity and does not estimate recruitment for the stock. Second, the mark-recapture provides a single snapshot in time and therefore results in high inter-annual variability in abundance and biomass estimates. Further, ADFG collects a significant amount of data in the NSEI through multiple surveys, logbooks, and port sampling, but is currently unable to fully integrate these data sources, explore historical trends, or adequately assess stock status or harvest strategies. Finally, strong recruitment from the 2014 and possibly 2013 and 2015 year classes were reported in the Federal assessment, prompting questions about how to treat the uncertainty in recruitment for State management (Hanselman et al. 2017, Sullivan and Williams 2018). An age-structured model coded in Template Model Builder (TMB) will allow more flexibility in exploring recruitment using random effects (Kasper et al. 2016).

Modeling approach

The statistical catch-at-age model presented here was coded in TMB, an R package library that leverages `C/C++` functionality to calculate first and second order derivatives and was inspired by a similar `C/C++` templating software ADMB (Kasper et al. 2016, Fournier et al. 2012). The TMB code replicates or makes refinements to methods used in a previous attempt at modeling the NSEI sablefish stock, which was based on ADMB code from an older Federal assessment of rockfish (Mueter 2010). Variable definitions for all equations can be found in Table 1.

Data inputs

Weight-at-age

Data from the 2002-2017 longline fishery and 1997-2017 ADFG longline surveys were used to obtain weight-at-age. We fit a three-parameter weight-based Ludwig von Bertalanffy growth model to weight-at-age data:

$$\ln(w_a) = \ln W_\infty + \beta \cdot \ln(1 - \exp(a - t_0)),$$

where w_a is weight at a given age (kg), W_∞ is the mean asymptotic weight (kg), β is the power in the allometric equation and relates to the rate at which W_∞ is reached, and t_0 is the theroectical age at weight zero (years). Data from the longline fishery in Chatham was used to estimate mean predicted weight-at-age in the fishery with sexes combined. Data from the longline surveys were used to obtain mean predicted weight-at-age in the longline survey for both sexes combined and females only. The female weight-at-age was used to estimate spawning stock biomass within the model.

Maturity-at-age

Data from the 2007-2017 ADFG longline surveys were used to fit a maturity curve for females and used to estimate spawning stock biomass within the model (Figure 2B). Alternative year-specific models were evaluated using Akaike Information Criterion (AIC) (Akaike 1974). The maturity curve fit to all years was the best-fitting model. We used a logistic regression approach in R, such that the probability p of being mature at a given age on the logit scale is a linear function of age (a):

$$\ln(\frac{p_a}{p_a - 1}) = \beta_0 + \beta_1 \cdot a.$$

We derived the age at 50% maturity (a_{50}) and the instantaneous rate of maturation (k_{mat}) as

$$a_{50} = \frac{-\beta_0}{\beta_1}$$

and

$$k_{mat} = \frac{\beta_0 + \beta_1 a}{a - a_{50}}.$$

The a_{50} and k_{mat} were estimated to be 6.4 years and 0.85 years^{-1}, respectively. Predicted proportions mature-at-age were used as inputs to the assessment model.

Sex ratios

Using sex ratio data from the 1997-2017 ADFG longline surveys, we fit a generalized additive model (GAM) using the `gam()` function in the `mgcv` R package (Wood 2011). The probability of being female-at-age r_a is modeled as a smooth function of age a

$$\ln(\frac{r_a}{r_a - 1}) = s(a).$$

Fits to the data suggest that female sablefish make up the majority of catch-at-age in the survey until roughly age-18 and then decline to 30% at age-40 (Figure 2C). Predicted values of proportion female-at-age were used to estimate spawning stock biomass within the model.

Catch

Catch data from 1980-2017 included all available sources of sablefish mortality in the NSEI, including harvest in the directed sablefish longline fishery, bycatch in other fisheries like the IFQ halibut longline fishery, and personal use (Figure 3A). Sport harvest is not currently accounted for in this model.

Indices of abundance

Fishery CPUE (kg per hook) from the 1980-2017 was used as an index of abundance is the model (Figure 3B). Two survey CPUEs (numbers per hook) were used as indices of abundance in the model, including a 1-hr soak time longline survey from 1988-1996 and a 3+ hour soak time longline survey from 1997-2017 (Figure 3C). Sigler (1993) found that the 1-hr soak time was likely too short to provide an accurate measure of relative abundance. However, following Carlile et al. (2002), we found these data to exhibit similar trends and magnitude and chose to estimate a separate catchability for this index instead of omitting it from the model. The mark-recapture abundance index was included for 2003-2010, 2012, 2013, 2015, and 2017. These estimates of abundance come from a time-stratified modified Petersen mark-recapture model that was implemented in `JAGS 4.3.0` (Sullivan and Williams 2018, Depaoli 2016). Further information about how these indices were derived can be found in Sullivan and Williams (2018).

Age compositions

Fishery age compositions from the 2002-2017 longline fishery and survey age compositions from ADFG longline survey were included in the model (Figure 4).

Natural mortality

Natural mortality M was assumed constant over time and age and is fixed at 0.10, which is consistent with past State and Federal assessments (Johnson and Quinn 1988, Hanselman et al. 2018).

Estimated parameters

Selectivity

At least four selectivity parameters are estimated: s_{50}^{fsh}, s_{95}^{fsh}, s_{50}^{srv}, s_{95}^{srv}, where s_{50} and s_{95} represent the ages at which 50% and 95% of individuals are selected by the longline gear for the fishery (fsh) and survey (srv) respectively. There is flexibility to define discrete time blocks h for both fishery and survey selectivity.

Catchability

Currently four parameters for catchability are estimated: $\ln(q_{fsh})$, $\ln(q_{srv1})$, $\ln(q_{srv2})$, and $\ln(q_{MR})$.

Recruitment

There is one parameter estimated for mean log-recruitment, μ_R, and -5 ($T + A$ - 2) log-recruitment deviations, τ_i (Figure cartoon). Following the Federal assessment, if recruitment is estimated using penalized likelihood, the parameter that describes the variability of recruitment deviations on the log-scale, $\ln(\sigma_R)$, is fixed at 0.1823 (Sigler et al. 2002, Hanselman et al. 2018). However, if recruitment deviations are estimated as random effects, $\ln(\sigma_R)$ is an estimated parameter.

Fishing mortality

There is one parameter estimated for mean log-fishing mortality, μ_F, and 38 (T) log-fishing mortality deviations, ϕ_t.

Population dynamics

The population dynamics of this model are governed by the following state dynamics equations, where the number of sablefish (N) in year ($t = 1$) and age (a) are defined as

$$N_{1,a} = \begin{cases} \exp(\mu_R - M(a - a_0) + \tau_i) & a_0 < a < a_+ \\ \exp(\mu_R - M(a_+ - 1))/(1 - \exp(-M)) & a = a_+ \end{cases}$$

where $i = A - a - 2$. Recruitment to age-2 in all years and the remaining projected N matrix is defined as

$$N_{t,a} = \begin{cases} \exp(\mu_R + \tau_i) & a = a_0 \\ N_{t-1,a-1}\exp(Z_{t-1,a-1}) & a_0 < a < a_+ \\ N_{t-1,a-1}\exp(Z_{t-1,a-1}) + N_{t-1,a}\exp(Z_{t-1,a}) & a = a_+ \end{cases}$$

where $i = A + t - 2$, and the total instantaneous mortality, $Z_{i,a}$, is the sum of natural mortality M and fishing mortality $F_{i,a}$.

Predicted recruitment (R_i) is computed as

$$R_i = \exp(\mu_R + \tau_i)$$

where i is indexed from 1 to $A + T - 2$.

Predicted values

Fishery and survey selectivity-at-age (s_a) were fit using a logistic function:

$$s_a = \frac{1}{1 + \exp\frac{\ln(19)(a - s_{50})}{s_{95} - s_{50}}}.$$

Predicted fishery CPUE (kg per hook) in year t $\hat{I}_t^{fsh}$ was defined as a function of catchability q_{fsh} and biomass (B):

$$\hat{I}_t^{fsh} = q_{fsh} \sum_{a=a_0}^{A} B_{t,a} \cdot s_a^{fsh}.$$

In contrast, predicted values in year t for the survey CPUE indices (both numbers per hook) and mark-recapture abundance were fit as a function of q and abundance (N):

$$\hat{I}_t^{srv1} = q_{srv1} \sum_{a=a_0}^{A} N_{t,a} \cdot s_a^{srv},$$

$$\hat{I}_t^{srv2} = q_{srv2} \sum_{a=a_0}^{A} N_{t,a} \cdot s_a^{srv}, \text{ and}$$

$$\hat{I}_t^{MR} = q_{MR} \sum_{a=a_0}^{A} N_{t,a} \cdot s_a^{srv}.$$

Additionally, we defined vulnerable abundance to the survey as $\sum_{a=a_0}^{A} N_{t,a} \cdot s_a^{srv} \cdot S^{srv}$, where S^{srv} is the fraction of individuals surviving to the beginning of the longline survey in July. We defined exploitable biomass as $\sum_{a=a_0}^{A} N_{t,a} \cdot w_a^{fsh} \cdot s_a^{fsh} \cdot S^{fsh}$, where w_a^{fsh} is mean fishery weight-at-age (sexes combined) and S^{fsh} is the fraction of individuals surviving to the beginning of the fishery in August. Spawning biomass was derived as $\sum_{a=a_0}^{A} N_{t,a} \cdot w_a^{f,srv} \cdot S^{spawn} \cdot p_a \cdot r_a$, where $w_a^{f,srv}$ is mean weight-at-age of females in the longline survey, S^{spawn} is the fraction of individuals surviving to spawn in February, p_a is the proportion of females mature in the survey, and r_a is the proportion of females at age in the survey.

Predicted survey age compositions were computed as

$$\hat{P}_{t,a}^{srv} = \frac{N_{t,a} \cdot s_a^{srv}}{\sum_{a=a_0}^{A} N_{t,a} \cdot s_a^{srv}}.$$

Similarly, predicted fishery age compositions were computed as

$$\hat{P}_{t,a}^{fsh} = \frac{C_{t,a}}{\sum_{a=a_0}^{A} C_{t,a}},$$

where $C_{t,a}$ is catch in numbers-at-age derived from the Baranov catch equation:

$$C_{t,a} = N_{a,t} \frac{F_{t,a}}{Z_{t,a}} (1 - \exp(-Z_{t,a})).$$

Finally, the predicted catch in biomass $\hat{Y}$ was calculated as the product of fishery weight-at-age w_a^{fsh} and catch in numbers-at-age:

$$\hat{Y}_t = \sum_{a=a_0}^{A} w_a^{fsh} \cdot C_{t,a}.$$

Likelihood components

The total likelihood to be maximized includes the sum of the following likelihood components L, which received individual weights λ:

1. Catch (Y) is modeled using a normal likelihood where σ_Y was assumed to be 0.05:

$$L(Y) = \lambda_Y \frac{1}{2\sigma_Y^2} \sum_{t=1}^{T} \left(\frac{Y_t - \hat{Y}_t}{\hat{Y}_t} \right)^2,$$

where $\lambda_Y = 1.0$.

2. Fishery CPUE, the two survey CPUE indices, and the mark-recapture abundance index were modeled using lognormal likelihoods, where σ_I was assumed to be 0.20 for the survey and fishery CPUEs and annual posterior standard deviations were used for the mark-recapture abundance index:

$$L(I) = \lambda_I \frac{1}{2\sigma_I^2} \sum_{t=1}^{T_I} \ln(I_t) - \ln(\hat{I}_t),$$

where T_I is the number of years of data for each index and λ_I is set to 1.0.

3. The fishery and survey age compositions P are modeled using a multinomial likelihood, where effective sample size ω was assumed to be 50:

$$L(P) = \lambda_P \sum_{t=1}^{T_P} -\omega \sum_{a=a_0}^{A} (P_{t,a} + c) \cdot \ln(\hat{P}_{t,a} + c),$$

where T_P is the number of years of data for each age composition, $lambda_P$ is set to 1.0, and c is a small constant set at 0.0001 that prevents the composition from being 0 in the likelihood calculation.

4. Annual log-fishing mortality deviations (ϕ_t) are included with a penalized lognormal likelihood, where

$$L(\phi) = \lambda_\phi \sum_{t=1}^{T} \phi_t^2,$$

where λ_ϕ=0.1.

5. Recruitment deviations (τ_i) can be included using a penalized lognormal likelihood

$$L(\tau) = \lambda_\tau \sum_{i=1}^{T+A-2} (\tau_i - 0.5\sigma_R^2)^2,$$

where λ_ϕ=0.1 and σ_R is fixed at 1.2 as in the Federal assessment (Hanselman et al. 2018).

Alternatively, recruitment deviations can be estimated as a random effect, where

$$L(\tau) = \sum_{i=1}^{T+A-2} \ln(\sigma_R) + \frac{(\tau_i - 0.5\sigma_R^2)^2}{2\sigma_R}.$$

All likelihood components assuming a lognormal distribution include a bias correction ($-0.5\sigma^2$) needed to obtain the expected value (mean) instead of the median.

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Tables

Variable	Definition
Indexing and model dimensions	
A	Number of ages
T	Number of years
a	Index for age in model equations
a_0	Recruitment age (age-2)
a_+	Plus group age (age-42)
t	Index for year in model equations
i	Index for recruitment in model equations ($A+T$-2)
fsh	Longline fishery
$srv1$	ADFG 1-hr soak time longline survey (1988-1996)
$srv2$	ADFG 3+hr soak time longline survey (1997-2017)
MR	Mark-recapture abundance estimates (2003-2010, 2012, 2013, 2015, 2017)
Estimated parameters	
s_{50}	Age at which 50% of individuals are selected to the gear
s_{95}	Age at which 95% of individuals are selected to the gear
q	Catchability
μ_R	Mean log recruitment
τ_i	Log recruitment deviations
μ_F	Mean log fishing mortality
ϕ_t	Log fishing mortality deviations
Data and predicted variables	
M	Instantaneous natural mortality
F	Instantaneous fishing mortality
Z	Total instantaneous mortality
S	Natural annual survival
s_a	Selectivity-at-age
w_a	Weight-at-age
p_a	Proportion mature-at-age
r_a	Proportion female-at-age
N	Numbers-at-age
R	Recruitment
C	Catch in numbers-at-age
$I, \hat{I}$	Indices of abundance, $\hat{I}$ are predicted values
$P, \hat{P}$	Age compositions, $\hat{P}$ are predicted values
$Y, \hat{Y}$	Catch in biomass, $\hat{Y}$ are predicted values
λ	Weight for likelihood component
L	Likelihood

Figures