Description of Operating and Estimation Models for Northeast Pacific Sablefish

Kapur, M.

This document describes the Operating and Estimation Models (OM) developed for use in a Management Strategy Evaluation (MSE) of northeast Pacific Sablefish. The models is written in R (R Core Team 2019) and Template Model Builder (Kristensen et al., 2016) and is 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 accommodate one to several spatial areas, with optional movement occurring between spatial areas. The following sections describe the equations used to initialize, project and estimate the population and fishery dynamics of the Northeast Pacific sablefish (*Anoplopoma fimbria*).

1. Basic Operating Model Features

The operating model is age-structured, two-sex, and proceeds at an annual timestep (*y)*. The plus-group age *A* for the entire model is 65 years; numbers- and biomass-at-age greater than *A* are collapsed into this terminal group for all applicable data sources. Here we provide a general description of the model dynamics through time; spatial components are introduced in Section 1.6.

* 1. Growth

Length-at-age follows a von Bertalanffy growth function (Bertalanffy, 1938), the parameterization of asymptotic length growth rate and age at length 0 therein varies depending on the spatial stratification of the OM, as shown in Table 1. Errors around length-at-age are normality distributed with mean zero and standard deviation Weight-at-age is allometric with respect to weight, with parameters and .

Equation 1

Equation 2

* 1. Equilibrium and Initialization

The model is initialized based on the unfished distribution, given by natural mortality at age *Ma*  and unfished recruitment : The initial spatial distribution is described in Section 1.6.

Equation 3

Unfished female spawning biomass is given by the product of age-specific weight for individuals , the numbers at age and the maturity at age . A 50:50 male:female sex ratio is assumed.

Equation 4 .

The initial conditions leading up to the fishery also includes years with recruitment deviations, allowing an entire cohort to undergo a full life cycle of dynamics before the actual model begins. The first year of the simulation is therefore initialized with the following age distribution (Equation 3):

Equation 5

where is the global number at age, , and is a bias adjustment factor (Methot et al., 2011). are annual recruitment deviations assumed to be normally distributed with mean zero and standard deviation . For *A* years prior to the fishery, we assume = 0. See Section 1.3 for a description of in the main model period.

* 1. Reproduction

Recruitment follows a Beverton-Holt stock recruitment curve with annual deviations

Equation 6

Where is the steepness of the stock recruitment curve (expected proportion of R0 at 0.2S0). In the model we use a bias adjustment “ramp”, as an input to the model following Methot and Taylor (2011). This step is required to ensure that average projected biomass is not higher than unfished biomass; for projected years we set to 0.5 which leads to a median under unfished conditions (Equation 6)

Equation 7

where are breakpoints for the change in bias adjustment.

is the range-wide spawning biomass in each year (Equation 8). Therefore, recruitment is calculated based on the global spawning biomass and allocated to areas according to movement at age (section 1.8).

Equation 8

* 1. Movement and Spatial Distribution

Operating models consist of one through five areas (*n* denotes the total number of areas present).

The initial spatial distribution of sablefish (first simulation year) is given by the overall numbers at age (Equation 1) multiplied by , a vector of length *n* which sums to 1 and defines the fraction of fish apportioned to each area *i* in the first simulation year.

Equation 13

Movement between areas is modeled using an array **X,** which consists of up to *A* matrices withelements representing the proportion of fish at age *a* in area *i* which leave for another area *j*. For OMs in which movement is “off”, all off-diagonal values of **X** are set to zero and diagonal elements are set to one; for non spatial (i.e. panmictic) operating models (n = 1) is simply one. Movement parameters were obtained by the analysis of several decades’ tag-recapture data for sablefish (cite Luke when ready), implemented here as a saturating function of age (Equation 11).

Equation 14

where is the maximum movement rate, determines the slope towards the maximum, and is the age at 50% of maximum movement rate. There are X other base assumptions to movement (as currently specified): A visualization of the various movement paradigms is presented in Figure X. The area-specific numbers at age in each year are calculated via Equation 12 where movement and total mortality are assumed to be co-incidental.

Equation 9

Where is the age and year specific fishing selectivity, and is the fishing mortality occurring in that year (Section 1.1).

Equation 15

* 1. Fishery Catch

Age- and area- specific fishery catch is modeled using the Baranov (cite) catch equation, applied to each area, where is inferred weight-at-age (Section 1.8).

Equation 11

The operating model calculates the annual fishing mortality, based on the abundance of the fished population using Pope’s approximation (Pope, 1972; Methot and Wetzel, 2013).

Equation 12

* 1. Fleet and Survey Selectivity

We model selectivity for fisheries and scientific surveys as a function of age. We assume that fishery selectivity does not change within a year, and that the scientific survey selectivity varies among surveys and within surveys at time blocks defined by changes in sampling design and/or gear type (Table 1).

* 1. Calculation of reference points

1. Operating Model Inputs

We developed operating models under three spatial configurations. The first (OM1) mimics the current spatial management regime, where the political boundaries of Alaska (AK), British Columbia (BC) and the West Coast of the United States (here, the California Current or CC) are treated as the boundaries of discrete sablefish stocks. However, the assumption of closed stocks, independent stock-recruit relationships and other limitations of the current management framework are not replicated here; in section 5, we describe changes to OM1 made to enable the exact replication of the current management framework. The goal of OM1 is to instead represent the dynamics of a connected sablefish population that happens to have some demographic features stratified at political boundaries. The stratification of OM2 follows demographic analyses by Kapur et al. (2019), which identified five unique regions of sablefish growth corresponding to major oceanographic features (Figure 1). OM3 is a panmictic model with no spatial substructure. Below, we describe the preparation of data sources and treatment of spatially-explicit variables (where applicable) for each OM (Table 1).

* 1. Re-aggregating fishery and survey data

To facilitate data generation under these various spatial strata, catch, survey and compositional data needed to be re-aggregated to match the model’s structure. The re-aggregation of catch data to match the regions was done via:

In addition, we performed a spatio-temporal standardization of fishery independent data across all regions to create indices of relative abundance specific to each region for each operating model using the Vectorized Auto-regressive Spatio Temporal tool (VAST, Thorson 2019). This standardization is described as a case study in Thorson et al. (in press). For all OMs, the index of relative abundance generally peaks around 19XX, after which it declines substantially. This decline persists for most regions as well as the panmictic model, except for British Columbia and the California Current (OM1) and Regions 1 through 3 (OM2) which experience a slight increase since 2010 (Figure 2).

* 1. Spatially-explicit demography

We separately estimated movement (cite Luke), growth (Kapur et al. 2019) and maturity parameters using data obtained from surveys to match the spatial stratifications used in our models (Table 1).

Growth

For OM1 regional growth parameters are fixed to the estimates from the latest assessment. Briefly, growth in OM2 follows a latitudinal cline whereby sablefish obtain a higher asymptotic length L∞ at more north-western locales. For this model, we implemented a time block in growth for all regions following findings by Kapur et al. that significant differences in growth parameters are present before and after 2010. Growth parameters for the panmictic model were estimated using length-at-age data from all regions with a correction for gear-based selectivity as in Kapur et al. (2019).

Describe weight at age if regional allometry somehow.

Movement, Maturity

Describe movement and maturity findings. Describe how initial proportions-in-area were determined (likely compare from assessments ca 1960)

Reproduction

* 1. Fleet and Survey Selectivity Inputs

1. Data Generation

Fishery and survey age compositions are generated per year . For the fisher(ies), the proportion of individuals at age in the catch for fleet *f* in year *y* is found by dividing the numbers at age by the total abundance of individuals at age

Equation 17

is the abundance of individuals at age in the catch. The survey is reported as the total biomass targeted by the survey, and thus does not report area specific biomass.

Equation 18

Where is the catchability coefficient, and is the survey selectivity. We assume that the survey observes biomass with error . The standard deviation is comprised of two different values where is a constant variance, and is a standard deviation specific to the survey years.

1. Estimation Models
2. Validation of Operating & Estimation Models

We undertook two validation steps to ensure the model and estimation framework were functioning as expected. The first step (referred to as “Validation Step 1”) was to modify OM1 (Table 2) such that all data were generated without error (i.e. all values denoted by σ in Table 1 were set to zero). We then fit this data using EM1 (which matches the spatial configuration of OM1) to confirm that the estimation method could return the exact values used in the OM, and thus act as an unbiased estimator. The second validation step (Validation Step 2) addressed the desire to recreate estimated values from the independent assessments at the current management stratification. For this, we modified OM1 (Table 2) so that all three management regions were present but not connected via movement; the initial spatial structure was modified so that, when multiplied by the global , each area obtained approximately the estimated in the pre-existing assessment. Reproduction was adjusted so that instead of being a function of global spawning biomass, individual regions generated recruits based on regional spawning biomass; fish of any age did not move into or out of any area.In addition, the 3 regional indices of relative abundance were replaced by six extant standardized indices (described in table XX) as currently used in the regional assessments.

1. Tables

|  |  |  |  |
| --- | --- | --- | --- |
| **Region** | **Data Type** | **Description & handling notes** | **Reference** |
| California Current | Landings | **2 Fleets (1990-present)**:  Fixed gear (Hook and 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) | 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) | 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). May need to re-standardize using VAST, as these are currently standardized using geographic extent of Alaskan sub-areas. | Hanselman et al. 2019 |

Table 1. Real input data considered for inclusion in operating model(s).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | | **Current management** | **Demographic Breaks** | **Panmictic** |
| **Symbol/name** | **Description** | **OM1** | **OM2** | **OM3** |
| *Spatial Structure* | | | | |
|  | Number of areas | 3 | 5 | 1 |
|  | Number of fleets | 7 (2 – CC, 3 – BC, 2 – AK) |  |  |
|  | Number of survey indices | 3 (1 per region) | 5 | 1 |
|  | Number of fleets with composition data | Ages: 3 (1 per region)  Lengths: 2 (one each from AK, BC) |  |  |
|  | Number of surveys with composition data | Ages: 5 (2 – CC, 2 – BC, 1 – AK) |  |  |
| *Growth* | | | | |
| L∞ | Asymptotic length (cm) | Sex, region and period specific (Table 3) | Sex, region and period specific (Table 3) | Fem: 72.6  Mal: 40.3 |
| *k* | Growth rate (cm yr-1) | Sex, region and period specific (Table 3) | Sex, region and period specific (Table 3) | Fem: 0.29  Mal: 2.46 |
| *a0* | Age at length 0 cm | Sex, region and period specific (Table 3) | Sex, region and period specific (Table 3) | Fem: -1.47  Mal: -0.39 |
|  | Standard deviation for length at age (cm) |  | 6.2 | 14.4 |
|  | Coefficient of length-weight relationship (lbs/cm) |  |  |  |
|  | Allometric exponent of length-weight relationship |  |  |  |
|  |  |  |  |  |
| *Movement* | | | | |
|  | Maximum movement rate | NA |  | [0.1;0.75] |
|  | Slope of movement rate | NA |  | 0.5 |
|  | Age at 50% maximum movement rate | NA |  | [5;10] |
|  | Vector of initial proportions in area |  |  |  |
| *Mortality & Reproduction* | | | | |
|  | Fecundity at age |  |  |  |
|  | steepness |  |  | 0.8 |
|  | Unfished recruitment |  |  | 2276865 |
|  | Natural mortality |  |  | 0.214 |
|  | Standard deviation of recruitment deviations |  |  | 1.4 |
| *Selectivity Patterns* | | | | |
| (n = 5) | Fisheries selectivity |  |  | [12,2.5,1.5,1.2,1.6] |
| (n = 4) | survey selectivity |  |  | [1.77,0.80,1.36,1.45] |
| *Survey, Fishery and Compositional Parameters* | | | | |
| q | Catchability coefficient |  |  | 1 |
|  | Dirichlet-Multinominal parameter in Catch |  |  |  |
|  | Dirichlet-Multinominal parameter in survey |  |  |  |
|  | Survey standard deviation |  |  | 0.26 |
|  | Standard deviation of selectivity |  |  | 1.4 |
| \*parameters regarding aging error\* |  |  |  |  |

Table 2. Overview of parameters used in operating model. Columns labeled “OM1” “OM2” and “OM3” contain information on parameter setup for operating models with different spatial stratifications. Acronyms referring to OM-specific regions are explained in-text and depicted in Figure 1.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Operating Model** | **Region** | **Sex** | **Period** | ***L∞*** | ***k*** | ***a0*** |
| OM1 | CC | Fem |  |  |  |  |
| OM1 |  | Mal |  |  |  |  |
| OM1 |  |  |  |  |  |  |
| OM1 |  |  |  |  |  |  |
| OM1 |  |  |  |  |  |  |
| OM1 |  |  |  |  |  |  |
| OM1 |  |  |  |  |  |  |
| OM1 |  |  |  |  |  |  |
| OM1 |  |  |  |  |  |  |
| OM2 | R1 | Fem | <2010 | 60.44 | 0.29 | -2.15 |
| OM2 | R1 | Fem | 2010+ | 62.86 | 0.16 | -4.31 |
| OM2 | R1 | Mal | All years | 55.11 | 0.28 | -2.59 |
| OM2 | R2 | Fem | <2010 | 69.14 | 0.22 | -0.96 |
| OM2 | R2 | Fem | 2010+ | 67.91 | 0.19 | -1.96 |
| OM2 | R2 | Mal | All years | 59.04 | 0.21 | -2.34 |
| OM2 | R3 | Fem | <2010 | 70.15 | 1.29 | 2.41 |
| OM2 | R3 | Fem | 2010+ | 69.21 | 1.18 | 2.32 |
| OM2 | R3 | Mal | All years | 60.26 | 2.12 | 3.54 |
| OM2 | R4 | Fem | <2010 | 74.66 | 0.66 | 1.93 |
| OM2 | R4 | Fem | 2010+ | 74.62 | 0.39 | 1.14 |
| OM2 | R4 | Mal | All years | 63.94 | 0.58 | 0.52 |
| OM2 | R5 | Fem | All years | 81.5 | 0.14 | -4.74 |
| OM2 | R5 | Mal | All years | 68.36 | 0.2 | -4.51 |

Table 3. Growth parameters used in OM1 and OM2, adapted from Kapur et al. 2019.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | | **Current management** | **Demographic Breaks** | **Panmictic** |
| **Symbol/name** | **Description** | **EM1** | **EM2** | **EM3** |
| \*parameters regarding aging error\* |  |  |  |  |
| *Other estimated quantities* | | | | |
|  | Recruitment deviations |  |  | (n = 72) |
|  | Selectivity deviations |  |  | (n = 135) |
| (n = 52) | Fully selected fishing mortality |  |  |  |
|  | Shape parameter for steepness distribution |  |  | 0.2 |
|  | Shape parameter for steepness prior distribution |  |  | 0.1 |
|  | Shape parameter for steepness prior distribution |  |  | 0.777 |
|  | Standard deviation for steepness prior distribution |  |  | 0.117 |
|  | Shape parameter for steepness distribution |  |  | 0.2 |
|  | Shape parameter for steepness prior distribution |  |  | 0.1 |

Table 4. Overview of parameters treatment in estimation models. Columns labeled “EM1” “EM2” and “EM3” contain information on parameter setup for estimation models with different spatial stratifications. Bounds are indicated between brackets. The treatment of some parameters varied depending on the OM from which data were generated. The number of parameters, if other than 1, is indicated by *n.*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | | **Validation Step 1:**  **Generate & fit data without error** | | **Validation Step 2:**  **Recreate current assessments** | |
| **Symbol/name** | **Description** | **Changes to OM1** | **Changes to EM1** | **Changes to OM1** | **Changes to EM1** |
|  | 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 |
|  | 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.

1. Figures

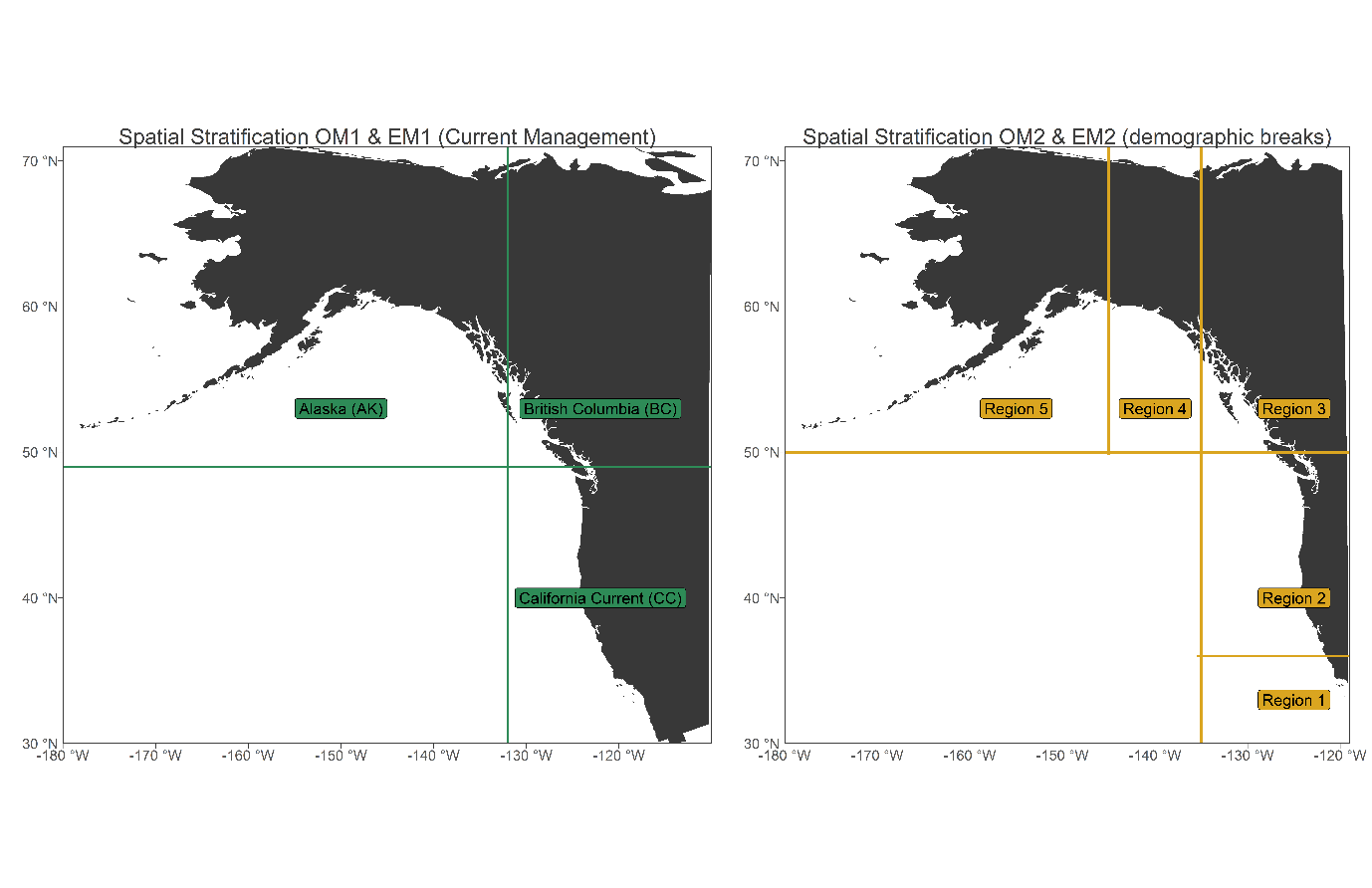


Figure 1. Map of spatial strata used for operating and estimation models 1 (left panel, green labels) and 2 (right panel, gold labels).

A close up of a map

Description automatically generated

Figure 2. Indices of relative abundance used in OM1, OM2 and OM3. All indices were generated using VAST (Thorson 2019).

Figure 3. Indices of relative abundance used in Validation Step 2. These are the most recent standardized indices available for the three management regions; data underlying these indices informed the spatio-temporal standardization presented in Figure 2 and used in the OMs for simulation purposes.

Figure 4. Plot of data used by year and source in Operating Models (SS\_datplot mimic). Bubble size indicates relative abundance of data.

A screenshot of a cell phone

Description automatically generated

Figure 5 +. Input growth curves by OM (still need to add OM1)

Figure 6. Input movement rates by OM.

Figure 7+. Input landings, selex, etc by OM.

Figure X (possibly) example of how data were collapsed for spatially mismatched EM.