A Transboundary Operating Model for Northeast Pacific Sablefish

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This document describes the Operating Model (OM) developed for use in a Management Strategy Evaluation (MSE) for northeast Pacific Sablefish, *Anoplopoma fimbria*. The OM is coded in R (R Core Team 2019) and Template Model Builder (Kristensen et al., 2016), and many elements are similar in structure to the widely-used statistical catch-at-age modeling software Stock Synthesis (Methot and Wetzel, 2013). The modeling framework was designed to represent several spatial areas, with movement occurring between spatial areas. The following sections describe the equations used to represent the population and fishery dynamics, and to condition the operating model.

Basic Operating Model Features

The operating model is age-structured, two-sex, and has an annual timestep (y). The plus-group age A for the model is 65 years; numbers- and biomass-at-age greater than age A are collapsed into this terminal group. Growth and selectivity are constant after this age. Here we provide a general description of the model dynamics through time. In this document, modeled spatial areas, termed sub-areas, are the union of biological stocks and political management regions (Figure 1). The biological stocks are defined by distinct demographic regimes, with growth described by Kapur et al. (2019) [include maturity & movement cite when ready]. Sub-areas corresponding to the Alaskan Federal management regime are labeled “A”; sub-areas corresponding to British Columbia with “B” and those from the West Coast of the United States/California Current using “C”. In equations, sub-areas are indexed using the letters i and j, stocks using the letter k, and management regions using the letter m.

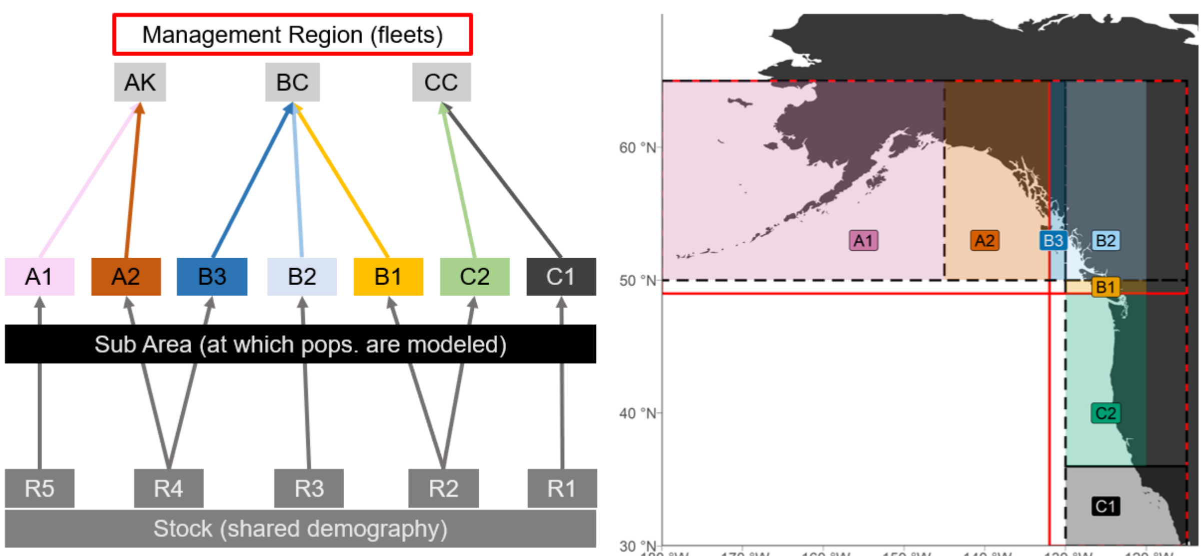

Figure 1. (**Left**) Schematic of biological area nesting within management regions. Biological areas (dark grey boxes) define the demographic regime within sub-areas (colored boxes), each of which corresponds to one of three management regions (light grey boxes), i.e., Alaska (AK), British Columbia (BC) or the California Current (CC). Colored arrows designate the sub-areas from which fish are surveyed and/or captured by fleets belonging to each management region. (**Right**) Map of spatial strata used in the operating model (shaded rectangles with labels). The red boxes delineate the current management regions. Stocks are demographically distinct, and there is movement between sub-areas as described in Rogers et al. (20xx).

Population Dynamics (Numbers at Age)

The basic dynamics of fish of sex γ in year y at age a within sub-area i are given by:

$$N^i_{y+1,\gamma,a} = \begin{cases} 0.5R^i_{y+1} & if\ a\ =\ 0 \\ \sum_{i\neq j}\left[\left(1-\boldsymbol{X}^{i,j}_a\right)N^i_{y,\gamma,a-1}e^{-Z^i_{y,a}} + \boldsymbol{X}^{j,i}_a N^j_{y,\gamma,a-1}e^{-Z^j_{y,a}}\right] & if\ 1 \leq a < A \\ \sum_{i\neq j}\left[\left(1-\boldsymbol{X}^{i,j}_a\right)\left(N^i_{y,\gamma,a-1}e^{-Z^i_{y,a}} + N^i_{y,\gamma,A-1}e^{-Z^i_{y,A-1}}\right)\right. & if\ a\ =\ A \\ \left. \ldots + \boldsymbol{X}^{j,i}_a\left(N^j_{y,\gamma,A}e^{-Z^j_{y,A}} + N^j_{y,\gamma,A-1}e^{-Z^j_{y,A-1}}\right)\right] & \end{cases} \quad \text{Equation 1}$$

where $N^i_{y,\gamma,a}$ is the number of animals of age a and sex γ in sub-area i at the start of year y

- $\boldsymbol{X}^{i,j}$ is the matrix of movement probabilities from sub-area i to sub-area j
- $Z^i_{y,a}$ is the total mortality experienced in sub-area i given fishery mortality and stock- and age-specific natural mortality M^k_a. See section on Catches for more detail on how total mortality is calculated
- R^i_y is the number of recruits spawned in sub area i at the start of year y (see section on Reproduction)
- A is the maximum age (treated as a plus-group).

The model operates on a yearly timestep, with the number of age-0 recruits defined as half of the expected annual recruitment for each sex in each sub-area. For ages 1 through the plus-group, the number of individuals at the start of the next year is the sum of individuals in sub-area i which survive and do not emigrate, or immigrate into i after surviving in the present year within another sub-area j. The plus group in sub-area i is comprised of individuals who age into or remain at age A in sub-area i, plus individuals who age into or remain at age A in sub-area j and immigrate into i.

Growth

Length-at-age is stock-specific and follows a von Bertalanffy growth function (Bertalanffy, 1938), which is incremented for each timestep y. The incremental setup prohibits fish from shrinking if they move into a sub-area corresponding to a stock with a lower L_∞, because the growth increment is a function of the ratio between current size and asymptotic size in the stock at hand.

$$L^k_{y,\gamma,a} = L^k_{y,\gamma,a} + (L^k_{y,\gamma,a} - L^k_{\infty,\gamma})\left(e^{-\kappa^k_\gamma} - 1\right)\ if\ a\ <\ A \quad \text{Equation 2}$$

For the plus group (age A) the mean size at the start of year y is calculated as the weighted average of fish entering and remaining in the plus-group. This calculation is based on the mean length at age in the middle of the year. This setup allows the size of fish in the plus group to reflect changes (i.e. declines) due to exploitation and/or natural mortality.

$$L^k_{y+1,\gamma,A} = \frac{N^k_{y+1,\gamma,A-1}\widetilde{L^k_{y,\gamma,A}} + N^k_{y+1,\gamma,A}\left[L^k_{y,\gamma,A} + (L^k_{y,\gamma,A} - L^k_{\infty,\gamma})\left(e^{-\kappa^k_\gamma} - 1\right)\right]}{N^k_{y+1,\gamma,A} + N^k_{y+1,\gamma,A-1}} \quad \text{Equation 3}$$

Where $\widetilde{L^k_{y,\gamma,a}}$ is the mean length-at-age at age a of sex γ in stock k at the midpoint of year y:

$$\widetilde{L^k_{y,\gamma,a}} = L^k_{y,\gamma,a} + (L^k_{y,\gamma,a} - L^k_{\infty,\gamma})\left(e^{-0.5\kappa^k_\gamma} - 1\right) \quad \text{Equation 4}$$

$L^k_{\infty,\gamma}$ is the stock and sex-specific asymptotic length (cm)

κ_γ^k is the stock and sex-specific growth rate (cm yr^{-1})

The growth module generates a stock- and sex-specific matrix $\boldsymbol{L}$ which defines the annual probability of being in each of l length bins at age a. This matrix defines the distribution of numbers-at-age for each stock and year. The mid-year size-at-age is used as an approximation to size-at-age for any samples collected during the year.

$$\boldsymbol{L}_{y,\gamma,a,l}^k = \begin{cases} \Phi(\theta_1, \widetilde{L_{y,\gamma,a}^k}, \sigma_{\gamma,a}^k) & if\ l = 1 \\ \Phi(\theta_{l+1}, \widetilde{L_{y,\gamma,a}^k}, \sigma_{\gamma,a}^k) - \Phi(\theta_l, \widetilde{L_{y,\gamma,a}^k}, \sigma_{\gamma,a}^k) & \text{if } 1 < l < A_l \\ 1 - \Phi(\theta_l, \widetilde{L_{y,\gamma,a}^k}, \sigma_{\gamma,a}^k) & if\ l = A_l \end{cases} \quad \text{Equation 5}$$

Where Φ is the standard normal cumulative density function, which is evaluated for θ_l given mean $L_{y,\gamma,a}^k$ and standard deviation $\sigma_{\gamma,a}^k$
θ_l is the integer value of the lth length bin (cm)
A_l is the index of the largest length bin
$\widetilde{L_{y,\gamma,a}^k}$ is the mean length at age a for sex γ in stock k, given by Equation 4
$\sigma_{\gamma,a}^k$ is the stock and sex-specific standard deviation of length at age.

Specific values for the growth parameters are shared among sub-areas from the same stock as shown in Table 1. Body weight is converted from length at age via

$$w_{\gamma,l}^k = \alpha_\gamma^k \bar{L}_l^{\beta_\gamma^k} \quad \text{Equation 6}$$

Where α_γ^k and β_γ^k are stock- and sex- specific constants of the allometric length-weight equation
$\bar{L}_l$ is the midpoint of the population length bin

The population-level body weight at age in a stock (or sub-area) is calculated using the stock- and sex-specific weight at age, the proportions at length, and the number present:

$$w_{\gamma,a}^k = (N_{y,\gamma,a}^k \boldsymbol{L}_{y,\gamma,a,l}^k) w_{\gamma,l}^k \quad \text{Equation 7}$$

Reproduction

Recruitment follows a Beverton-Holt stock recruitment curve with annual deviations. Density-dependence is assumed to occur at the level of the stock (k) and is determined by the biomass (converted from numbers, as described above) of mature females in the stock, which may be the sum across two or more sub-areas, at the start of year y. The stock-recruitment approach assumes that recruitment deviates occur at the stock level (and are thus equivalent among sub-areas within a stock).

$$R_y^k = \frac{4h^k R_0^k S_y^k}{S_0^k(1-h) + S_y^k(5h-1)} e^{-0.5\sigma_R^2 + \tilde{R}_y^k} \quad \text{Equation 8}$$

where h^k is the steepness of the stock recruitment curve (expected proportion of R_0 at $0.2S_0$) for stock k
R_0^k is the virgin recruitment by stock
$\tilde{R}_y^k$ are random annual recruitment deviations specific to stock k and assumed to be normally distributed with mean zero and standard deviation σ_R

S_y^k is the spawning biomass (mature females) in stock k at the start of year y

$$S_y^k = \sum_{i \epsilon k} \sum_a N_{y,\gamma=female,a}^i w_{\gamma=female,a}^k E_a^k \qquad \text{Equation 9}$$

E_a^k is the proportion of females at age in stock k which have reached maturity at age a

S_0^k is the unfished female spawning biomass in stock k.

Recruits are allocated from stock k to sub-area i based on a fixed proportion $\omega^{i,k}$, which is the eigenvector of the movement transition matrix described in the Movement section, with an entry for each sub-area within each stock. The resulting annual recruitment spawned within each sub-area is used in Equation 1.

$$R_y^i = \omega^{i,k} R_y^k \qquad \text{Equation 10}$$

Fleets

A fleet is a discrete survey or fishing operation. There are several fleets f in each management region m, and there may be more than one fleet operating in each sub-area (Figure 2). All management regions have coverage by at least one fishery fleet, survey, and have length or age composition data from one or more fleets. Temporal coverage varies by management region, with catch records extending back to the early 1900s for Alaska and the California Current (Table 1).

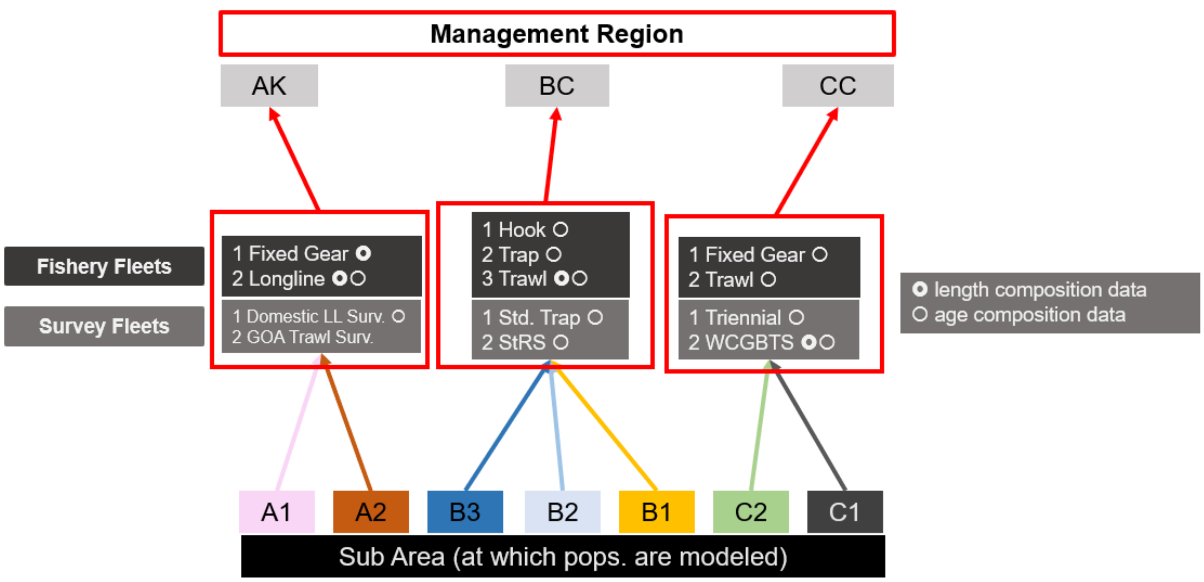

Figure 2. Schematic of available survey fleets (light grey boxes) fishery fleets (dark grey boxes) and associated compositional data (circular symbols) available for each of three management regions (lightest grey boxes at top). The modeled sub-areas are fished/sampled by the fleets to which colored arrows point. Note that indices of relative abundance were re-created using a spatio-temporal model which reduced the number of survey fleets for several regions; compositions were retained at original fleet resolution.

Catches

Catches accrue to one of three management regions, which are comprised of at least one modeled sub-area i. The data used to condition and test this OM are aggregated at the fleet level f, which are nested within management regions m and may exploit more than one sub-area i.

Discards

Total fishing mortality reflects both retained fish (according to a retention function) and the fraction of catches which are discarded and assumed to not survive. Ω is a logistic function defining the fraction of retained catch in age bin *a*, during year *y* for fishery fleet *f* and sex γ. Discarded catch is simply 1- Ω. The mortality of discarded catch may vary by the age of fish.

$$\Omega^{f}_{y,\gamma,a} = \beta_3^{y,f,\gamma,a}\left(1 + exp(-a - (\frac{\beta_1^{y,f,\gamma,a} + \beta_4^{y,f,\gamma,a}}{\beta_2^{y,f,\gamma,a}})\right)^{-1} \quad \text{Equation 11}$$

Where $\beta_1^{y,f,\gamma,a}$ is the age at the inflection point of the logistic retention function
$\beta_2^{y,f,\gamma,a}$ is the slope at the point of inflection
$\beta_3^{y,f,\gamma,a}$ asymptotic fraction retained (note that discards + retained must sum to 1)
$\beta_4^{y,f,\gamma,a}$ is 0 for females and an arithmetic offset for male ages

Retained Catch

Fleet- and age-specific fishery catch is modeled using the Baranov (Ricker 1975) catch equation. The annual catch for each fleet in each management region $C_y^{m,f}$ is obtained by summing the catches by fleet *f* across all sub-areas *i* which are both fished by *f* and nested within management region *m*. No fleet fishes more than one management region. The use of the Baranov equation ensures that the numbers-at-age in any given year are always greater than zero.

$$C_y^{m,f} = \sum_{i\epsilon m}\sum_a w_a^f \frac{\phi_f^i s_a^f \Omega_{y,a}^f F_y^f}{Z_{y,a}^i} N_{y,a}^i (1 - e^{-Z_{y,a}^i}) \quad \text{Equation 12}$$

Where w_a^f is the fleet-specific weight at age for captured fish (assumed equivalent for all sub-areas *i* fished by *f*)
ϕ_f^i is a matrix indicating whether fleet *f* occurs in sub-area *i* (ϕ_f^i is set to 1 if fleet *f* occurs in sub-area *i*, and 0 otherwise)
s_a^f is the selectivity on animals from fleet *f* and age *a* (see section on Selectivity)
$\Omega_{y,a}^f$ is the retention function for fish of age *a* from fleet *f*
F_y^f is the fishing mortality rate on fully recruited animals by fleet *f* during year *y* (described in more detail below)
$Z_{y,a}^i$ is the total fishing mortality enacted by all fleets on fish of age *a* in sub-area *i* during year *y*, in addition to natural mortality. As in Equation 1, we assume that F^f is equivalent across sub-areas (i.e. the fishing mortality of fleet *f* in sub-area *i* is the same as the fishing mortality of fleet *f* in sub-area *j*).

$$Z_{y,a}^i = M_a^k + \sum_f \phi_f^i\left(s_a^f \Omega_{y,a}^f F_y^f + s_a^f(1 - \Omega_{y,a}^f)F_y^f V^f\right) \quad \text{Equation 13}$$

Where V^f is the fleet-specific mortality rate of discarded fish; if set to zero, all discards are assumed to survive and only retained catches figure into total mortality

Fishing Mortality

The annual fishing mortality enacted by each fleet F_y^f is determined using the "hybrid" method, which has been implemented in the Stock Synthesis modeling software (Methot & Wetzel 2013), among others. The premise behind the hybrid method arises from the fact that F_y^f cannot be solved for explicitly, but would be computationally expensive to estimate. Instead, the method algorithmically tunes the continuous *F* values for each fleet until the observed catches by fleet (across one or more sub-areas, as necessary) are matched. This is preferable to the Pope's approximation, which is invoked to provide the starting values for the tuning algorithm. The steps in the hybrid approach are as follows.

1) Identify an initial guess $\tilde{F}_f^1$ for the annual fishing mortality of each fleet *f*. This initial guess is the ratio of the fleet's observed catch in year *y* to the total exploitable biomass available at the start of the year *y*. In the case where fleet *f* fishes more than one sub-area, the total exploitable biomass (denominator) necessarily sums biomass from each sub-area i where f is active. Therefore, the resultant $\tilde{F}_f^1$ corresponds to the entirety of by fleet *f's* exploitation:

$$\tilde{F}_{f,y}^1 = \frac{C_{obs,y}^f}{\sum_i \sum_a \phi_f^i N_{y,a}^i w_a^f s_a^f + C_{obs,y}^f} \qquad \text{Equation 14}$$

where C_{obs}^f is the observed retained catch for fleet *f*
$N_{y,a}^i, w_a^f, s_a^f$ are the same as in Equation 12

2) This initial guess is modified to become the starting value F_f^1 following Pope's approximation:

$$F_{f,y}^1 = -ln\left(1 - \left[\tilde{F}_{f,y}^1\left(\frac{1}{1+exp(30(\tilde{F}_{f,y}^1 - v)}\right) + v(1 - \left(\frac{1}{1+exp(30(\tilde{F}_{f,y}^1 - v)}\right)\right]\right) \qquad \text{Equation 15}$$

where v controls the upper limit on F_f^1, as $\tilde{F}_f^1 \to \infty, F_f^1 \to -ln(1-v)$. This was set to 0.95, which corresponds to $F_f^1 = 3.0$. In other words, harvest rates above 0.95 are converted to an *F* corresponding to a harvest rate close to 0.95.

3) Compute model-predicted catches for each fleet (following the same equation structure as Equation 12). This includes summation of biomass across all sub-areas fished by *f*, defined by ϕ_f^i. At this point, $Z_{y,a}^i$ is the total mortality in sub-area *i* implied by the current guesses for fishing mortality F_f^1, as in Equation 13.

$$C_{pred,y}^f = \sum_i \sum_a w_a^f \frac{\phi_f^i s_a^f \Omega_{y,a}^f F_{f,y}^1}{Z_{y,a}^i} N_{y,a}^i (1 - e^{-Z_{y,a}^i}) \qquad \text{Equation 16}$$

4) Compute an adjustment factor *Adj* which will be used to tune total mortality. *Adj* is calculated using the ratio of the sums of observed and predicted catches from all fleets *f* nested within management region *m,* and accordingly may involve multiple sub-areas:

$$Adj_y = \sum_{f\epsilon m} C_{obs,y}^f / \sum_{f \epsilon m} C_{pred,y}^f \qquad \text{Equation 17}$$

5) Re-scale total mortality in the sub-area, $Z^i_{y,a}$, using *Adj*. and the extant guess for fishing mortality:

$$\tilde{Z}^i_{y,a} = M^k_a + \sum_f \phi^i_f Adj_y \left(s^f_a \Omega^f_{y,a} F^1_{f,y} + s^f_a (1 - \Omega^f_{y,a}) F^1_{f,y} V^f\right) \quad \text{Equation 18}$$

6) For the next iteration, the value of F_f is given by updating C^f_{pred} (Equation 16) with the new $\tilde{Z}^i_{y,a}$ and repeating steps 2-4. The new F_f "guess" represents the ratio between the observed catches for fleet *f* and total exploitable biomass available to fleet *f*, given the adjusted value for total mortality found in Step 5.

$$\widetilde{F^2_{f,y}} = \frac{C^f_{obs}}{\sum_i \sum_a w^f_a \frac{\phi^i_f s^f_a \Omega^f_{y,a} F^1_{f,y}}{\tilde{Z}^i_{y,a}} N^i_{y,a} (1 - e^{-\tilde{Z}^i_{y,a}})} \quad \text{Equation 19}$$

7) This $\widetilde{F^2_f}$ is again modified following Equation 8, with the change that *v* is multiplied by *Fmax*, here set to 2. This ensures that as $\widetilde{F^2_f}$ (or any subsequent iterations) approaches 0. 95Fmax, F^2_f approaches Fmax.

$$F^2_{f,y} = -ln\left(1 - \left[\tilde{F}^2_{f,y}\left(\frac{1}{1+exp(30(\widetilde{F^2_{f,y}} - vF_{max})}\right) + v(1 - \left(\frac{1}{1+exp(30(\widetilde{F^2_{f,y}} - vF_{max})}\right)\right]\right) \quad \text{Equation 20}$$

8) Steps 2-6 are repeated several times. The final iteration terminates with a value of $F_{f,y}$ following Equation 16, which is applicable to the entire exploitation activity of a given fleet across a management region.

Surveys

Surveys occur at the start of the year. The operation of some survey fleets span more than one sub-area, in which case survey biomass B^f_y is computed as the sum across sub-areas (the assumption of homogeneity within stocks is held). For fleets which do not record the ages of surveyed fish, the *a* subscript is ignored.

$$B^f_y = \epsilon^f_y q^f \sum_i \sum_a \phi^i_f s^f_a N^i_{y,a} w^{k,f}_a \quad \text{Equation 21}$$

Where ϵ^f_y is the survey fleet- and year-specific error term, drawn from a lognormal distribution via the following. A fixed observation error component of 0.2 (Francis, 2001) is added to a fleet-specific standard deviation specific to survey years, calculated externally to the model :

$$\epsilon^f_y \sim lognormal(0, 0.2 + \sigma^f_y) \quad \text{Equation 22}$$

q^f is the catchability coefficient for survey fleet *f*,

ϕ^i_f defines whether *f* operates in *i*

s^f_a is the survey selectivity for survey fleet *f*, which may follow one of three functional forms (see below)

Selectivity (in Fleets & Surveys) – not ready

Selectivity, or the preferential sampling of sablefish, is both age-and length-specific in the operating model. For fleets operating in AK and CC management regions, the length-based selectivity function is 1.0 for all fleets and lengths as these assessments have historically not modeled length-based selectivity for any fleet. Aside from this constant (fully-selected) setup, selectivity curves can follow

$$s_a^f = (1 + e^{-(a-a_{50}^f)/\delta^f})^{-1}$$ Equation 23

a_{50}, δ are the parameters of the (logistic) selectivity ogive;

Movement – Luke to revise as necessary

Movement between areas is modeled using a matrix **X**, which models the distribution of fish at age *a* in sub-area *i* at the time when the catch is removed/when the surveys are conducted. The rows of the matrix correspond to the modelled areas in Figure 1. the column headers correspond to the management regions which consists of up to *A* matrices with elements representing the proportion of fish at age *a* in area *i* which move to another area *j* at the time when the catch is removed / when the surveys are conducted. For simulations in which movement is "off", all off-diagonal values of **X** are set to zero and diagonal elements are set to one; Movement parameters were obtained by the analysis of several decades' tag-recapture data for sablefish (cite Luke), implemented here as a saturating function of age.

$$\boldsymbol{X}_a^{i,j} = \frac{\kappa^{i,j}}{1+e^{\left(-\lambda^{i,j}(a-a_{50})\right)}}$$ Equation 24

Where κ is the maximum movement rate
λ determines the slope towards the maximum
a_{50} is the age at 50% of maximum movement rate

Equilibrium Abundance

To initialize the model, we calculate the unfished age distribution at the stock level and partition into sub-areas based:

$$N_{0,\gamma,a}^i = \begin{cases} 0.5\omega^{i,k} R_0^k e^{-\sum_a M_a^k} & if\ a < A \\ \omega^{i,k} \frac{N_{\gamma,A-1}^i e^{\sum_a M_a^k}}{1-e^{-M_a^k}} & if\ a = A \end{cases}$$ Equation 25

Where $\omega^{i,k}$ is the eigenvector of the movement transition matrix described in the Movement section, with an entry for each sub-area within each stock

The unfished spawning biomass is therefore as follows, assuming a 50:50 sex ratio:

$$S_0^k = 0.5 \sum_a R_0^k e^{-M_a^k} w_{\gamma=female,a}^k$$ Equation 26

Initial Conditions

The model is initialized with *A* years (denoted "init") of movement, recruitment deviations, and without fishing:

$$N_{init,\gamma,a}^i = \begin{cases} 0.5\omega^{i,k} R_0^k e^{-\sum_a M_a^k} e^{-0.5\sigma_R^2 + \tilde{R}_{init-1}^k} & if\ a < A \\ \omega^{i,k} \frac{N_{init-1,\gamma,A-1}^i e^{\sum_a M_a^k}}{1-e^{-M_a^k}} e^{-0.5\sigma_R^2 + \tilde{R}_{init-1}^k} & if\ a = A \end{cases}$$ Equation 27

Data Generation – NOT READY BELOW THIS POINT

Age & Length Compositions

Fishery and survey age compositions φ are generated per year for applicable fleets. For the fisheries, the proportion of individuals at age in the catch for fleet f in year y is found by dividing the prevalence in catch at age by the total caught biomass at age. The same formula is followed for length compositions, if applicable.

$$\varphi_{y,a}^{f} = \frac{C_{y,a}^{f}}{\sum_a C_{y,a}^{f}} \qquad \text{Equation 28}$$

Collapsing Surveys & Compositional Data – not sure if necessary here

Some data generation exercises required combining one or more datasets for experiments involving coarser spatial structure. Converting survey index information from individual fleets and years B_y^f into a single index is achieved using a summation across fleets among years:

$$B_y^{f'} = q^{f'} \sum_f \sum_a s_a^f N_{y,a}^i w_a^k \qquad \text{Equation 29}$$

where $q^{f'}$ is the catchability coefficient for the new survey. This protocol was not followed for panmictic experiments (single survey for the entire NE pacific), wherein a novel index of abundance was generated. See "Conditioning the Operating Model" for more details.

To combine length and/or age compositions from multiple surveys, the fleet-specific proportions φ_a^f are weighted by the total number observed in sub-areas exploited by fleet f in that year $N_{y,\gamma,a}^i$, which is calculated within the OM. These weighted values are then summed across fleets for each year and divided by the total number observed in all areas concerned, returning the proportions-at-age for a single survey combining multiple fleets.

$$\varphi_{y,a}^{f'} = \frac{\sum_{f \epsilon f'} \sum_{i \epsilon f} \varphi_a^f N_{y,a}^i}{\sum_{i \epsilon f} N_{y,a}^i} \qquad \text{Equation 30}$$

Reference Points – where to put this

Operating Model Data Inputs and Treatment

Input parameters, estimation boundaries and data used in conditioning the OM are available in Tables. Below we describe the data sources for the OM and treatment thereof.

Demographic Parameters

The spatial structure of "stocks" (black lines, Figure 1) are based upon the growth analyses performed by Kapur et al. (2019), which identified five unique regions of sablefish growth corresponding to major oceanographic features. In brief, growth in the OM follows a latitudinal cline whereby sablefish obtain a higher asymptotic length L_∞ at more north-western locales (i.e. sub-areas A1 and A2). The OM also has a time block in growth for all regions following findings by Kapur et al. (2019) that significant differences in growth parameters are present before and after 2010. [Describe re-estimation of strata-based sigma; Overview movement & maturity].

Fleets and Catches

The available fleets and compositional data corresponding to each region are shown in Figure 2; coverage by sample size and year is shown in Figure 3.

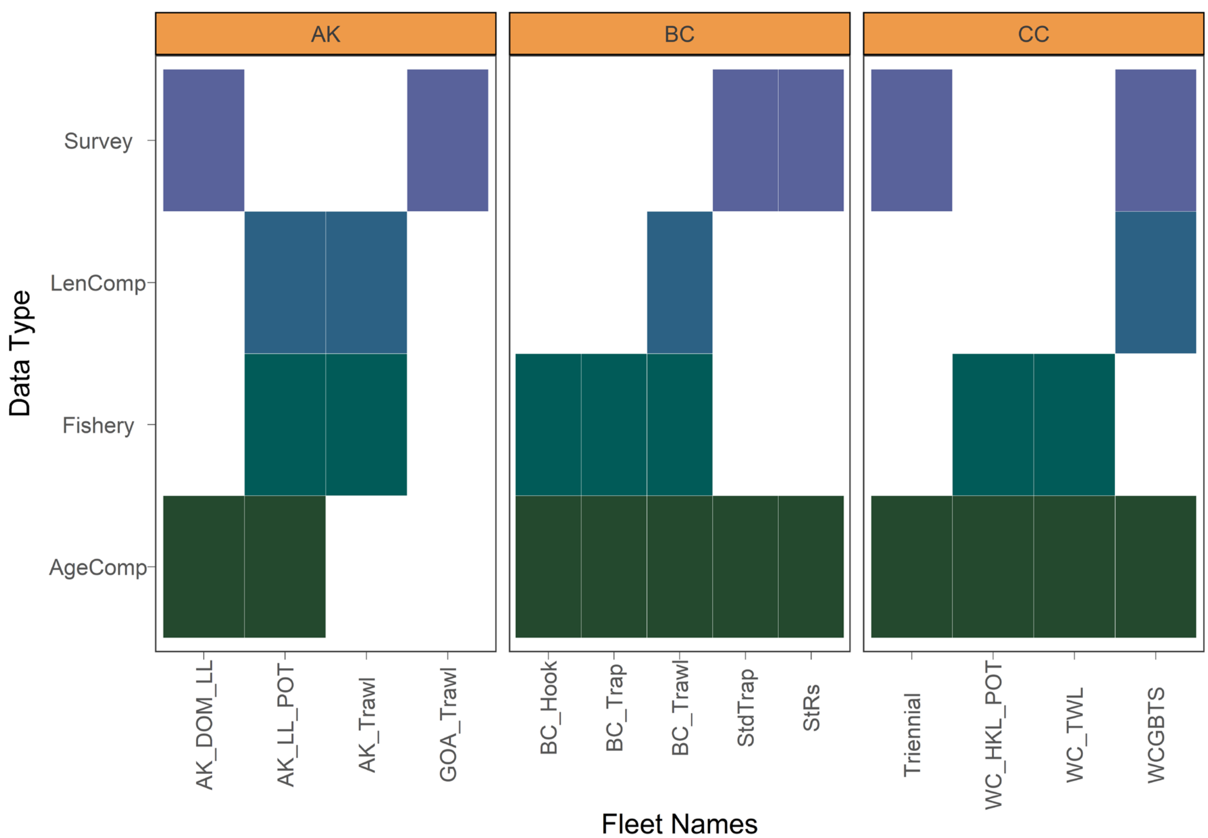

Figure 3. Plot of data available by source in Operating Model (Replace with SS_datplot mimic later). Available data is colored by data type and paneled by management region (AK = Alaska, BC = British Columbia, CC = US West Coast/California Current).

Fishery Catches

[Describe fishery fleets, and combination of fixed gears where appropriate]

Fishery Discards

The treatment of discarded catch varies by fleet and management region. For the CC, discard mortality is 20% for sablefish caught with fixed gear and 50% for sablefish captured with trawls, except for age-0 fish which were assumed to experience 100% discard mortality.

Survey Fleets

We developed a new index of relative abundance using the Vectorized Auto-regressive Spatio-Temporal model (VAST, Thorson, 2019) which enabled the combination of various survey fleets into management-region specific indices (see Supplementary Material for full description of the modeling effort and findings). The indices were calibrated to roughly mimic the trend of individual indices used in separate assessment efforts. The index of relative abundance peaks for AK and the CC in the early 1990s, after which it declines substantially (Figure 2). The index for BC peaks in about 2004; indices for all management areas show slight increases since 2010.

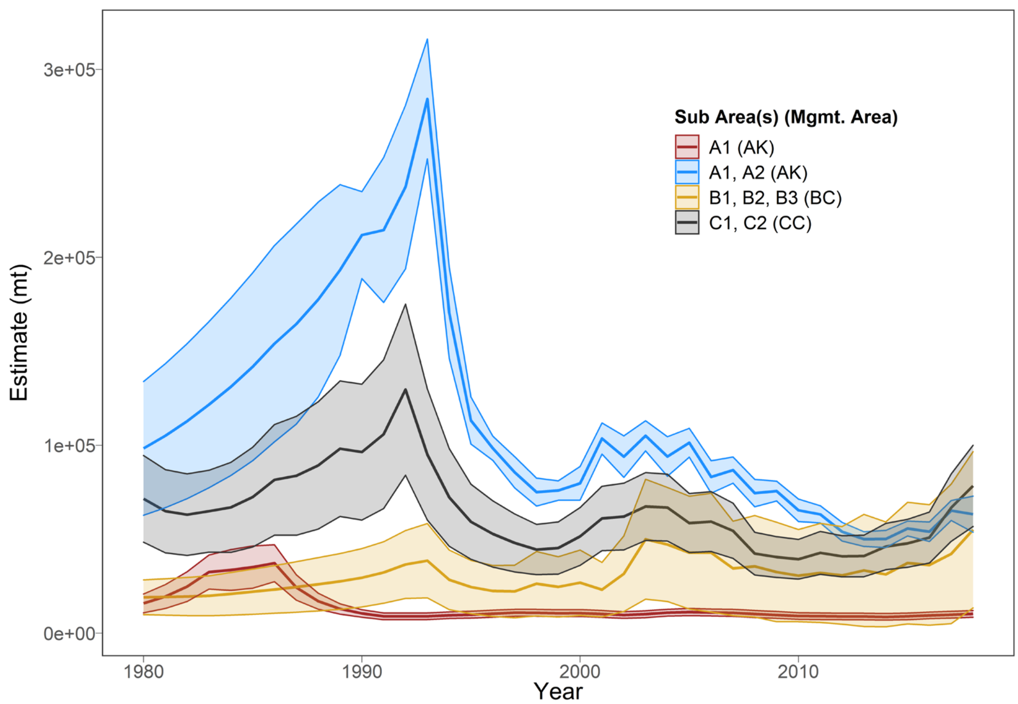

Figure 4. Indices of relative abundance developed for use in the operating model. Shaded intervals are 95% confidence intervals for estimated relative abundance in each management region. Colors correspond to the individual or collection of sub-areas surveyed by the index.

Compositional Data

[Describe comps and any treatment eg aging error, expansions, or weighting by catches]

Conditioning the Operating Model

Here, "conditioning" refers to the procedure undertaken to estimate and/or define the parameters used in the Operating Model. As mentioned in the Demographic Parameters section, many model values concerning growth, movement and maturity were estimated externally and thus were not revisited in OM development. The goal of this step was to find model outputs which roughly mimic reality (i.e. the general trend in spawning biomass observed from respective management regions in recent stock assessments). We do not expect model results or likelihoods to be identical to any current assessments, as the spatial nature of the OM, combined with the novel survey indices developed for this study, and the inclusion of movement render such comparisons unreasonable.

For this conditioning step, an estimation model (EM) which mimics the OM's structure and functional forms was developed in Template Model Builder (TMB, **cite**). The likelihood functions used in the maximum likelihood framework are described below, and are ordered to match the description of the OM.

Likelihood Components

This section provides an overview of the contribution to the objective function by data type. Table 2 specifies which form (e.g. normal, beta-distributed) is followed for each estimated parameter.

General parameters

The growth parameters used in the Operating model were estimated externally, so the input parameters defining the expected distribution of length at age were fixed to those presented in Table 3.

Steepness

Steepness *h* is estimated using a beta-distributed penalty on stock-specific deviations from mean *h.*

A penalty on deviations on steepness, h, as a beta-function $-\log(L_h) \sim beta(h, \alpha, \beta)$ where $\beta = \tau\mu$ and $\alpha = \tau(1-\mu)$. $\mu = \frac{(h_{prior} - h_{mini})}{h_{maxi} - h_{mini}}$ and $\tau = \frac{((h_{prior} - h_{min})(h_{max} - h_{prior}))}{\sigma_h^2} - 1$

Recruitment Deviations

The recruitment deviations are assumed to be lognormally distributed.

$$L_{Rec} = 0.5\left(\frac{\widetilde{R}_y^2}{\sigma_R^2} + b_y \ln(\sigma_r^2)\right)$$

3.2 Recruitment deviations

The contribution of the deviations in recruitment to the objective function is:

$$L_R = \frac{1}{2}\left[\sum_{y=1}^{N_y} \frac{\widetilde{R}_y^2}{\sigma_R^2} + b_y \ln\left(\sigma_R^2\right)\right] \qquad \text{(A.3.11)}$$

The second term of the recruitment deviation penalty scales according to the recruitment bias adjustment parameter which can range from 1.0 for data-rich, to 0.0 for data-poor years.

Catch and Discards

Discards are assumed to follow a t-distribution:

$$L_{2,f} = \sum_f^{A_f} 0.5\left(df_f + 1\right)\ln\left[\frac{1 + \left(d_{y,f} - \hat{d}_{y,f}\right)^2}{df_f \sigma_{y,f}^2}\right] + \tilde{\sigma}\ln\left(\sigma_{y,f}\right)$$

Equation 31

Annual catches follow a lognormal distribution, with a very small standard deviation (0.01) to nearly fit catches without error.

$$L_{7,f} = \sum_{t=1}^{N_t} \frac{\left(\ln\left(C_{t,f}\right) - \ln\left(\hat{C}_{t,f} + x\right)\right)^2}{2\sigma_{t,f}^2}$$ Equation 32

Survey Biomass

Estimates of relative abundance (biomass) from each survey are fit following a lognormal distribution for each year *y* present in the survey timeseries for fleet *f*, which are equivalent across fleets:

$$L_{surv}^{f} = \sum_{y} \frac{(ln(B_{Obs,y}^{f}) - ln(q^f B_y^f))^2}{2{\epsilon_y^f}^2} + ln(\epsilon_y^f)$$ Equation 33

Recall that the adjusted standard deviation is a constant variance term plus a time-varying term calculated externally as a part of the kriging and extrapolation procedures within VAST.

Composition Data

- A Dirichlet-Multinomial fit to age composition data from both survey and catches $-logL(\varphi,\theta|\tilde{\varphi},n) = log\Gamma(n + 1) - \sum((log\Gamma(n\tilde{\varphi} + 1) + log\Gamma(\theta n) - \log\Gamma(n + \theta n) + \sum(\log\Gamma(n\tilde{\varphi} + \theta n\varphi) + log\Gamma(\theta n\varphi)$ where *n* is the number of samples in the observations, and θ is the Dirichlet-Multinomial shape parameter pertaining to catch or survey fleet

$$L_{4,f} = \sum_{y=1}^{N_y} \sum_{\gamma=1}^{A_y} \sum_{l=1}^{A_l} n_{1,y,f,\gamma} p_{1,y,f,\gamma,l} \ln\left(p_{1,y,f,\gamma,l} / \hat{p}_{1,y,f,\gamma,l}\right)$$ Equation 34

Tables

Region	Data Type	Description & handling notes	Reference
California Current	Landings	**2 Fleets (1990-present)**: Fixed gear (Hook & Line, and Pot), and Trawl	Haltuch et al. 2019
	Compositions	**Fishery-Dependent:** Ages from all fleets (via commercial port sampling) **Fishery-Independent:** Lengths & Ages from West Coast Groundfish Bottom Trawl Survey (2003-present) Ages from Triennial survey (1980-2004)	Haltuch et al. 2019
	Indices of Abundance	**Fishery-Dependent:** Commercial CPUE series have not been included in any recent sablefish stock assessment. **Fishery-Independent:** ●Both standardized using VAST: Triennial survey (1980-2004) and West Coast Groundfish Bottom Trawl Survey (2003-present) ⁑California Current Index of Relative Abundance (1980-2018)	Haltuch et al. 2019
British Columbia	Landings	**3 Fleets (1965-present):** Commercial longline trap, Longline hook, and Trawl	Fenske et al. 2019
	Compositions	**Fishery-Dependent:** Ages from the fishery, primarily the trap sector; lengths from commercial trawl **Fishery-Independent:** Ages from trap-based Standardized Survey (1991-2009); trap-based Stratified Random Survey (2003-present)	Fenske et al. 2019; DFO (2019)
	Indices of Abundance	**Fishery-Dependent**: nominal trap fishery CPUE (1979-2009) **Fishery-Independent:** ●Standardized trap-based Standardized Survey CPUE (1991-2009); trap-based Stratified Random Survey CPUE (2003-present) ⁑British Columbia Index of Relative Abundance (1980-2018)	Fenske et al. 2019
Alaska	Landings	**2 fleets (early 1900s-present; typically cut to 1970 onward):** Fixed-gear (longline & pot) and Trawl	Hanselman et al. 2019
	Compositions	**Fishery-Dependent:** Lengths (1990-present) and ages (1999-present) from Fixed-gear fishery; occasional lengths from trawl fishery **Fishery-Independent:** Ages from longline surveys (1979-present, with some collection variability)	Hanselman et al. 2019
	Indices of Abundance	**Fishery-Dependent:** Filtered nominal CPUE scaled to area for longline fishery **Fishery-Independent:** ●Domestic Longline Survey (1979-present) and NMFS AFSC Gulf of Alaska Bottom Trawl Survey (1980-present). ⁑Gulf of Alaska Index of Relative Abundance (1980-2018) ⁑Aleutian Islands Index of Relative Abundance (1980-2018)	Hanselman et al. 2019

Table 1. Input data available for inclusion in operating model(s). ●Original treatment of survey data (i.e. in recent stock assessments used for management). ⁑New index of relative abundance standardized using VAST, which combines survey(s) from this management region across space and time.

Symbol	Description	Operating Model Treatment	Estimated? [bounds]
Model Structure			
	Number of sub areas	7	
	Number of stocks	5	
	Number of management regions	3	
	Number of fishing fleets	7 (2 – CC, 3 – BC, 2 – AK)	
	Number of survey fleets	4 (1 per management region, 2 for AK)	
	Number of fishing fleets with composition data	Ages: 3 (1 per management region) Lengths: 2 (one each from AK, BC)	
	Number of survey fleets with composition data	Ages: 5 (2 – CC, 2 – BC, 1 – AK)	
Growth			
M_a^k	Stock-specific natural mortality at age		
$L_{\infty,\gamma}^k$	Asymptotic length (cm)	Sex, stock and year specific (Table 3)	
κ_γ^k	Growth rate (cm yr^{-1})	Sex, stock and year specific (Table 3)	
σ_γ^k	Standard deviation for length at age (cm)	Sex, stock and year specific (Table 3)	
α_γ^k	Coefficient of length-weight relationship (lbs/cm)	Sex and stock specific	
β_γ^k	Allometric exponent of length-weight relationship	Sex and stock specific	
Reproduction			
h^k	steepness of the stock recruitment curve (expected proportion of R_0 at $0.2S_0$) for stock k	Estimated from beta-distribution for each stock with	
E_a^k	proportion of females at age in stock k which have reached maturity at age a	See Table X	
$\tilde{R}_y^k$	random annual recruitment deviations specific to stock k	normally distributed with mean zero and standard deviation σ_R	
σ_R	Standard deviation of recruitment deviations	log(1.4)	
R_0^k	Unfished recruitment by stock		
Catches			
$\beta_{1,2,3,4}^{y,f,\gamma,a}$	Age @ inflection point, slope @ inflection point, asymptotic selection and male offset for logistic retention curve		
$w_a^{k,f}$	stock- and fleet-specific weight-at-age of captured fish	See Table X	
a_{50}, δ	Selectivity parameters	Fleet-specific, see Table 4	
Surveys			
σ_y^f	Annual standard deviation of relative abundance by fleet	See Table 5	

$w_a^{k,f}$	stock- and fleet-specific weight-at-age of sampled fish	See Table X	
a_{50}, δ	Selectivity parameters	Fleet-specific, see Table 4	
q^f	Survey catchability coefficient		
Age & Length Compositions			
θ_C		Yes	Dirichlet-Multinominal parameter in Catch
θ_{survey}		Yes	Dirichlet-Multinominal parameter in survey
Movement			
$\mathbf{X}^{ij}$	Sub-area movement matrix	See table X.	
$\omega^{i,k}$	Initial proportions in stock (eigenvector of **X**)		
σ_{sel}	Standard deviation of selectivity		
parameters regarding aging error			

Table 2. Overview of parameters used in operating model. Acronyms referring to OM-specific regions are explained in-text and depicted in Figure 1.

Region	Sex	Period	L_{∞}^{k}	κ_{γ}^{k}	σ^{k}
C1	Fem	<2010	60.44	0.29	
C1	Fem	2010+	62.86	0.16	
C1	Mal	All years	55.11	0.28	
C2, B1	Fem	<2010	69.14	0.22	
C2, B1	Fem	2010+	67.91	0.19	
C2, B1	Mal	All years	59.04	0.21	
B2	Fem	<2010	70.15	1.29	
B2	Fem	2010+	69.21	1.18	
B2	Mal	All years	60.26	2.12	
A2, A3	Fem	<2010	74.66	0.66	
A2, A3	Fem	2010+	74.62	0.39	
A2, A3	Mal	All years	63.94	0.58	
A1	Fem	All years	81.5	0.14	
A1	Mal	All years	68.36	0.2	

Table 3. Growth parameters used in Operating Model, adapted from Kapur et al. 2019.

Mgmt. Region	Fleet Name	Fleet Type	Years	Selectivity form
AK		Survey	1980-2018	
AK		Fishery (retained)		
		Fishery (discard)		

Table 4. Survey and Fishery Fleets, years of available data, and form of selectivity curve.

Table 5. Survey values and sigmas (from data_for_ss3.csv).

		Validation Step 1: Generate & fit data without error		Validation Step 2: Recreate current assessments	
Symbol/name	**Description**	**Changes to OM**	**Changes to EM**	**Changes to OM**	**Changes to EM**
	Number of survey indices			6 (2 per area)	6 (2 per area)
X	Movement-at-age matrix			Off-diagonals set to 0; diagonal set to 1	Off-diagonals set to 0; diagonal set to 1

ω_i	Vector of initial proportion-in-area			Changed to recreate r0 from assessments	
Stock-recruit relationship			Do not estimate recruitment deviations	Generate Ry based on Sy on a regional basis	Estimate Ry based on Sy on a regional basis
R0	Virgin recruitment			Sum of assessment values for each of three regions	Estimated as sum of all three regions
h	Steepness			fixed to assessment values for each of three regions	Estimated within assessment bounds for each of three regions

Table 5. Changes to Operating Model 1 (OM1) and Estimation Model 1 made for data validation steps described in Section 5. In Operating Model validation step 1 OM1 was used with movement rates. In the Operating Model validation step 2, error terms (denoted with σ) were set to zero. A blank cell indicates no change was made to that model for that validation step.

Figures

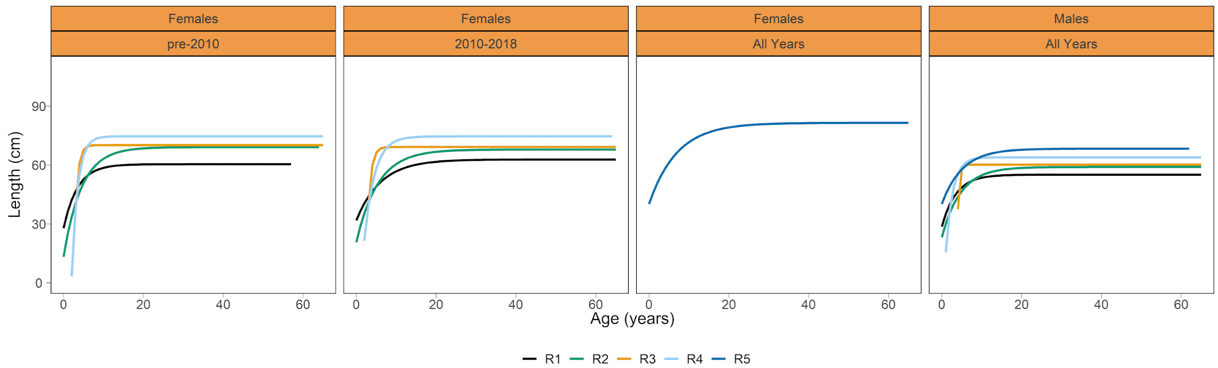

Figure 5 +. Input growth curves by stock. Labels R1-R5 correspond to light grey boxes in Figure 1 (left panel).

Figure 6. Input movement rates.

Figure 7+. Input landings histogram, selex, etc.