Appendix B. Preliminary results for a statistical catch-at-age 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, with active management in the Northern Southeast Inside (NSEI) management area beginning in 1945 (Figure 2 in Carlile et al. 2002). Early attempts to track fishery performance and estimate abundance of sablefish in NSEI included a vessel logbook program that began in 1932 and a tagging experiment in 1951 (Carlile et al. 2002). A number of statistical catch-at-age models for NSEI sablefish have been developed; however, none of these models have been used to set annual harvest quotas (Carlile et al. 2002, Dressel 2009, Mueter 2010, Williams and Van Kirk 2017).

Currently the Alaska Department of Fish and Game (ADF&G) conducts an annual mark-recapture survey that serves as the basis for stock assessment and managment (Stahl and Holum 2010). Fish are tagged during a pot survey in May, with recaptures occurring in the ADF&G longline survey in July and the longline fishery in August (Beder and Stahl 2016). A time-stratified Chapmanized Petersen model is used to estimate abundance in a Bayesian framework using `JAGS 4.3.0` (Chapman 1951, Sullivan and Williams 2018, Depaoli 2016). Abundance estimates are partitioned into age classes in order to estimate biomass at age using age composition and weight-at-age data collected during the longline survey and fishery. ADF&G has defined Acceptable Biological Catch (ABC) as F_{ABC}=$F_{50\%}$ for the NSEI sablefish stock (Dressel 2009). A yield-per-recruit model is used to estimate $F_{50\%}$ using the `optim()` function in the statistical software `R` (R Core Team 2018).

Several factors motivated the development of a statistical catch-at-age model. The current ADF&G framework relies heavily on the mark-recapture experiment, which may be vulnerable to future budget cuts. Further the mark-recapture estimate provides a single snapshot in time and is susceptible to high inter-annual variability in abundance and biomass estimates. Consequently, it is difficult to fully integrate all available data sources, explore historical trends, or fully assess stock status or harvest strategies. ADF&G collects a significant amount of data in the NSEI through multiple surveys, logbooks, and port sampling (Figure 1). Moving to a new modeling framework will allow us to better utilize these data and will make management more resilient to potential budget cuts. Additionally, the current assessment relies on Federal estimates of selectivity and does not estimate recruitment for the stock. If there are differences in availability, gear selectivity, or stock dynamics between Federal waters and NSEI, we are unable to detect them. 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 uncertainty in recruitment for State management (Hanselman et al. 2017, Sullivan and Williams 2018). A statistical catch-at-age model coded in Template Model Builder (`TMB`) will allow more flexibility in exploring recruitment using random effects (Kristensen et al. 2016).

Modeling approach

The statistical catch-at-age model presented here was coded in `TMB`, an `R` library that leverages `C/C++` functionality to calculate first and second order derivatives and was inspired by a similar `C/C++` templating software `ADMB` (Kristensen 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 (Mueter 2010); this model was based on `ADMB` code from an older Federal assessment of sablefish that has also been adapted for Alaska rockfish stocks (Kimura 1990, Sigler 1999). The model can be run as either a single-sex or sex-structured model; however, data inputs are only shown for the sex-structured option. Variable definitions for all equations used in the statistical catch-at-age model can be found in Table 1.

Data inputs

The data used as inputs to the `TMB` model, including point estimates, variance, and sample sizes for composition data, can be found in `seak_sablefish/data/TMB_inputs`. A summary of the available data by year can be found in Figure 1.

Weight-at-age

Data from the 2002-2018 longline fishery and 1997-2018 ADF&G longline surveys were used to obtain weight-at-age. We fit sex-specific three-parameter weight-based Ludwig von Bertalanffy growth models to weight-at-age data:

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

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 theoretical age at weight zero (years).

The Federal assessment uses survey weight-at-age exclusively to fit to catch and effort indices (Hanselman et al. 2018). However, because discarding is permitted in the State fishery, there are large differences in survey and fishery weight-at-age, especially at younger ages (Figure 2A). Consequently fishery weight-at-age was fit to landed catch biomass, while survey weight-at-age was used to estimate exploitable biomass, spawning biomass, and other quantities of interest in the model (Figure 2A).

Maturity-at-age

Data from the 1997-2018 ADF&G longline surveys were used to fit a maturity curve for females and estimate spawning stock biomass within the model (Figure 2B). Alternative length, age, and year-specific models were evaluated using Akaike Information Criterion (AIC) (Akaike 1974). The length-based 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 length on the logit scale is a linear function of length (l):

$$\ln(\frac{p_l}{1 - p_l}) = \beta_0 + \beta_1 \cdot l. \tag{2}$$

Predicted maturity-at-length was transformed to maturity-at-age using fitted values from a length-based von Bertalanffy growth curve. The length at 50% maturity is 61 cm and the age at 50% maturity is 6.4 years. Predicted proportions mature-at-age were used as inputs to the assessment model and in the calculation of spawning stock biomass (Figure 2B).

Sex ratios

A generalized additive model (GAM) was fit to sex ratio information from the 1997-2018 ADF&G longline surveys 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

$$\ln(\frac{r_a}{1-r_a}) = s(a). \tag{3}$$

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 <40% by age-30 (Figure 2C). Predicted values of proportion female-at-age were used to estimate spawning stock biomass in the single sex model. These data are not used in the sex-structured model.

Catch

Catch data from 1980-2018 include harvest in the directed sablefish longline fishery, ADF&G longline survey removals, and sablefish retained in other fisheries like the IFQ halibut longline fishery (Figure 3A). Catch was assumed to be lognormally distributed, with a fixed log standard deviation of 0.05.

Changes in the management structure during this period included a move to Limited Entry in 1985 and the Equal Quota Share (EQS) Program in 1994. Additional sources of mortality that are not currently included in this model include sport, subsistence and personal use harvest, estimated bycatch mortality in the halibut fishery, and estimated deadloss, which includes mortality from sand fleas, sharks, and whales. Currently these additional sources of mortality are accounted for in the decrements process used to calculate the Annual Harvest Objective. Methods should be developed to incorporate these data into the model in the future.

Fishery CPUE

Fishery catch-per-unit-effort (CPUE) in kg per hook was used as an index of abundance from 1980-2018 (Figure 3B). This index was assumed to be lognormally distributed, with a fixed log standard deviation of 0.1 for the historical data (1980-1996) and 0.08 for the contemporary data (1997 to present). Separate catchabilities and selectivity curves were assumed for pre-EQS and EQS time periods (Table 2).

Survey CPUE

Longline survey CPUE in numbers per hook was used as an index of abundance from 1997-2018 (Figure 3C). This index was assumed to be lognormally distributed, with a fixed log standard deviation of 0.1. An earlier ADF&G longline survey in 1988-1996 used a shorter soak time of 1-hr instead of the current 3-11 hr (Carlile et al. 2002). These data were omitted because the 1-hr soak time was likely too short to provide an accurate measure of relative abundance (Sigler 1993).

Mark-recapture abundance

The mark-recapture abundance index was included for 2003-2010, 2012, 2013, 2015, 2017, and 2018 (Figure 3D). A time-stratified Petersen mark-recapture model implemented in `JAGS 4.3.0` was used to estimate abundance (Sullivan and Williams 2018, Depaoli 2016). Further information about how these indices were derived can be found in Sullivan and Williams (2018). This index was assumed to be lognormally distributed, and the log standard deviation was approximated as the coefficient of variation from the posterior distribution of the mark-recapture abundance estimates.

Age compositions

Fishery age compositions from the 2002-2018 longline fishery and survey age compositions from the 1997-2018 ADF&G longline surveys were included in the model (Figure 4). Sample sizes were deemed insufficient to fit age compositions by sex, so age data have been aggregated for both the survey and fishery. Age compositions were assumed to follow the multinomial or Dirichlet-multinomial distributions (only results for the multinomial are shown in this report). Until more sophisticated tuning methods or estimates of effective sample size can be developed for NSEI, effective sample sizes were calculated as the square root of the total sample size in a given year.

An ageing error matrix for NSEI is currently being developed in conjunction with the ADF&G Age Determination Unit. Until this has been fully developed and reviewed, the Federal sablefish ageing error matrix has been made available to the State (D. Hanselman, Fisheries Research Biologist, NOAA, Juneau, personal communication April 2019; Hanselman et al. 2018; Heifetz et al. 1999; Figure 5). The ageing error matrix ($\Omega_{a',a}$) is the proportion observed at age a given the true age a'. Ageing error matrices are critical for correcting observed age compositions and estimating recruitment (Fournier and Archibald 1982).

Length compositions

Length data from the 2002-2018 longline fishery and 1997-2018 ADF&G longline surveys were summarized using the Federal conventions for length compositions (Hanselman et al. 2018). The Federal assessment uses 2-cm length bins ranging from 41-99 cm. Fish less than 41 cm (l_0) were omitted from the analysis, and fish greater than 99 cm were aggregated into the 99 cm length bin (l_+). Sample sizes were adequate to separate length compositions by sex.

Length distributions in fishery (Figure 6) show dramatically different patterns than the survey (Figure 7), with the fishery length distribution truncated at approximately 60 cm. Full retention is not a requirement in State waters and the length differences between the survey and fishery are attributed to discarding of small fish in the fishery. Because of the bias introduced by allowing fish to be released in the fishery, there is a question of whether fishery age and length compositions should be included in model.

Finally, the selective harvest of larger-bodied individuals results in large differences between survey and fishery size-at-age. Until an age-length key is developed for NSEI, the Federal age-length keys ($\Lambda_{a,l,k}$) will be used to fit both survey and fishery length compositions (D. Hanselman, Fisheries Research Biologist, NOAA, Juneau, personal communication April 2019; Hanselman et al. 2018; Echave et al. 2012; Figure 8). Ultimately, separate age-length keys should be developed for each data source to account for the differences in survey and fishery size-at-age.

Retention probability

To model the discarding behavior in the NSEI fishery, processor grade and price per pound data were used to inform retention probabilities at size (Figure 9). Based on conversations with ADF&G port sampling staff and fishermen, the lower bound of the Grade 2/3 (1.4 kg) was assigned a 10% retention probability, the lower bound of the Grade 3/4 (2.2 kg) was assigned a 50% retention probability, and everything greater than 6.4 kg was assigned a 100% retention probability (A. Olson, Groundfish Project Leader, ADF&G July 2018). Remaining retention probabilities were interpolated between these fixed values. Weight-based retention probabilities were translated to sex and age $R_{a,k}$ using sex- and weight-based von Bertalanffy growth curves (Figure 9).

Model parameters

Natural mortality

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

Discard mortality

Stachura et al. (2012) estimated discard mortality D of sablefish to be 11.7% using release-recapture data from a longline survey in Southeast Alaska. It is likely that discard mortality in a fishery is higher due to careful fish handling on survey vessels during tagging experiments. Therefore the discard mortality rate from the Pacific halibut fishery, D=16%, was used (Gilroy and Stewart 2013). The halibut fishery is assumed a reasonable proxy for sablefish, because the fisheries utilize similar gear and frequently the same vessels and crew participate in both fisheries. Moreover, both species are considered hardy, do not experience barotrauma, and are known to survive well in laboratory experiments.

Selectivity

The longline fishery and survey are assumed to follow a logistic selectivity pattern. Currently two parameterizations of logistic selectivity are available in the `TMB` model.

The first parameterization uses s_{50} and s_{95}, which represent the ages at which 50% and 95% of individuals are selected by the gear. Selectivity-at-age (s_a) for this parameterization is defined as

$$s_a = \frac{1}{1 + \exp\frac{-\ln(19)(a - s_{50})}{s_{95} - s_{50}}}. \tag{4}$$

The second parameterization uses s_{50} and δ, which represent the ages at which 50% of individuals are selected by the gear and the shape or slope of the logistic curve, respectively. Selectivity-at-age (s_a) for this parameterization is defined as

$$s_a = \frac{1}{1 + \exp(-k(a - s_{50}))}. \tag{5}$$

Selectivity is fit separately for the longline fishery (fsh) and survey (srv). There is flexibility to define discrete time blocks for both fishery and survey selectivity.

Currently fishery and survey selectivity are fixed in the model using Federal selectivity values for the derby (pre-EQS), contemporary fishery (EQS), and longline survey (Hanselman et al. 2018, Figure 10, Table 2).

Estimating selectivity will be challenging when accounting for fishery discards because no age or length data are available on the discarded population. One potential solution is to estimate a single selectivity for the longline survey and then apply that selectivity curve to the fishery. Further information is needed to better characterize how discarding behavior has changed over time and if discarding was common pre-EQS.

Catchability

Currently four parameters for catchability are estimated: two for fishery catchability (pre-EQS and EQS) $\ln(q_{fsh})$, one for the ADF&G longline survey $\ln(q_{srv})$, and one for the mark-recapture abundance index $\ln(q_{MR})$.

Recruitment and initial numbers-at-age

The numbers-at-age matrix N is parameterized with mean log-recruitment μ_R, 39 (T) log-recruitment deviations τ, mean log initial numbers-at-age μ_N, and 28 ($A-2$) deviations from mean log initial numbers-at-age ψ.

Following the Federal assessment, if recruitment is estimated using penalized likelihood, the parameter that describes the variability of τ and ψ, $\ln(\sigma_R)$, is fixed at 0.1823 (Sigler et al. 2002, Hanselman et al. 2018). However, if τ and ψ are estimated as random effects, $\ln(\sigma_R)$ is an estimated parameter. Results are only shown for the penalized likelihood approach.

Fishing mortality

There is one parameter estimated for mean log-fishing mortality, μ_F, and 39 (T) log-fishing mortality deviations ϕ.

Population dynamics

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

$$N_{1,a,k} = \begin{cases} 0.5 \cdot \exp(\mu_R - M(a-a_0) + \psi_a) & a_0 < a < a_+ \\ 0.5 \cdot \exp(\mu_R - M(a_+ - 1))/(1-\exp(-M)) & a = a_+ \end{cases} \tag{6}$$

Recruitment to age-2 in all years and the remaining projected N matrix is defined as

$$N_{t,a,k} = \begin{cases} 0.5 \cdot \exp(\mu_R + \tau_t) & a = a_0 \\ 0.5 \cdot N_{t-1,a-1,k} \exp(Z_{t-1,a-1,k}) & a_0 < a < a_+ \\ 0.5 \cdot N_{t-1,a-1,k} \exp(Z_{t-1,a-1,k}) + N_{t-1,a,k} \exp(Z_{t-1,a,k}) & a = a_+ \end{cases} \tag{7}$$

where the total instantaneous mortality, $Z_{t,a,k}$, is the sum of natural mortality M and fishing mortality $F_{t,a,k}$.

Total annual fishing mortality F_t is defined as

$$F_t = \exp(\mu_F + \phi_t). \tag{8}$$

Fishing mortality is modeled as a function of fishery selectivity $s_{t,a,k}$, retention probability $R_{a,k}$ (the age-specific probability of being landed given being caught, Figure 9), and discard mortality D:

$$F_{t,a,k} = s_{t,a,k}^{fsh}(R_{a,k} + D(1-R_{a,k}))F_t. \tag{9}$$

Predicted values

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

$$\hat{I}_t^{fsh} = q_{fsh} \sum_{k=1}^{2} \sum_{a=a_0}^{a+} w_{a,k}^{srv} \cdot s_{t,a,k}^{fsh} \cdot N_{t,a,k} \cdot S^{fsh}, \tag{10}$$

where $w^{srv}_{a,k}$ is mean weight-at-age by sex in the longline survey and S^{srv} is the fraction of individuals in year t surviving to the beginning of the fishery in August. Survival equations include natural and fishing mortality because the model assumes continuous fishing mortality.

Predicted longline survey CPUE (numbers per hook) in year t ($\hat{I_t}^{srv}$) was defined as a function survey catchability q^{srv}, abundance available to the survey, and survival to the beginning of the survey in July (S^{srv}):

$$\hat{I_t}^{srv} = q_{srv} \sum_{k=1}^{2} \sum_{a=a_0}^{a+} s^{srv}_{t,a,k} \cdot N_{t,a,k} \cdot S^{srv}. \tag{11}$$

Predicted mark-recapture abundance in year t ($\hat{I_t}^{MR}$) was defined as a function of mark-recapture catchability q^{MR}, abundance available to the fishery, and survival to the beginning of the NSEI fishery in August (S^{fsh}):

$$\hat{I_t}^{MR} = q_{MR} \sum_{k=1}^{2} \sum_{a=a_0}^{a+} s^{fsh}_{t,a,k} \cdot N_{t,a,k} \cdot S^{fsh}. \tag{12}$$

Spawning biomass SSB was calculated as

$$SSB = \sum_{a=a_0}^{a+} w^{srv}_{a,f} \cdot N_{t,a,f} \cdot S^{spawn} \cdot p_a, \tag{13}$$

where $w^{srv}_{a,f}$ is mean weight-at-age of females in the longline survey, S^{spawn} is the fraction of individuals surviving to spawn in February, and p_a is the proportion of females mature in the survey at age. In the single sex model, proportion of females at age in the survey r_a is used to get the female portion of the N matrix.

Predicted survey age compositions (sexes combined) were computed as

$$\hat{P}^{srv}_{t,a} = \Omega_{a',a} \frac{\sum_{k=1}^{2} N_{t,a,k} \cdot s^{srv}_{a,k}}{\sum_{k=1}^{2} \sum_{a=a_0}^{a+} N_{t,a,k} \cdot s^{srv}_{a,k}}, \tag{14}$$

where $\Omega_{a',a}$ is the ageing error matrix. Predicted fishery age compositions (sexes combined) were computed as

$$\hat{P}^{fsh}_{t,a} = \Omega_{a',a} \frac{\sum_{k=1}^{2} C_{t,a,k}}{\sum_{k=1}^{2} \sum_{a=a_0}^{a+} C_{t,a,k}}, \tag{15}$$

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

$$C_{t,a,k} = N_{t,a,k} \frac{R_{a,k} F_{t,a,k}}{Z_{t,a,k}} (1 - \exp(-Z_{t,a,k})), \tag{16}$$

where $R_{a,k}$ is the assumed probability of retention by age and sex (Figure 9).

Predicted landed catch in biomass $\hat{Y}$ was calculated as the product of fishery weight-at-age $w^{fsh}_{a,k}$ and landed catch in numbers-at-age:

$$\hat{Y}_t = \sum_{k=1}^{2} \sum_{a=a_0}^{a+} w^{fsh}_{a,k} \cdot C_{t,a,k}. \tag{17}$$

The biomass of discarded sablefish estimated to die (W_t) with an assumed discard mortality (D) of 0.16 is

$$W_t = \sum_{k=1}^{2} \sum_{a=a_0}^{a+} w_{a,k}^{srv} N_{t,a,k} \frac{D(1 - R_{a,k}) F_{t,a,k}}{Z_{t,a,k}} (1 - \exp(-Z_{t,a,k})). \tag{18}$$

Predicted survey length compositions were calculated using the sex-specific age-length keys ($\Lambda_{a,l,k}$), such that

$$\hat{P}_{t,l,k}^{srv} = \Lambda_{a,l,k} \frac{N_{t,a,k} \cdot s_{a,k}^{srv}}{\sum_{a=a_0}^{a+} N_{t,a,k} \cdot s_{a,k}^{srv}}. \tag{19}$$

Fishery length compositions were calculated as

$$\hat{P}_{t,l,k}^{fsh} = \Lambda a, l, k \frac{C_{t,a,k}}{\sum_{a=a_0}^{a+} C_{t,a,k}}. \tag{20}$$

Likelihood components

The objective function, or the total negative log-likelihood to be minimized, included the sum of the following likelihood components L, which received individual weights λ:

1. Landed catch biomass (Y) was modeled using a lognormal likelihood where σ_Y was assumed to be 0.05:

$$-\ln L(Y) = \lambda_Y \frac{1}{2\sigma_Y^2} \sum_{t=1}^{T} \Big(\ln(Y_t + c) - \ln(\hat{Y}_t + c) \Big)^2, \tag{21}$$

   where $\lambda_Y = 1.0$ and c is a small constant set at 0.0001 to allow approximately zero catches in log-space.

2. Fishery CPUE, survey CPUE, and the mark-recapture abundance index were modeled using lognormal likelihoods, where σ_I was assumed to be 0.08 for the fishery and survey CPUEs and annual posterior standard deviations were used for the mark-recapture abundance index:

$$-\ln L(I) = \lambda_I \frac{1}{2\sigma_I^2} \sum_{t=1}^{T_I} \Big(\ln(I_t + c) - \ln(\hat{I}_t + c) \Big)^2, \tag{22}$$

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

3. Fishery and survey age compositions were modeled using the multinomial likelihood (P^{age}), where effective sample size ω_t was calculated as the square root of the total sample size in year t:

$$-\ln L(P^{age}) = \lambda_{P^{age}} \sum_{t=1}^{T_P^{age}} -\omega_t \sum_{a=a_0}^{a+} (P_{t,a} + c) \cdot \ln(\hat{P}_{t,a} + c), \tag{23}$$

   where T_P^{age} is the number of years of data for each age composition, $\lambda_{P^{age}}$ is set to 1.0, and c prevents the composition from being 0 in the likelihood calculation. Standard methods of tuning the effective sample size or iterative re-weighting have not yet been applied to this assessment model (McAllister and Ianelli 1997, Francis 2011). Alternatively, effective sample size can be calculated through the estimation of an additional parameter θ using the Dirichlet-multinomial likelihood (Thorson et al. 2017):

$$-\ln L(P^{age}) = \sum_{t=1}^{T_P^{age}} -\Gamma(n_t+1) - \sum_{a=a_0}^{a+} \Gamma(n_t P_{t,a}+1) + \Gamma(n_t\theta) - \Gamma(n_t+\theta n_t) + \sum_{a=a_0}^{a+} \left[\Gamma(n_t P_{t,a}+\theta n_t \hat{P}_{t,a}) - \Gamma(\theta n_t \hat{P}_{t,a})\right], \tag{24}$$

where n is the input sample size. The relationship between n, θ, and ω is

$$\omega_t = \frac{1+\theta n_t}{1+\theta}. \tag{25}$$

Because the implementation of the alternative Dirichlet-multinomial likelihood is currently under development, only results for the multinomial likelihood are presented here.

4. Fishery and survey length compositions by sex were modeled using the multinomial likelihood (P^{len}), where effective sample size ω_t was calculated as the square root of the total sample size in year t:

$$-\ln L(P^{len}) = \lambda_{P^{len}} \sum_{k=1}^{2} \sum_{t=1}^{T_P^{len}} -\omega_t \sum_{l=l_0}^{l+} (P_{t,l}+c) \cdot \ln(\hat{P}_{t,l}+c). \tag{26}$$

T_P^{len} is the number of years of data for each length composition and λ_{Plen} is set to 1.0.

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

$$-\ln L(\phi) = \lambda_\phi \sum_{t=1}^{T} \phi_t^2, \tag{27}$$

where λ_ϕ=0.1.

6. Recruitment deviations (τ_t) can be included using a penalized lognormal likelihood

$$-\ln L(\tau) = \lambda_\tau \sum_{i=1}^{T+A-2} (\tau_i - 0.5\sigma_R^2)^2, \tag{28}$$

where $-0.5\sigma^2$ is a bias correction needed to obtain the expected value (mean) instead of the median. The λ_ϕ=2.0 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

$$-\ln L(\tau) = \sum_{i=1}^{T+A-2} \ln(\sigma_R) + \frac{(\tau_i - 0.5\sigma_R^2)^2}{2\sigma_R}. \tag{29}$$

Initial numbers-at-age deviations ψ_a are implemented in the same way as recruitment deviations and are governed by the same σ_R. Only results for the penalized likelihood approach are shown.

7. Because the mark-recapture abundance index scales the exploitable population, a normal prior is imposed on q_{MR} of 1.0 with a standard deviation of 0.1. Vague priors are assigned to fishery and survey q. Future work on this model should include the development of priors for fishery and survey q.

Preliminary results and discussion

A summary of parameter estimates and standard errors are reported in Table 3. The objective function value (negative log likelihood) was 1,007.1. The maximum gradient component was 0.00086, barely passing the minimum convergence criteria of 0.001. A summary of the contributions of each likelihood component to the total objective function can be found in Table 4.

In particular, mean recruitment and deviations were difficult to estimate (Table 3).
Initially, the weight on this likelihood component was assumed to be low ($\lambda_{\tau} = 0.1$), but this yielded an improbably large spike (>40 times the mean value) in age-2 recruitment in 2016 corresponding to the 2014 year class. Increasing the λ_{τ} to 2.0 resulted in more reasonable parameter estimates and decreased the age-2 recruitment to ~8 times mean recruitment. Alternatively, it may be that the parameter governing variability in recruitment σ_R should be reduced or estimated using random effects. Currently σ_R is fixed to 1.2; however, it is possible σ_R is too high for a low productivity species like sablefish (Sigler et al. 2002, Hanselman et al. 2018). Future work should include an analysis to evaluate assumptions about σ_R.

Preliminary fits to catch and indices of abundance are shown in Figure 11. Results suggest that the model fits catch, pre-EQS fishery CPUE, and mark-recapture abundance reasonably well in most years. Contemporary fishery CPUE (EQS) does not fit well, with long runs of positive or negative residuals (Figure 12). The model performs poorly during the period directly following the implementation of EQS in 1994 for all indices, including catch (Figure 12). Prior to implementing this model for management, further consideration should be given to which abundance indices should be used in the model. For example, because discarding is legal in NSEI and past logbook data have not required released fish to be recorded, fishery CPUE may not be a suitable index of abundance. Starting in 2019, fishermen will be required to provide an estimate of number of released sablefish by set; however, there will still be no record of length or weight of these discards. Finally, variability in catch, survey, and fishery CPUE indices was assumed (Figure 3). Future enhancements could include estimating this variability using available data.

Preliminary fits to fishery and age compositions are shown in Figures 13 and 14, respectively. Although the model fits the general shape of the age compositions in most years, there are poor residual patterns (Figure 15). Fits to male and female fishery length compositions are shown in Figures 16 and 17, respectively. Fits to male and female survey length compositions are shown in Figures 18 and 19, respectively. Similar to the age compositions, the model predicts the general shape of the length compositions in for both the survey and fishery in most years. Despite this, there are also poor residual patterns in the length compositions (Figure 20).

There are several caveats to the preliminary fits to composition data. First, no efforts have been made to externally estimate, tune, or iteratively re-weight the input effective samples sizes for the composition data (McAllister and Ianelli 1997, Francis 2011). This exercise should be completed prior to implementation of this model. Second, results presented here assume fixed selectivity equal to the Federal fishery. Because no data on discards exist, it may not be possible to estimate fishery selectivity while fitting to the composition data. Stock assessments that account for discarded catch frequently have observer data and will overcome this challenge through the estimation of a separate selectivity for discarded catch. An alternative approach is to estimate survey selectivity and then assume fishery and survey selectivity are equal. Finally, fishery size-at-age is larger than survey size-at-age, especially at younger ages. Consequently, fits to fishery length compositions may benefit from the development of separate age-length keys for the NSEI survey and fishery.

Derived indices of age-2 recruitment, female spawning stock biomass, and exploitable abundance and biomass (i.e. available to the fishery) suggest that this stock has been in a period of low productivity since the mid-1990s (Figure 21). Recruitment trends are comparable with Federal values, and estimates of spawning stock biomass, exploitable biomass, and exploitable abundance are in par with past and current ADF&G estimates (Hanselman et al 2018, Sullivan and Williams 2018). A time series of fishing mortality and harvest rate (defined as the ratio of predicted total catch to exploitable biomass) shows that peak exploitation occurred in the decade following the transition to EQS, 1995-2005 (Figure 22). The model suggests that harvest rates were more than four times what they are today during this time period.

Although not currently ready to be considered for management, the statistical catch-at-age model outlined in this paper is planned to be presented as a management alternative in 2020. Here we provide a summary of future developments to this model by priority level.

High priority

The following tasks must be completed in order for this model to be considered for management:

- Complete the development and estimation of management reference points.
- Develop rationale for the choice of fishery-dependent data sources to include in the model and whether fishery selectivity should be fixed or estimated. This relates to the challenge of accounting for unobserved discards while estimating fishery selectivity and fitting to landed catch compositions.
- Improve weighting methods and tune model to composition data.

Short-term

These tasks should be completed within 1-2 years of implementation. They are critical components of a well-developed statistical catch-at-age model.

- Implement Bayesian analysis to evaluate posterior densities of estimated and derived quantities of interest.
- Evaluate estimation and assumptions about recruitment variability.
- Conduct retrospective analysis to determine model performance over time.
- Develop framework to conduct projections to evaluate stock status and assess risk.

Long-term:

These tasks should be completed within 2-4 years of implementation. While they are not critical to the implementation of the model, they will improve model-based inference, understanding of stock dynamics, and data quality.

- Develop ageing error matrices and age-length keys for NSEI.
- Review indices of abundance. In particular the fishery and survey CPUE have little contrast and may not be useful indices of abundance. This may include standardizing CPUE through generalized linear or addition modeling to account for variables to affect CPUE. It may also include developing algorithms to identify trip and set targets and allocating total trip landings to set effort.
- Evaluate alternative harvest policies and biological reference points.
- Improve methods for accounting for fishery discards, including conducting research to better understand discarding behavior and how it has changed over time.
- Develop priors for catchability and other relevant parameters.
- Assess alternative sources of data, especially historical biological and catch data (Carlile et al. 2002).
- Develop methods to account for additional sources of mortality, including sport, subsistence and personal use harvest, estimated bycatch mortality in the halibut fishery, and estimated deadloss, which includes mortality from sand fleas, sharks, and whales.

Acknowledgements

We are grateful to Dana Hanselman, Kari Fenske, and Curry Cunningham from the NOAA Alaska Fisheries Science Center for their technical expertise and willingness to share data. In addition, we thank Grant Adams and Andre Punt from the University of Washington for their assistance with `TMB` and modeling.

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Tables

Table 1: Variable definitions for the statistical catch-at-age model.

Variable	Definition
Indexing and model dimensions	
T	Number of years in the model
t	Index for year in model equations
A	Number of ages in the model
a	Index for age in model equations
a_0	Recruitment age (age-2)
a_+	Plus group age (age-31)
l	Index for length bin in model equations
l_0	Recruitment length bin (41 cm)
l_+	Plus group length bin (99 cm)
fsh	NSEI longline fishery
srv	ADF&G longline survey
MR	Mark-recapture abundance
Parameters	
M	Instantaneous natural mortality
F	Instantaneous fishing mortality
Z	Total instantaneous mortality
S	Total annual survival
D	Discard mortality
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
δ	Slope parameter in the logistic selectivity curve
q	Catchability
μ_R	Mean log recruitment
τ_t	Log recruitment deviations
μ_N	Mean log initial numbers-at-age
ψ_a	Log deviations of initial numbers-at-age
σ_R	Variability in recruitment and initial numbers-at-age
μ_F	Mean log fishing mortality
ϕ_t	Log fishing mortality deviations
θ	Dirichlet-multinomial parameter related to effective sample size
Data and predicted variables	
w_a	Weight-at-age
p_a	Proportion mature-at-age
r_a	Proportion female-at-age
R	Retention probability
s_a	Selectivity-at-age
$\Omega_{a',a}$	Ageing error matrix (proportion observed at age given the true age a')
$\Lambda_{a,l,k}$	Age-length key (proportion in length bin given age and sex)
N	Numbers-at-age
C	Landed catch in numbers-at-age
I, $\hat{I}$	Indices of abundance, $\hat{I}$ are predicted values
P_a, $\hat{P}_a$	Age compositions, $\hat{P}_a$ are predicted values
P_l, $\hat{P}_l$	Length compositions, $\hat{P}_l$ are predicted values
Y, $\hat{Y}$	Landed catch biomass, $\hat{Y}$ are predicted values
$\hat{W}$	Estimated mortality from discards (biomass)
λ	Weight for likelihood component

L	Likelihood
ω	Effective sample size for age and length compositions
n	Input sample size for Dirichlet-multinomial likelihood
c	Small constant (0.00001)

Table 2: Assumed selectivity parameters for the fishery before the Equal Quota Share program started in 1994 (pre-EQS), the fishery since the implementation of EQS, and the ADF&G longline survey for females (black points) and males (grey triangles). These parameters estimates were borrowed from the Federal stock assessment, where the Federal derby fishery, IFQ fishery, and NMFS Cooperative Longline Survey were assumed to represent pre-EQS, EQS, and the ADF&G longline survey (Hanselman et al. 2018).

	Male		Female	
	s_{50}	δ_{50}	s_{50}	δ_{50}
Pre-EQS Fishery	5.12	2.57	2.87	2.29
EQS Fishery	4.22	2.61	3.86	2.61
Longline survey	3.72	2.21	3.75	2.21

Table 3: Parameter estimates from the statistical catch-at-age model. Estimates of recruitment, initial numbers-at-age, and fishing mortality deviations were excluded for brevity.

Parameter	Estimate	Standard error
Pre-EQS catchability, $\ln(q_{fsh,pre-EQS})$	-17.618	0.044
EQS catchability, $\ln(q_{fsh,EQS})$	-16.911	0.024
Survey catchability, $\ln(q_{srv})$	-16.276	0.023
Mark-recapture catchability, $\ln(q_{MR})$	-0.038	0.010
Mean log recruitment, μ_R	6.224	0.093
Mean log initial numbers-at-age, μ_N	6.561	0.127
Mean log fishing mortality, μ_F	-2.601	0.359

Table 4: Negative likelihood values and percent of each component to the total likelihood. The data likelihood is the sum of all likelihood contributions from data. The difference between the total likelihood and the data likelihood is the contribution of penalized likelihoods, including recruitment and fishing mortality.

Likelihood component	NLL	% of NLL
Catch	13.1	1.3
Fishery CPUE	133.6	13.3
Survey CPUE	52.0	5.2
Mark-recapture abundance	52.0	5.2
Survey ages	181.1	18.0
Fishery ages	146.2	14.5
Survey lengths	107.7	10.7
Fishery lengths	284.7	28.3
Data likelihood	970.5	96.4
Total likelihood	1007.1	100.0

Figures

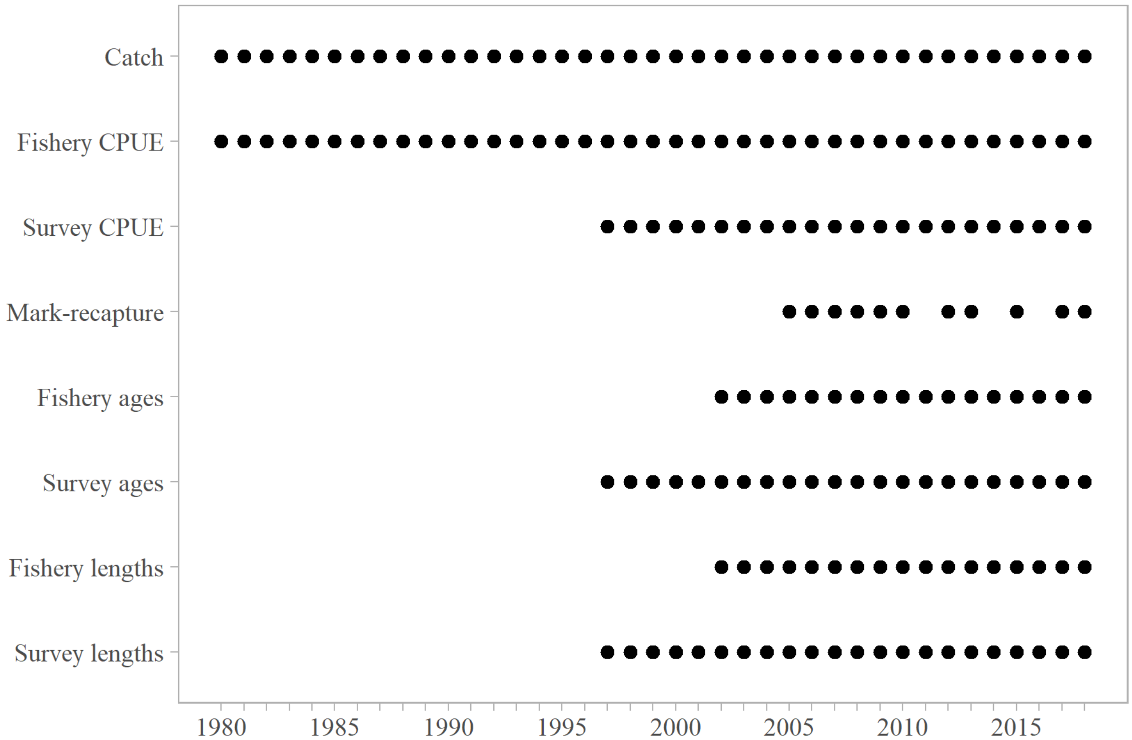

Figure 1: A summary of the available data sources in NSEI by year.

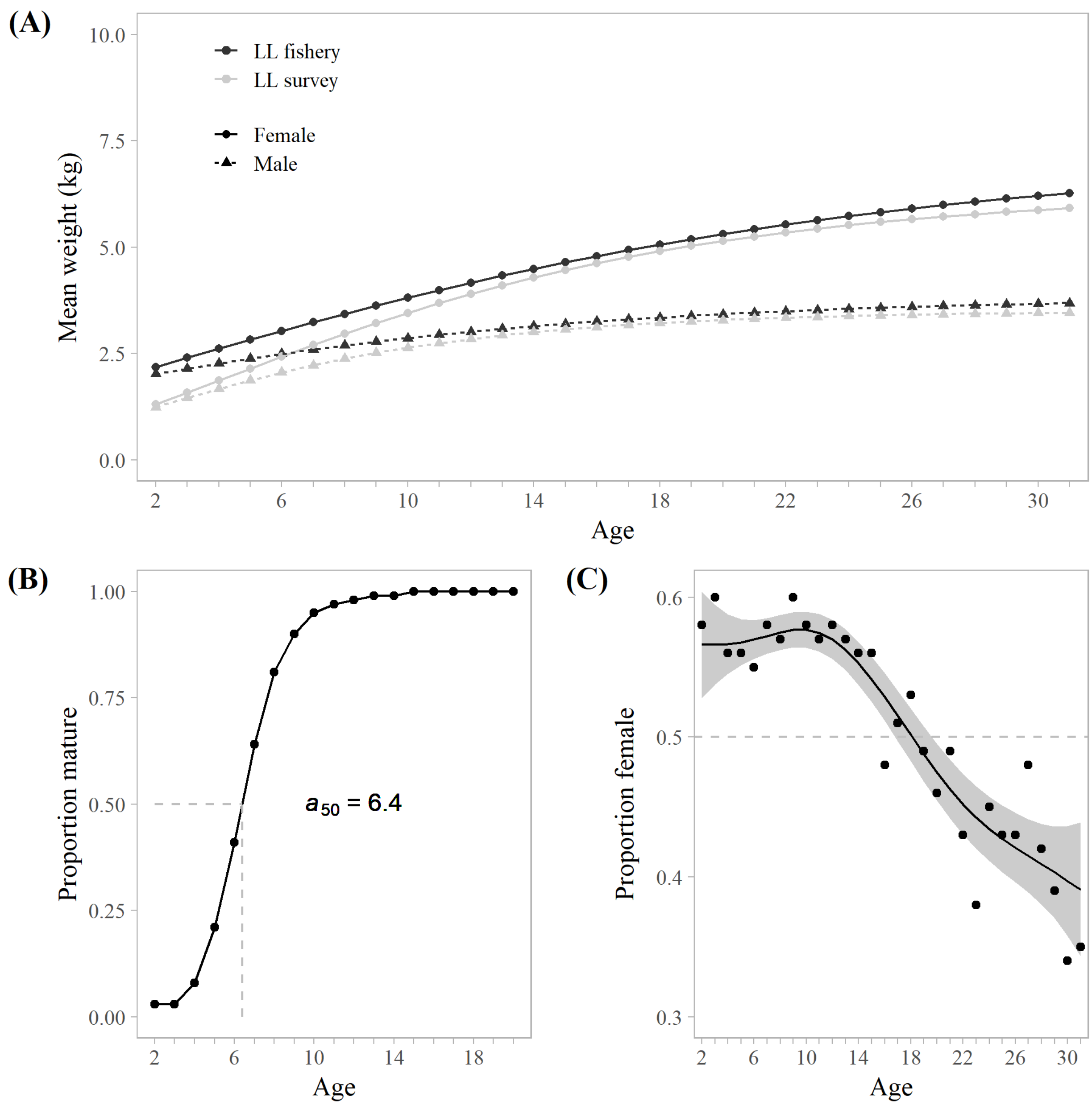

Figure 2: Biological inputs to the statistical catch-at-age model, including: (A) von Bertalanffy growth model predictions of weight-at-age (kg) by sex from the longline fishery (black) and ADF&G longline survey (grey); (B) proportion mature at age for females estimated from the longline survey with the age at 50% maturity (a_{50}=6.4 yr); and (C) proportion female in the longline survey, where the curve is the fitted line from a generalized additive model +/- 2 standard error.

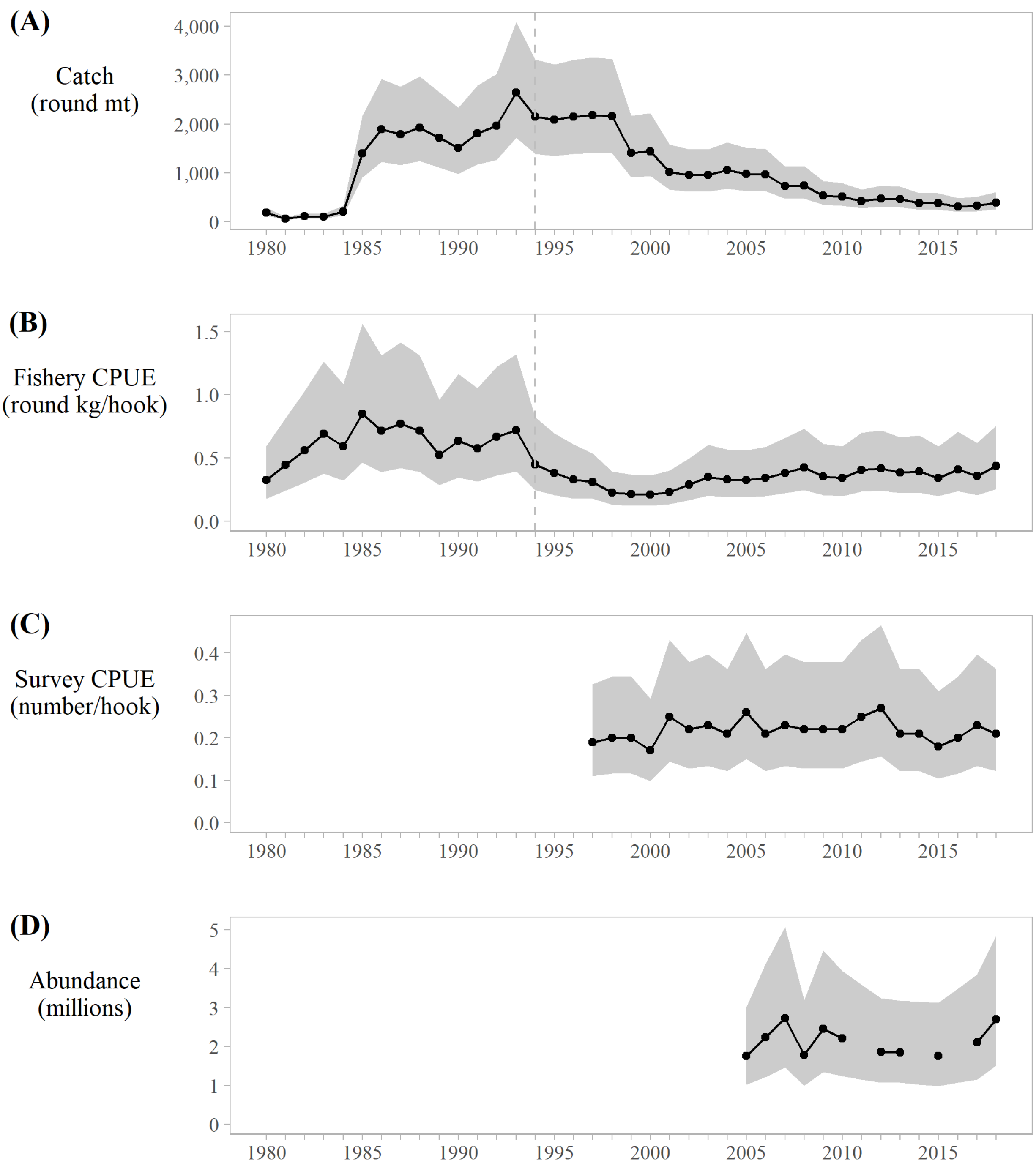

Figure 3: Indices of catch and abundance with the assumed error distribution, including: (A) harvest (round mt), (B) fishery catch per unit effort in round kg per hook, (C) survey catch per unit effort in number of fish per hook, and (D) mark-recapture abundance estimates in millions. The dashed vertical line in 1994 mark the transition to the Equal Quota Share program.

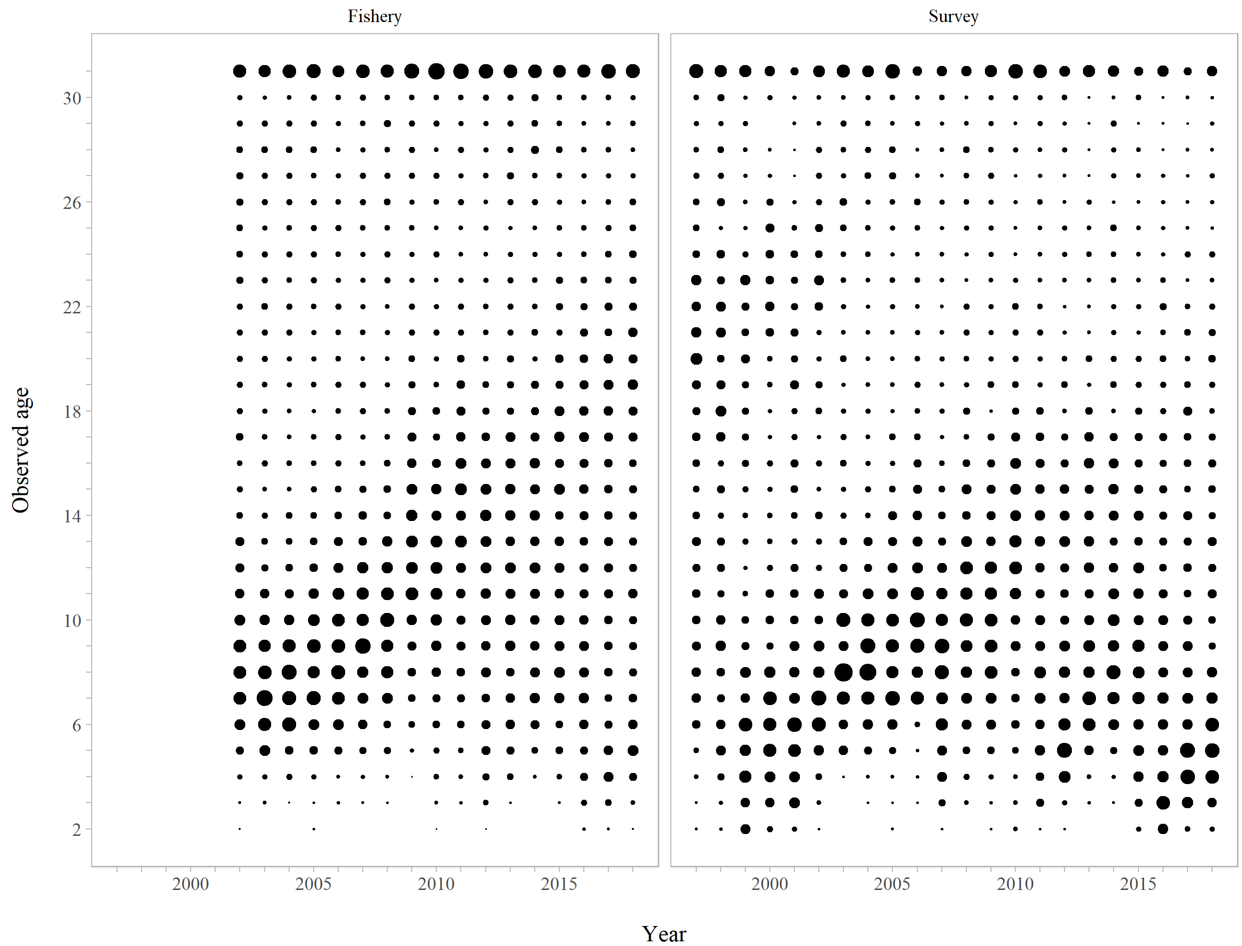

Figure 4: Proportions-at-age for in the NSEI longline fishery (2002-2018) and ADF&G longline survey (1997-2018).

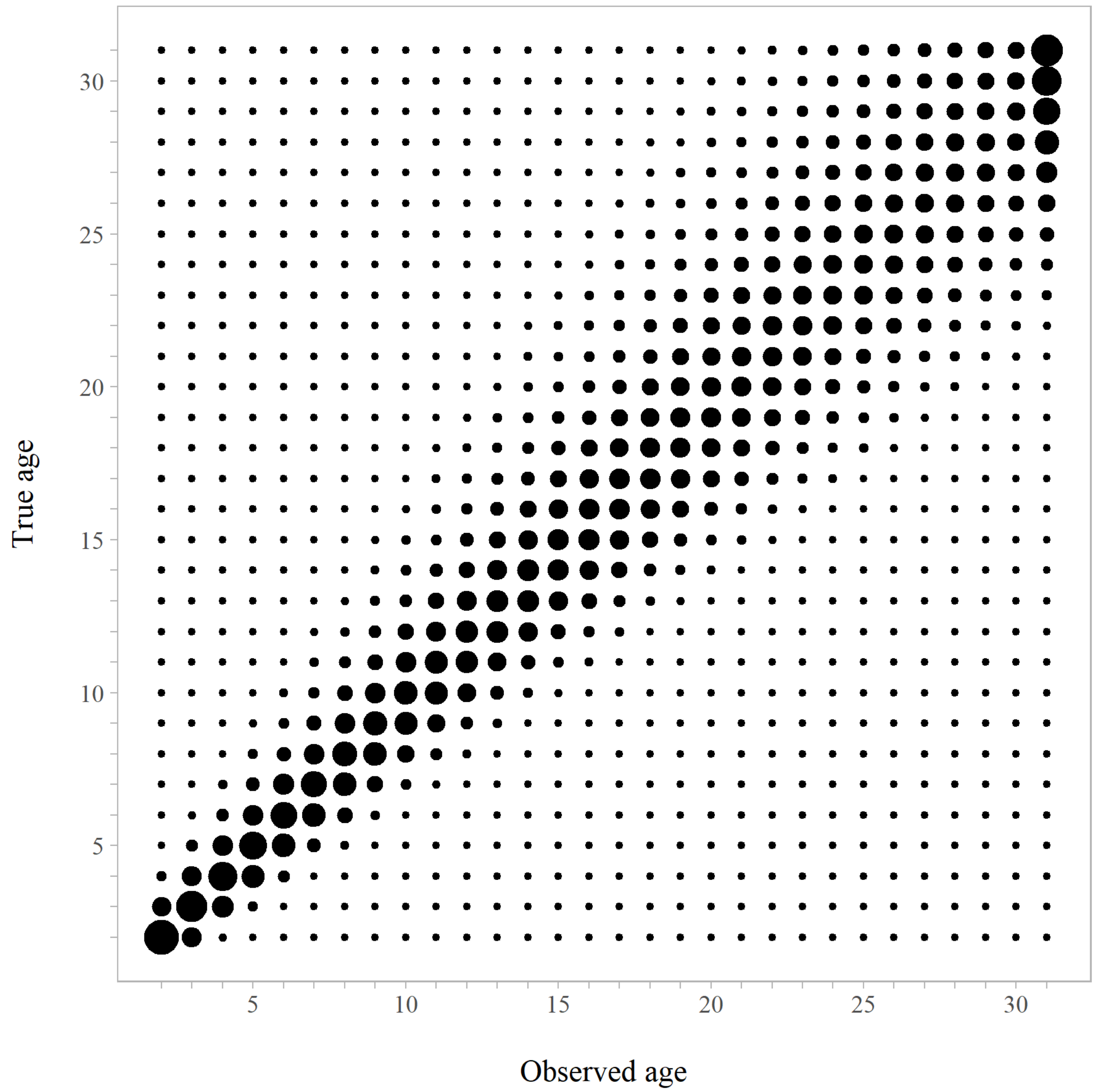

Figure 5: Ageing error matrix used in the model, showing the probability of observing an age given the true age (Heifetz et al. 1999).

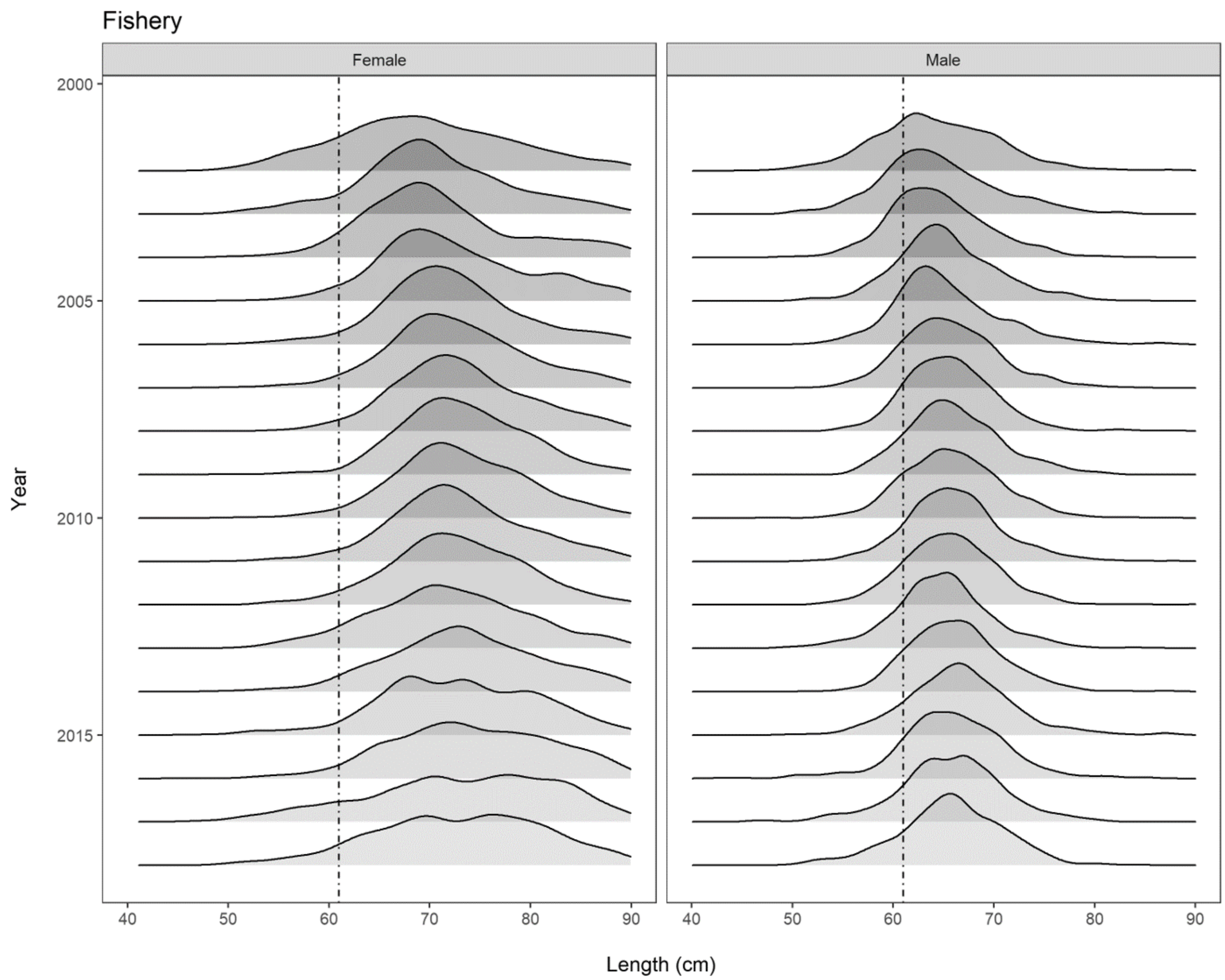

Figure 6: Fishery length distributions by sex from 2002-2018. The dashed vertical line at 61 cm represents the length at 50% maturity.

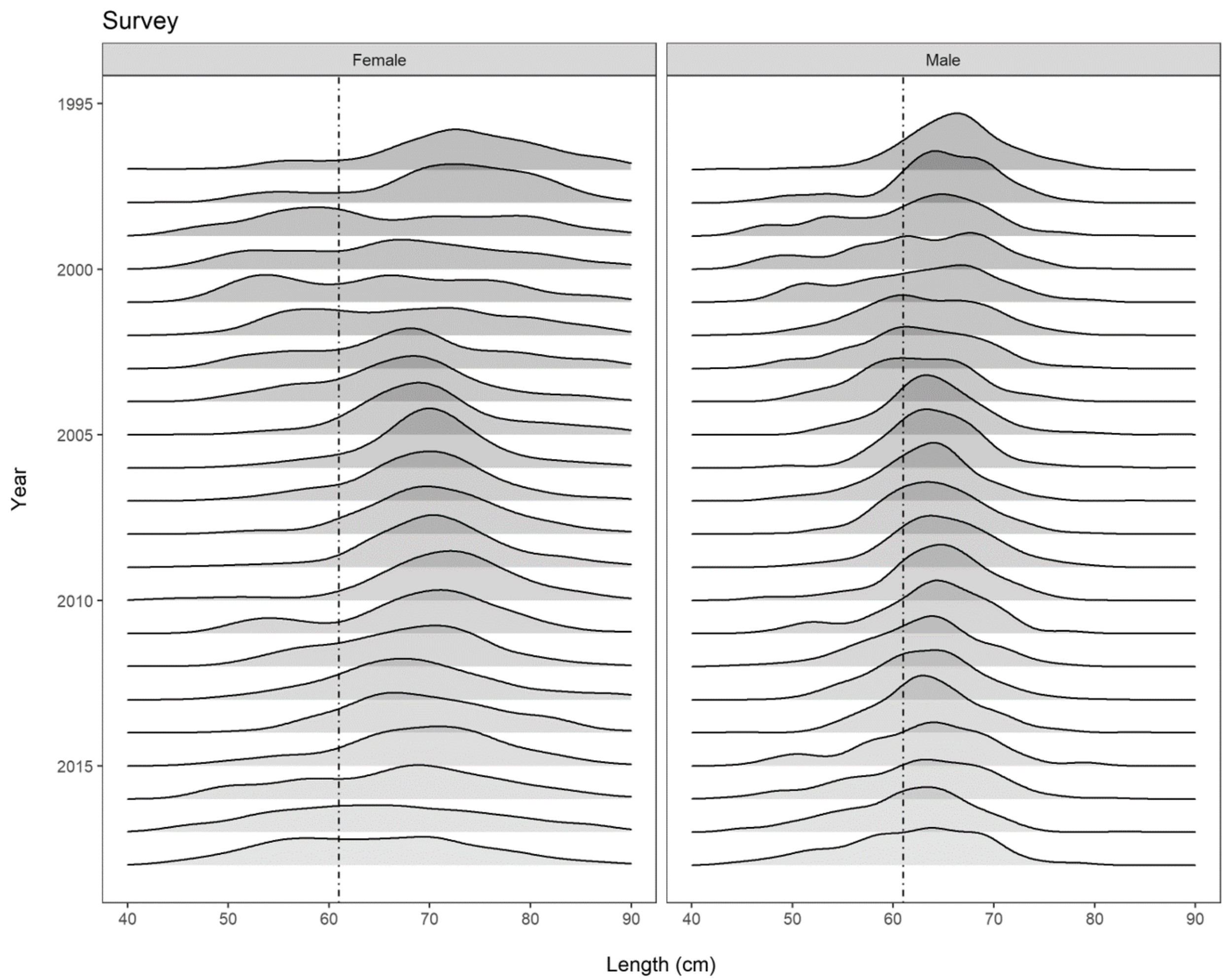

Figure 7: Longline survey length distributions by sex from 1997-2018. The dashed vertical line at 61 cm represents the length at 50% maturity.

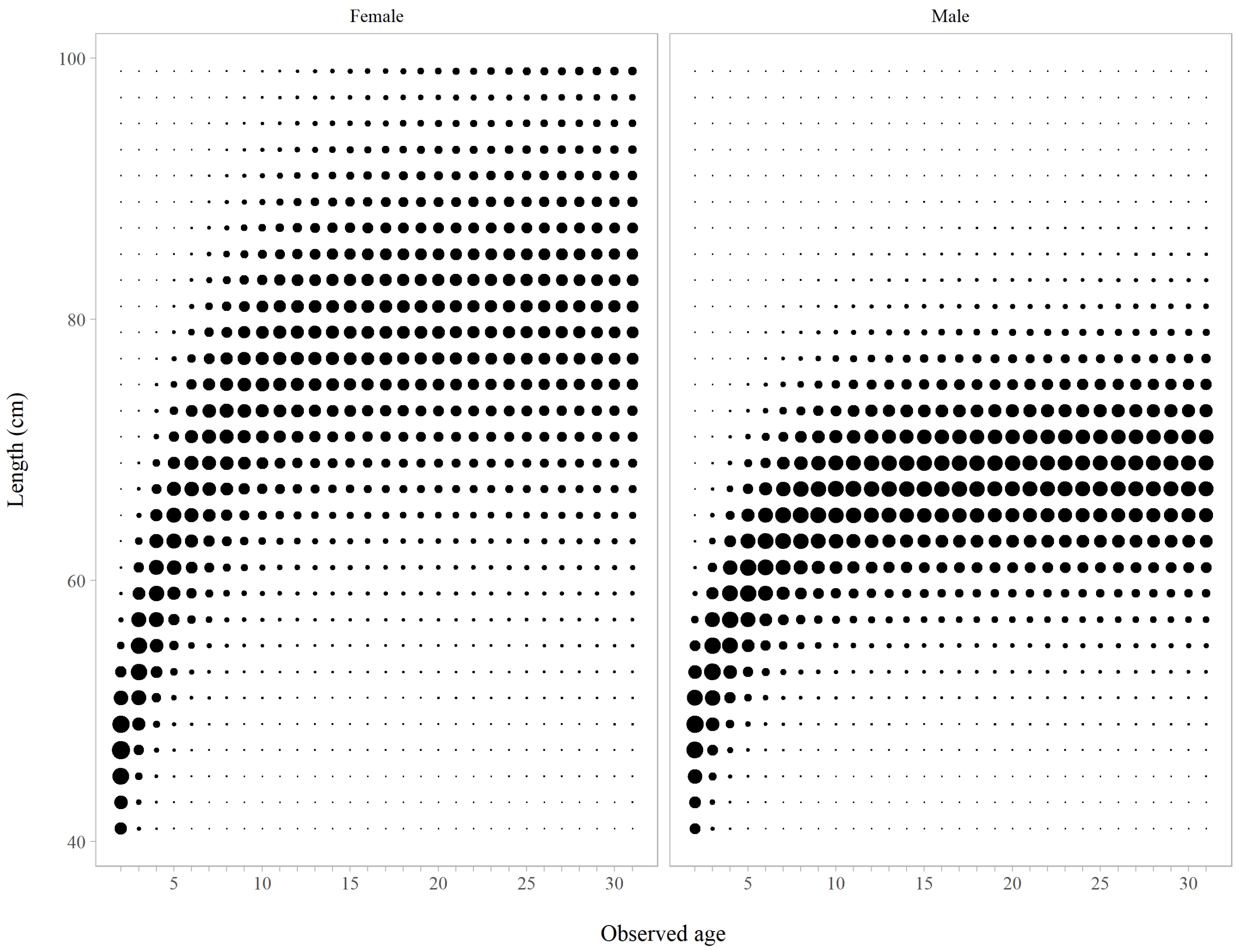

Figure 8: Age-length key used in the model, with the relative size of the bubbles reflecting the probability that a fish of a given age falls within a certain length bin (Echave et al. 2012). The probabilities sum to 1 across each age.

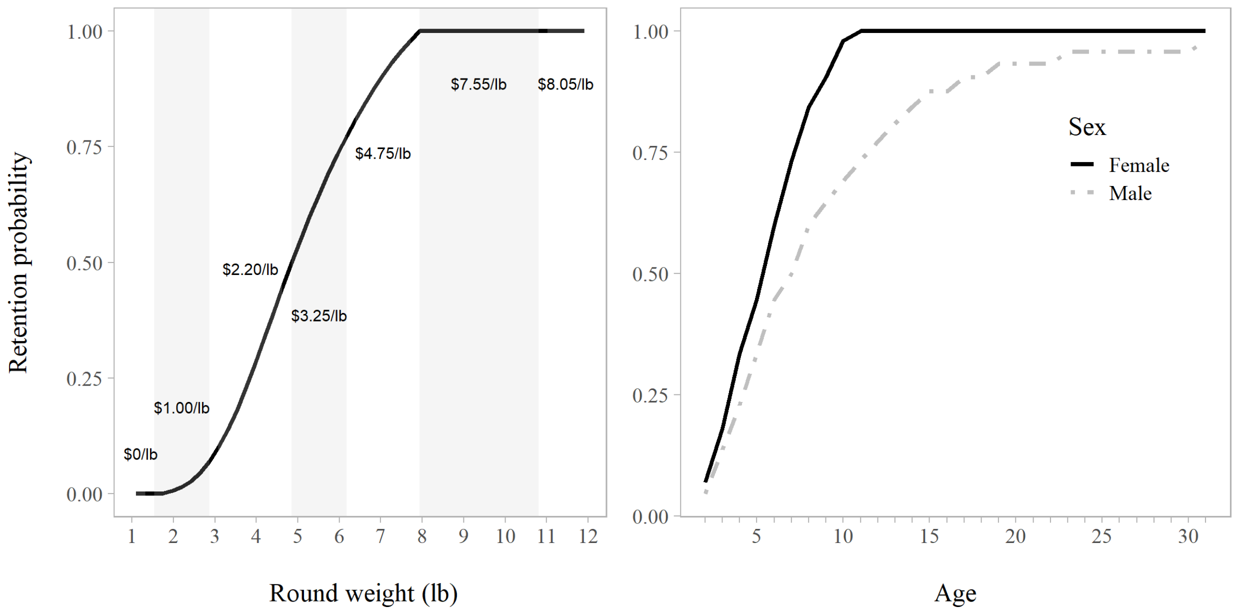

Figure 9: The probability of retaining a fish as a function of weight (left), sex, and age (right).

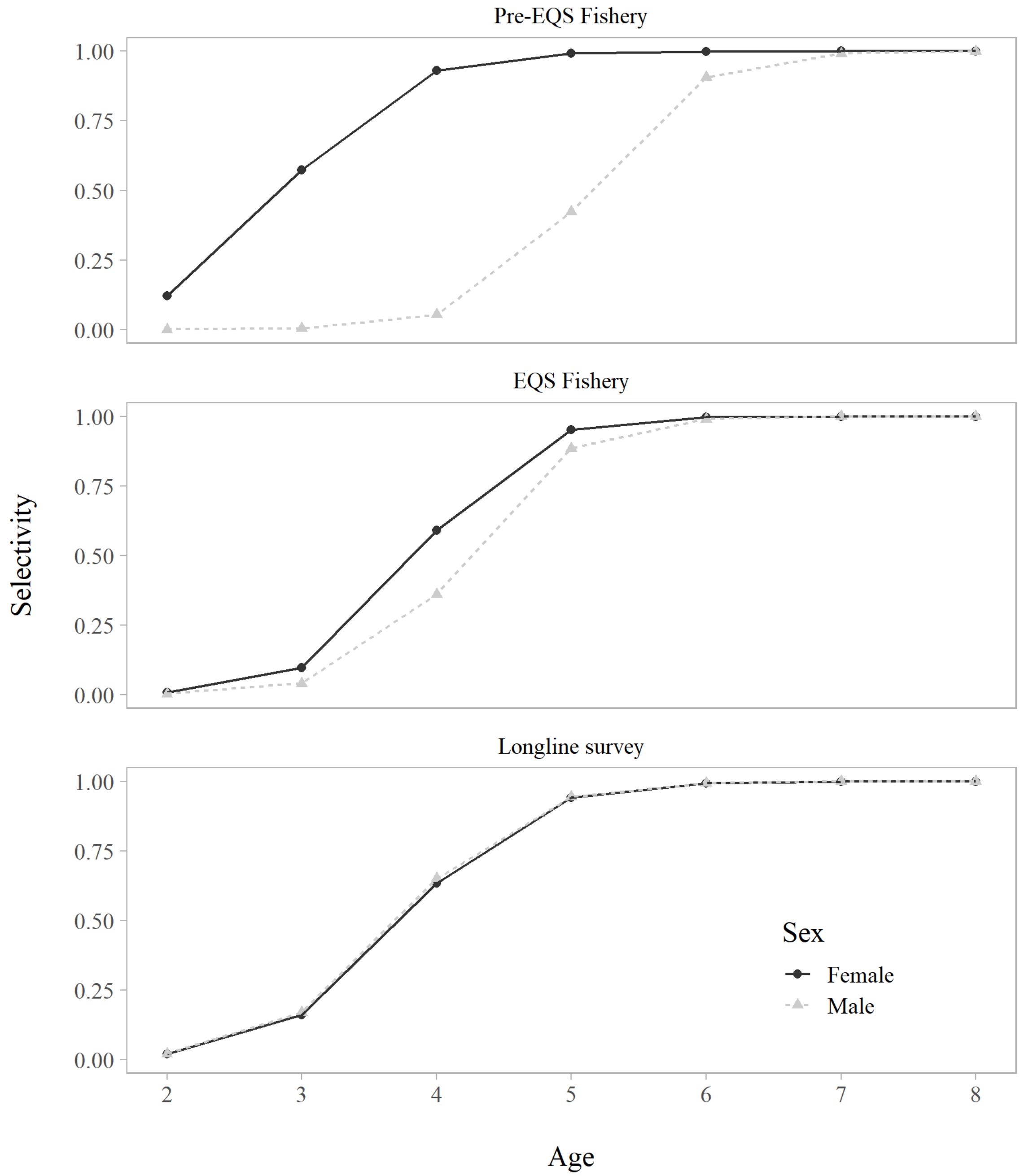

Figure 10: Fixed age-based selectivity curves for the fishery before the Equal Quota Share program started in 1994 (pre-EQS), the fishery since the implementation of EQS, and the ADF&G longline survey for females (black points) and males (grey triangles). These parameters estimates were borrowed from the Federal stock assessment for the derby fishery (pre-EQS), IFQ fishery (EQS), and NMFS Cooperative Longline Survey (Hanselman et al. 2018).

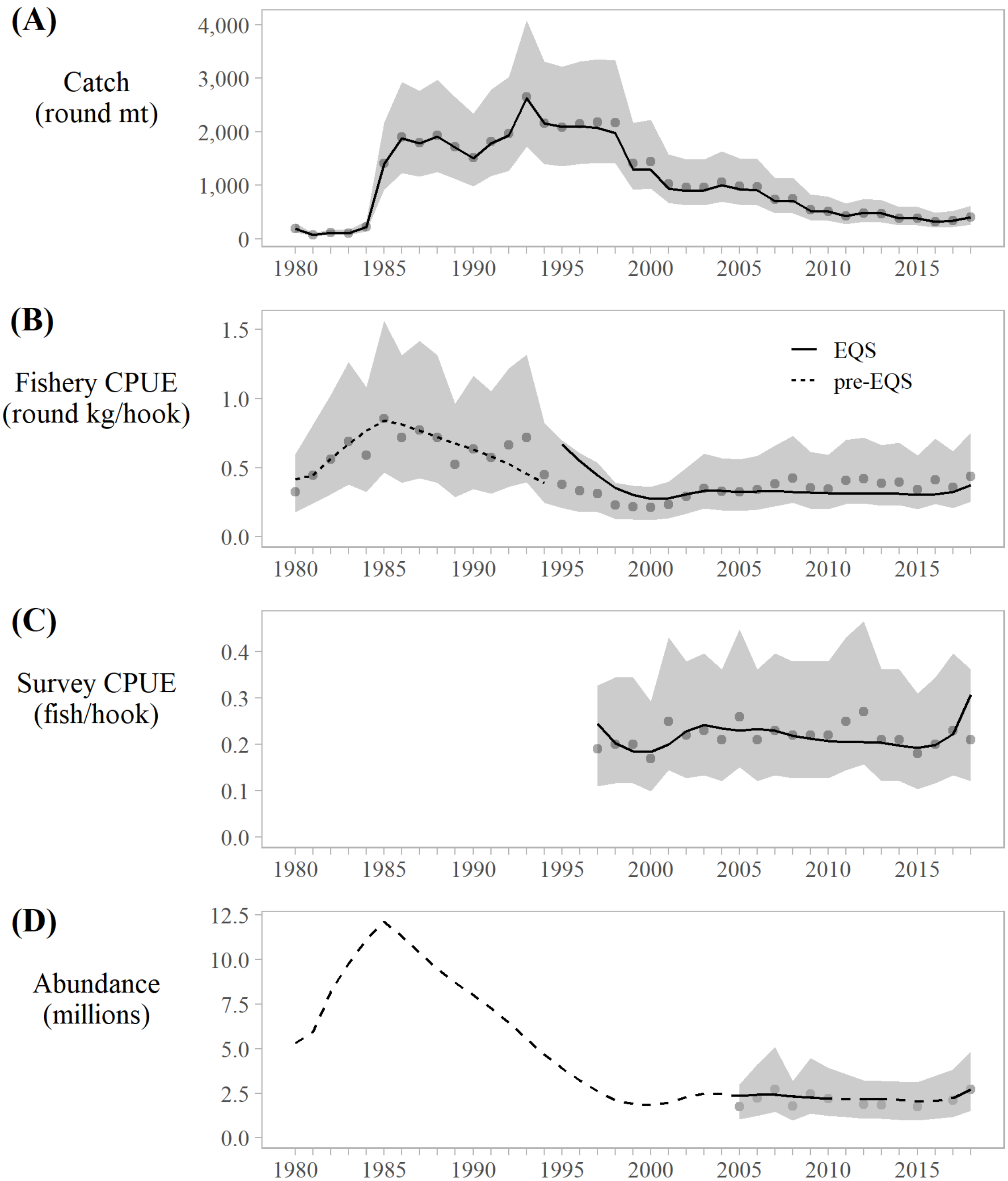

Figure 11: Fits to indices of catch and abundance with the assumed error distribution shown as shaded grey polygons. Input data are shown as grey points and model fits are shown in black. Indices include (A) harvest (round mt); (B) fishery catch per unit effort in round kg per hook with separate selectivity and catchability time periods before and after the implementation of the Equal Quota Share program in 1994; (C) survey catch per unit effort in number of fish per hook; and (D) mark-recapture abundance estimates in millions. Solid and dashed lines in panel D reflect years for which data were and were not available, respectively.

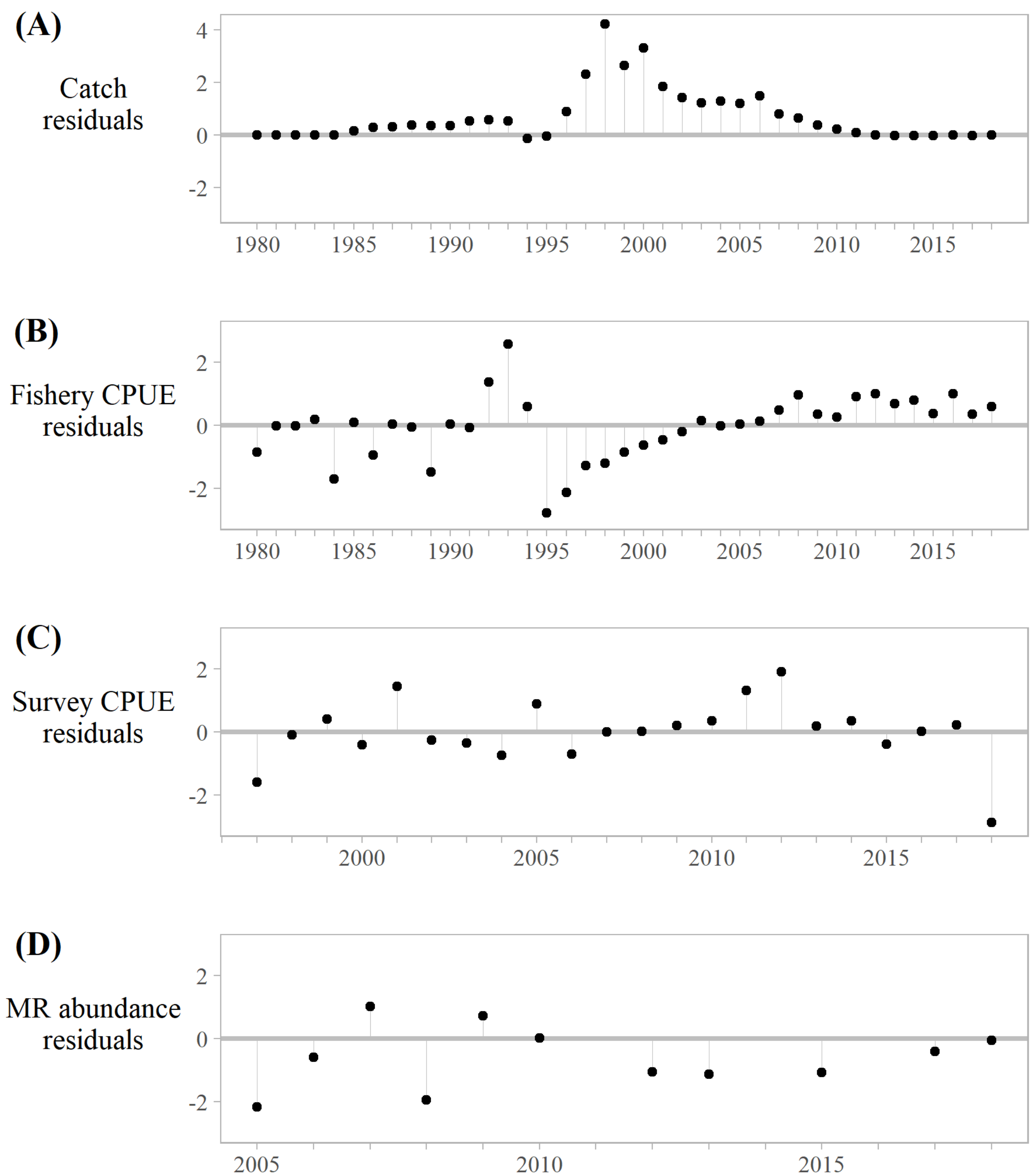

Figure 12: Standardized residuals of fits to indices of catch and abundance, including: (A) harvest, (B) fishery catch per unit effort, (C) survey catch per unit effort, and (D) mark-recapture (MR) abundance.

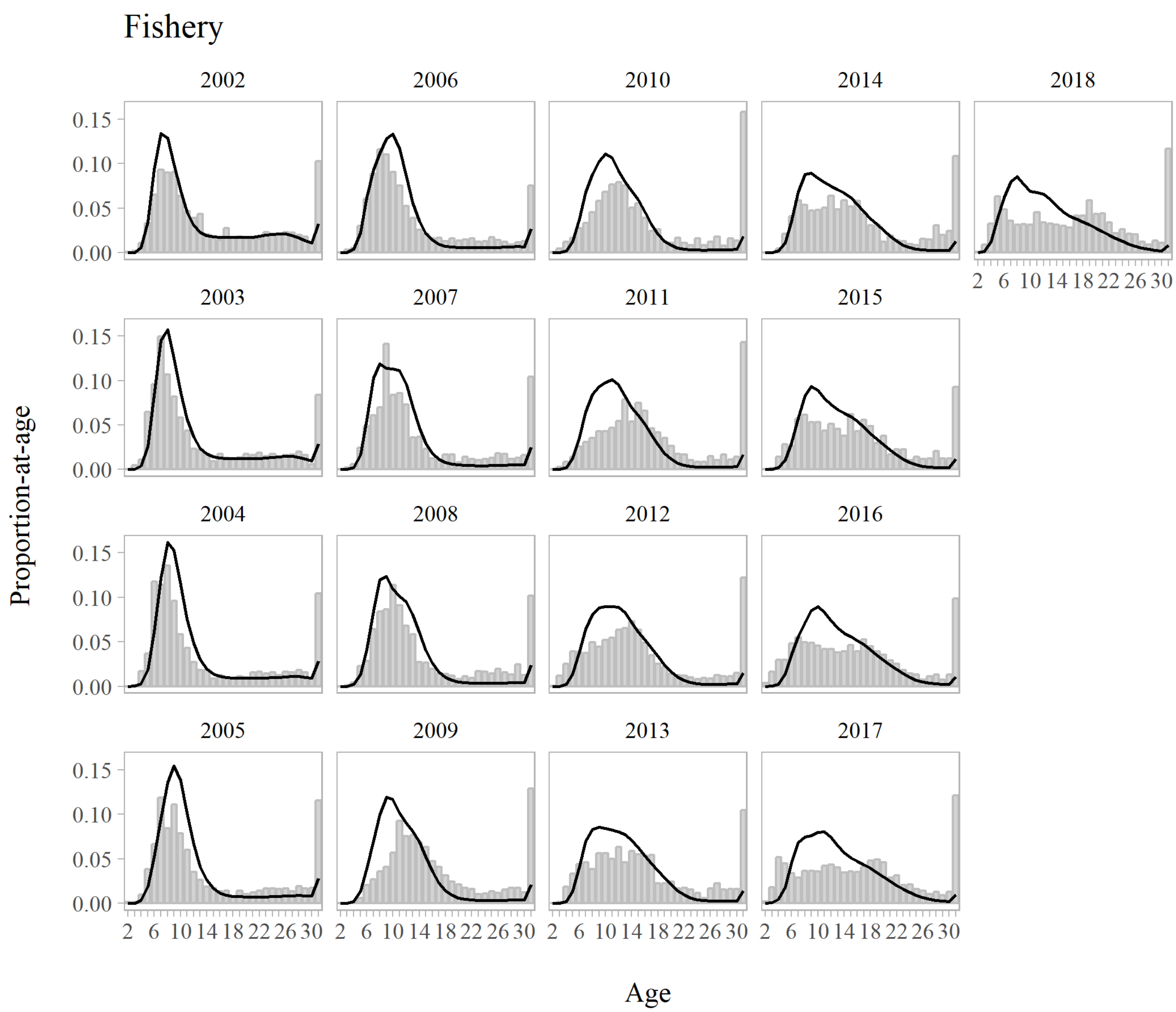

Figure 13: Fits to fishery age compositions, 2002-2018. Observed and predicted proportions-at-age shown as grey bars and black lines, respectively.

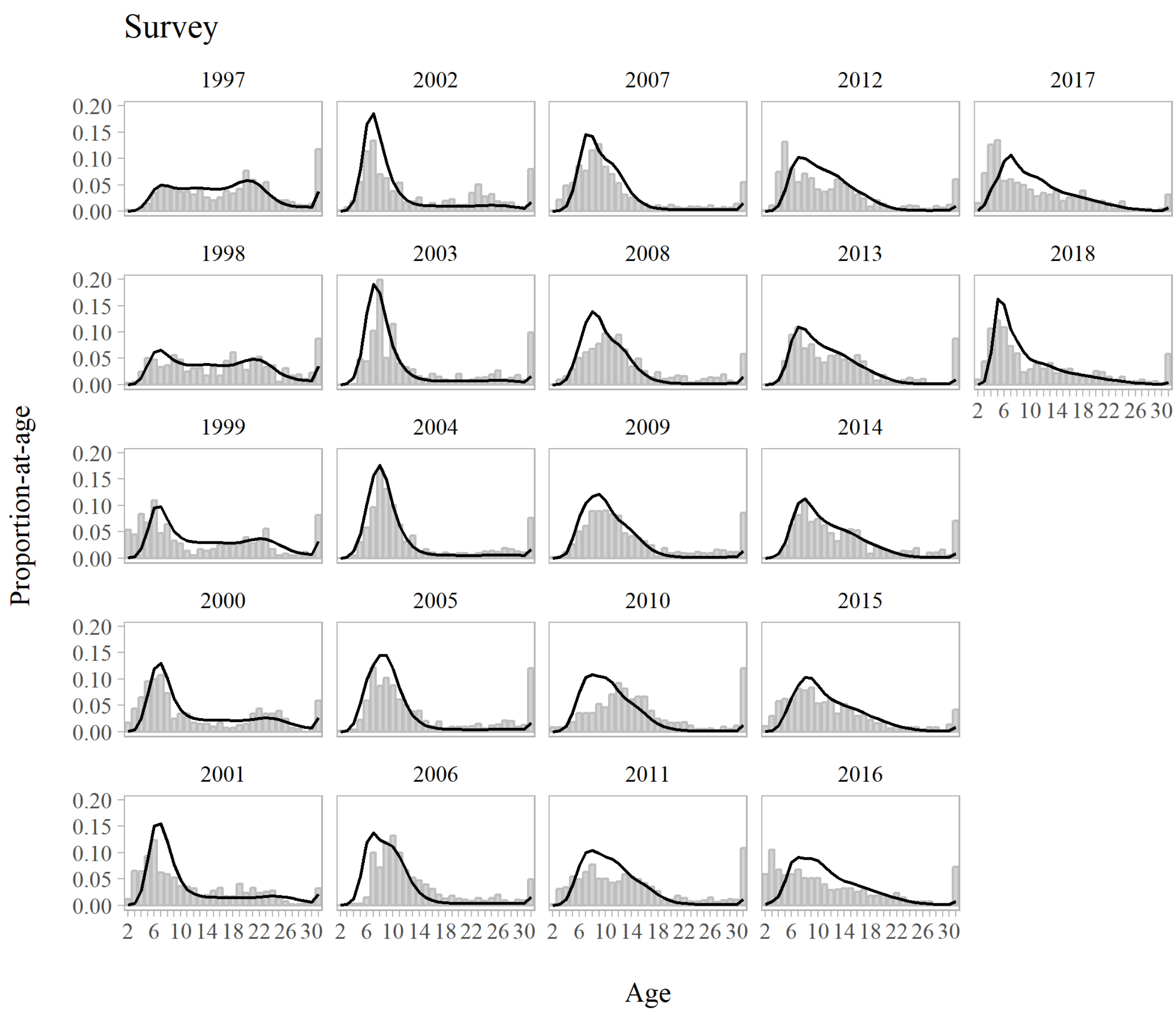

Figure 14: Fits to survey age compositions, 1997-2018. Observed and predicted proportions-at-age shown as grey bars and black lines, respectively.

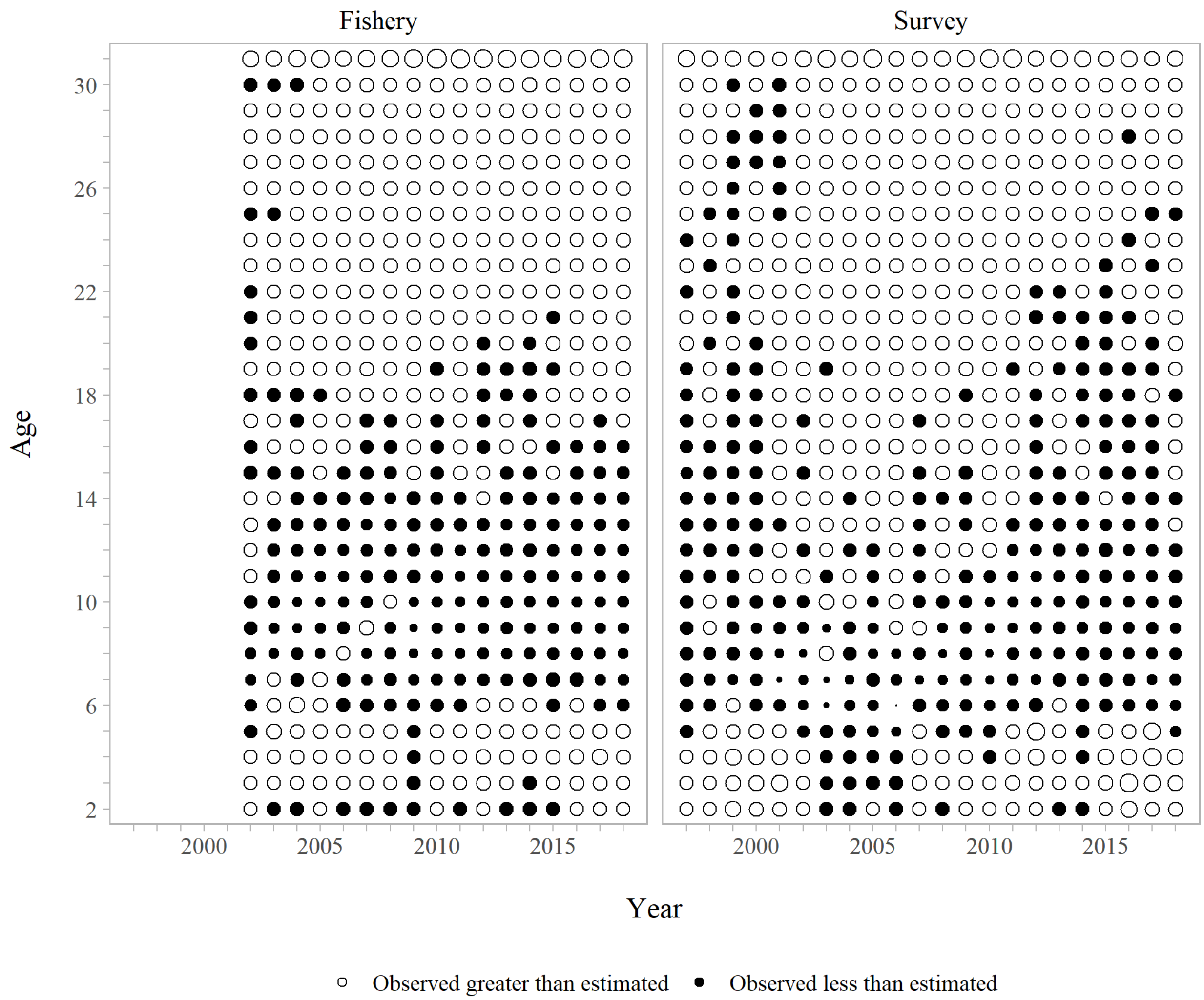

Figure 15: Standardized residuals of fits to fishery (2002-2018) and survey (1997-2018) age compositions. Size of residual scales to point size. Black points represent negative residuals (observed < predicted); white points represent positive residuals (observed > predicted).

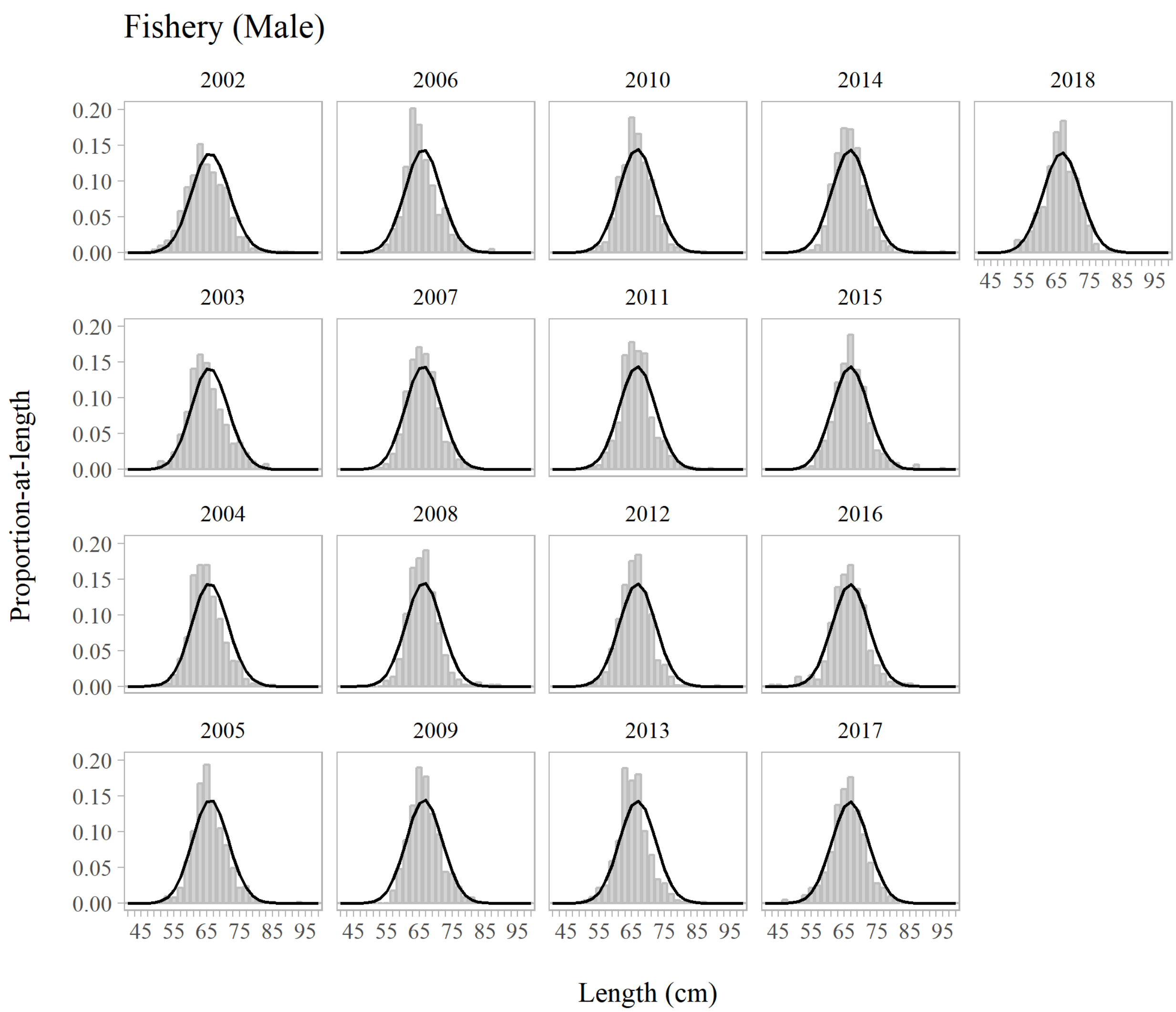

Figure 16: Fits to male fishery length compositions, 2002-2018. Observed and predicted proportions-at-age shown as grey bars and black lines, respectively.

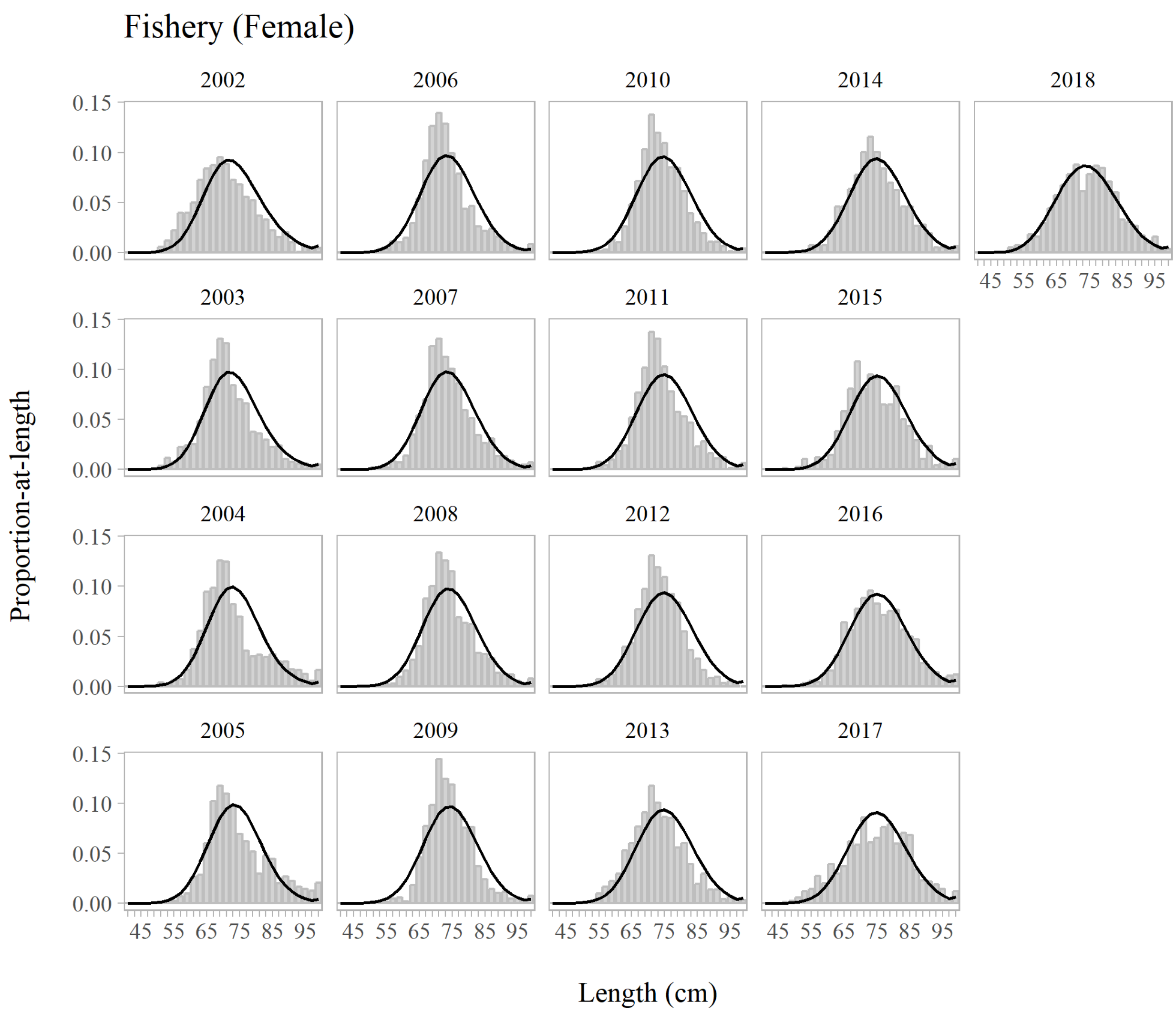

Figure 17: Fits to female fishery length compositions, 2002-2018. Observed and predicted proportions-at-age shown as grey bars and black lines, respectively.

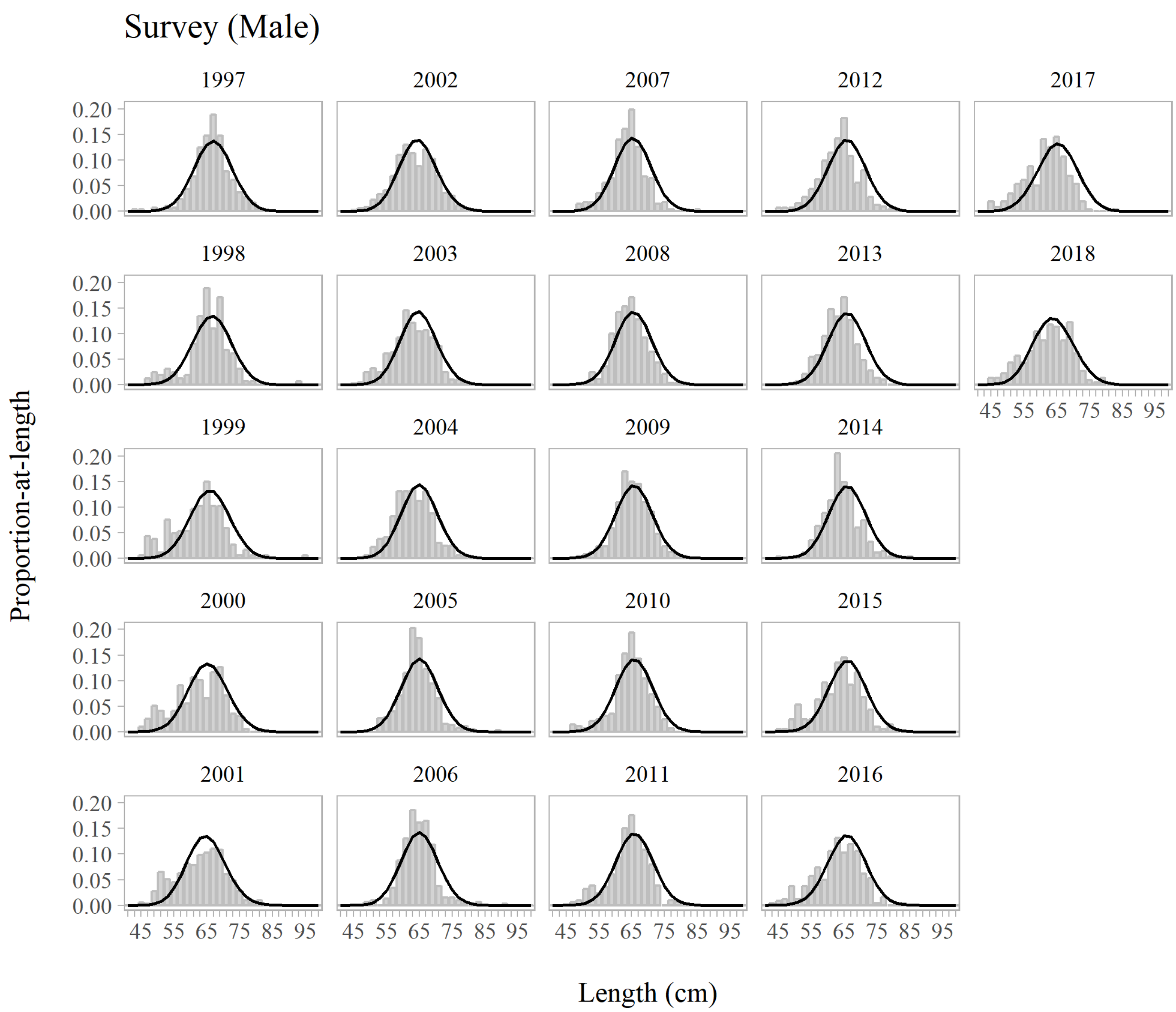

Figure 18: Fits to male survey length compositions, 1997-2018. Observed and predicted proportions-at-age shown as grey bars and black lines, respectively.

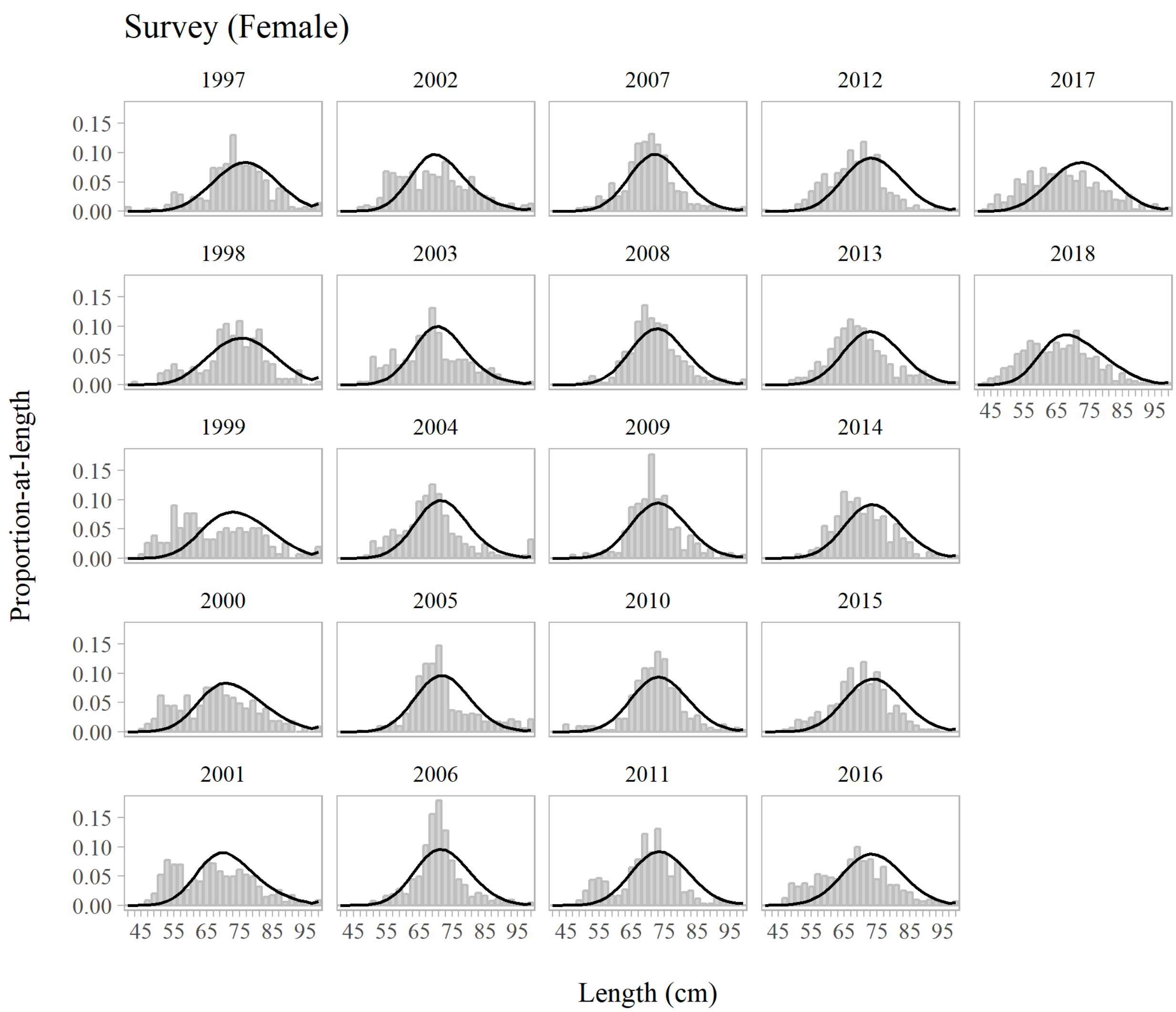

Figure 19: Fits to female survey length compositions, 1997-2018. Observed and predicted proportions-at-age shown as grey bars and black lines, respectively.

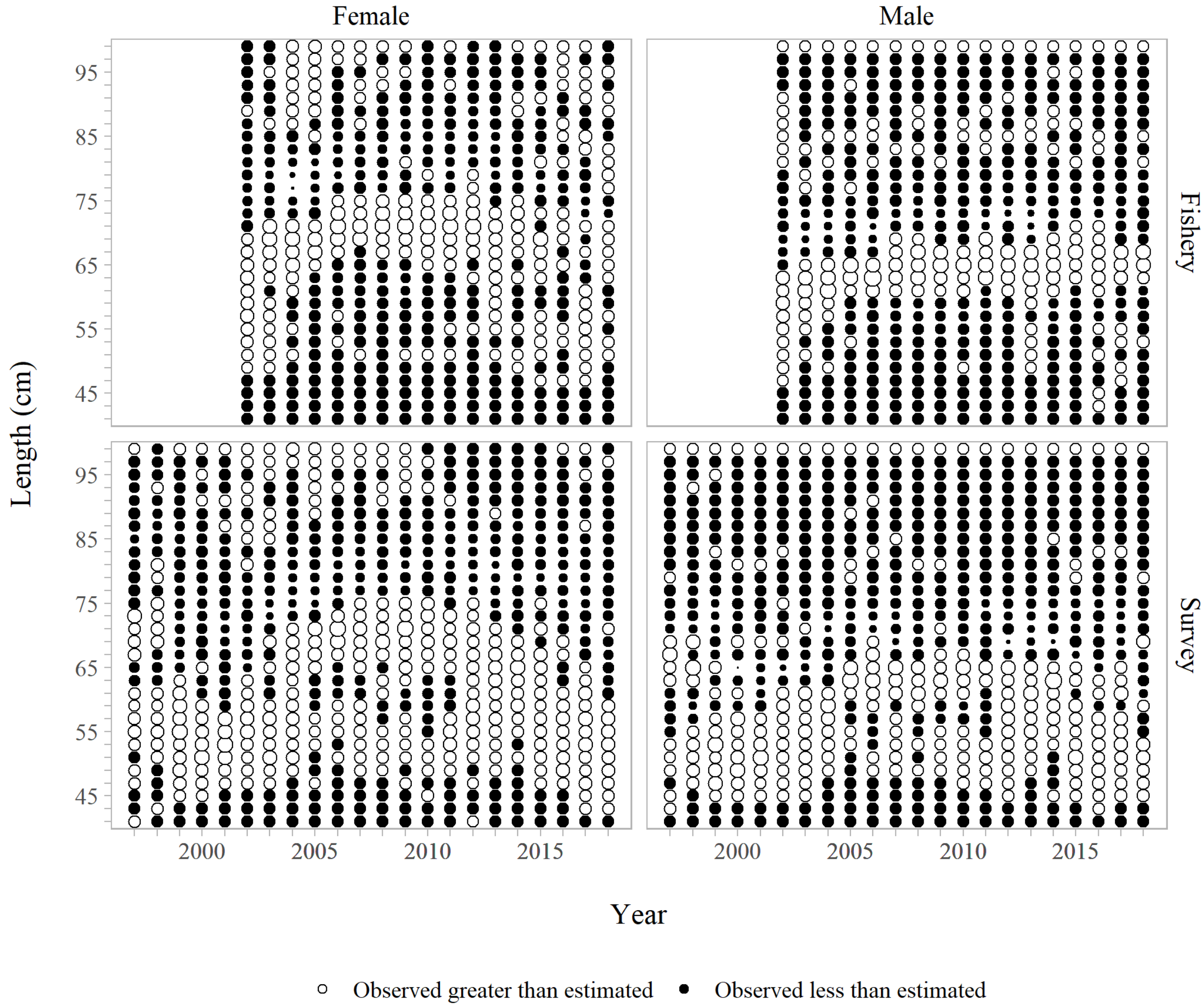

Figure 20: Standardized residuals of fits to fishery (2002-2018) and survey (1997-2018) length compositions for males and females. Size of residual scales to point size. Black points represent negative residuals (observed < predicted); white points represent positive residuals (observed > predicted).

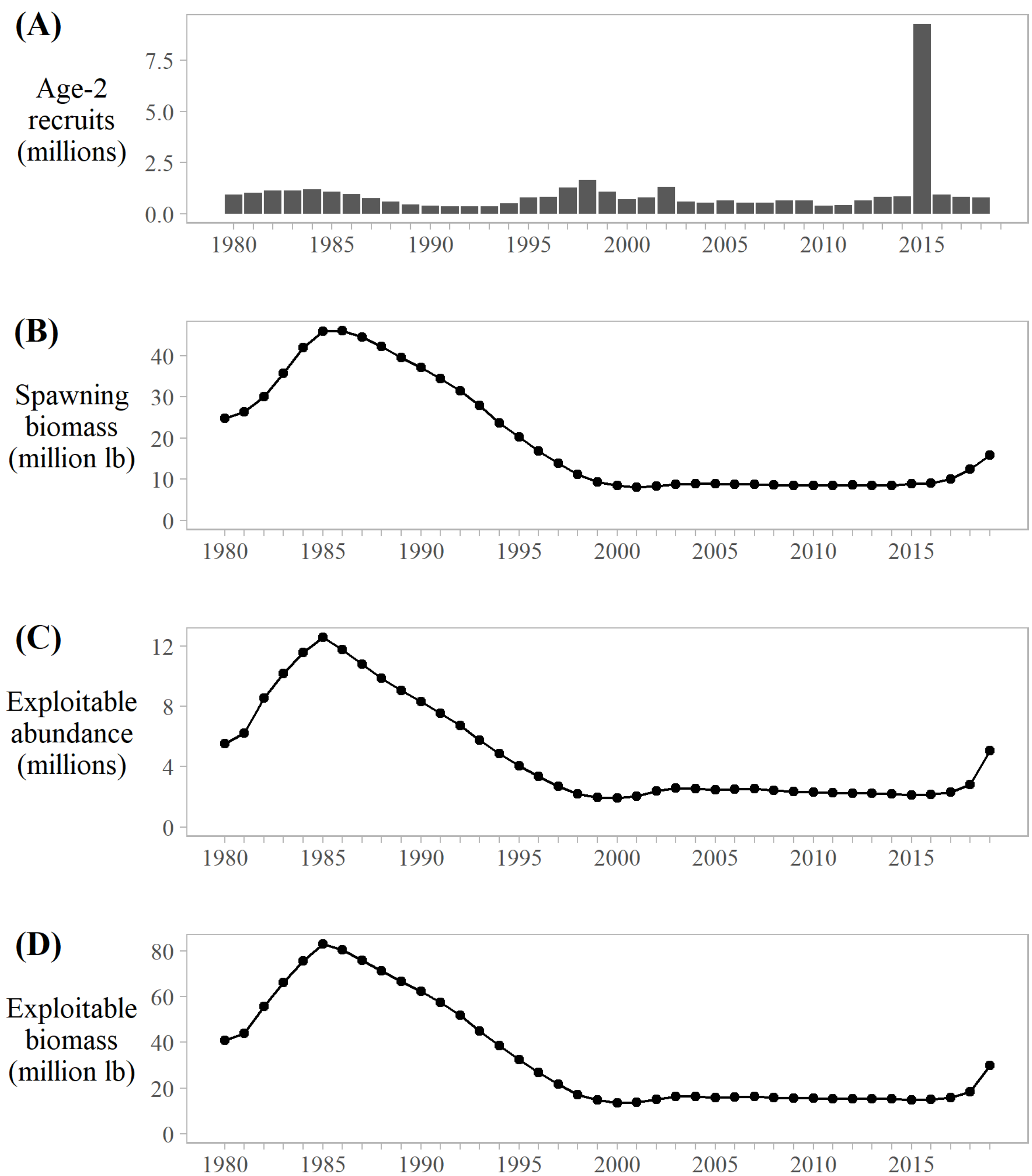

Figure 21: Model predictions of (A) age-2 recruitment (millions), (B) female spawning stack biomass (million lb), (C) exploitable abundance (millions), and (D) exploitable biomass (million lb).

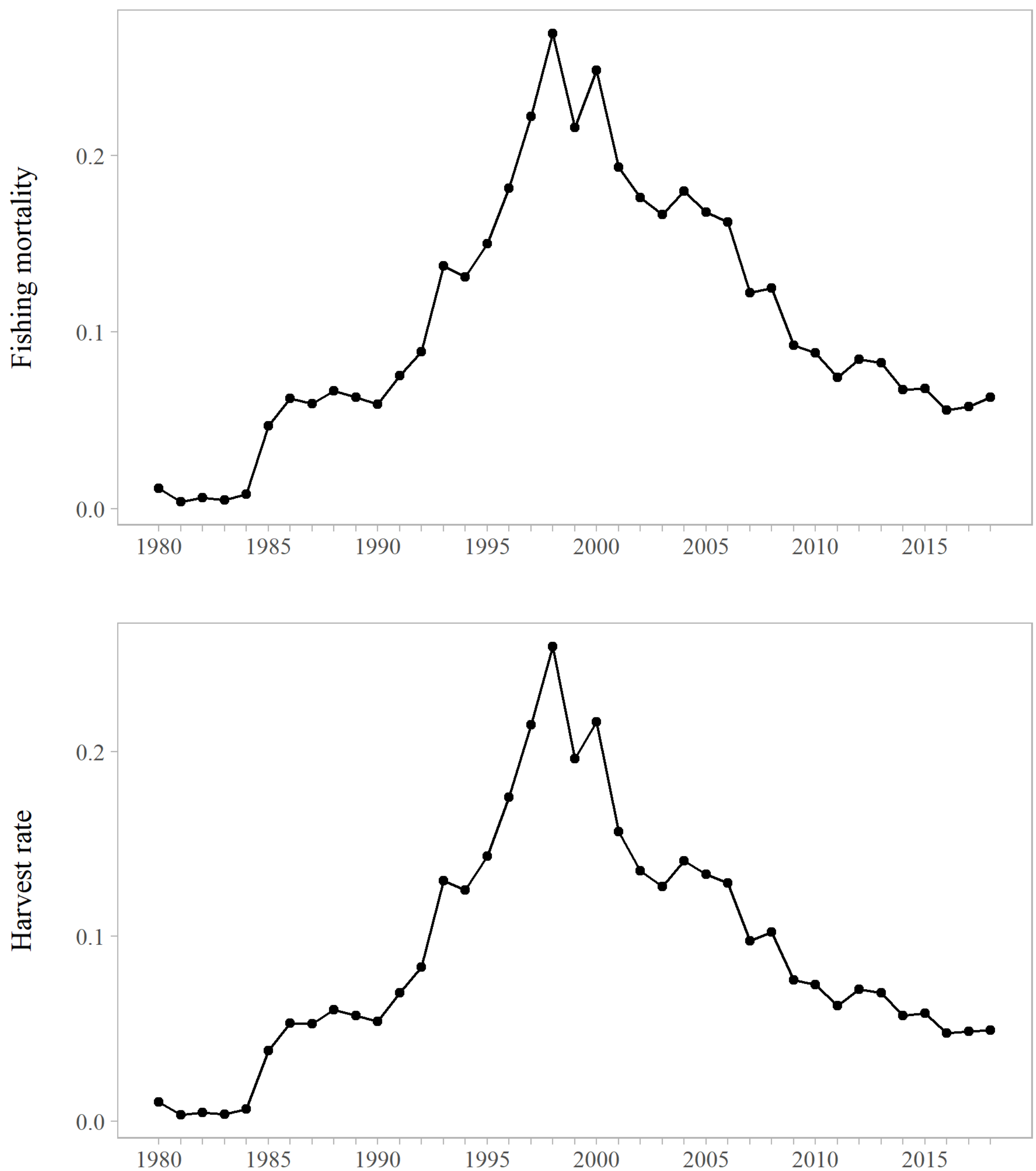

Figure 22: Model-estimated fishing mortality rate (top) and realized harvest rate (bottom), defined as the ratio of total predicted catch to exploitable biomass. Total predicted catch is the sum of landed catch and discarded biomass assumed to die post-release.