Appendix 1. Halibut ABM Single-species Operating Model (OM)

The purpose of this analysis is to evaluate abundance-based PSC management alternatives for Pacific halibut in the Bering Sea. Following advice from NPFMC SSC (June 2018) we have developed a single-species, age and sex structured, simulation model with two spatial regions. The simulation model tracks the population dynamics of Pacific halibut in two areas (1) the Being Sea and Aleutian Islands (4ABCDE) and (2) the remaining distribution of Pacific halibut along the US West Coast. Here we provide a description of the simulation model and several examples of outcome sensitivity to recruitment allocation among model areas and assumed movement rates.

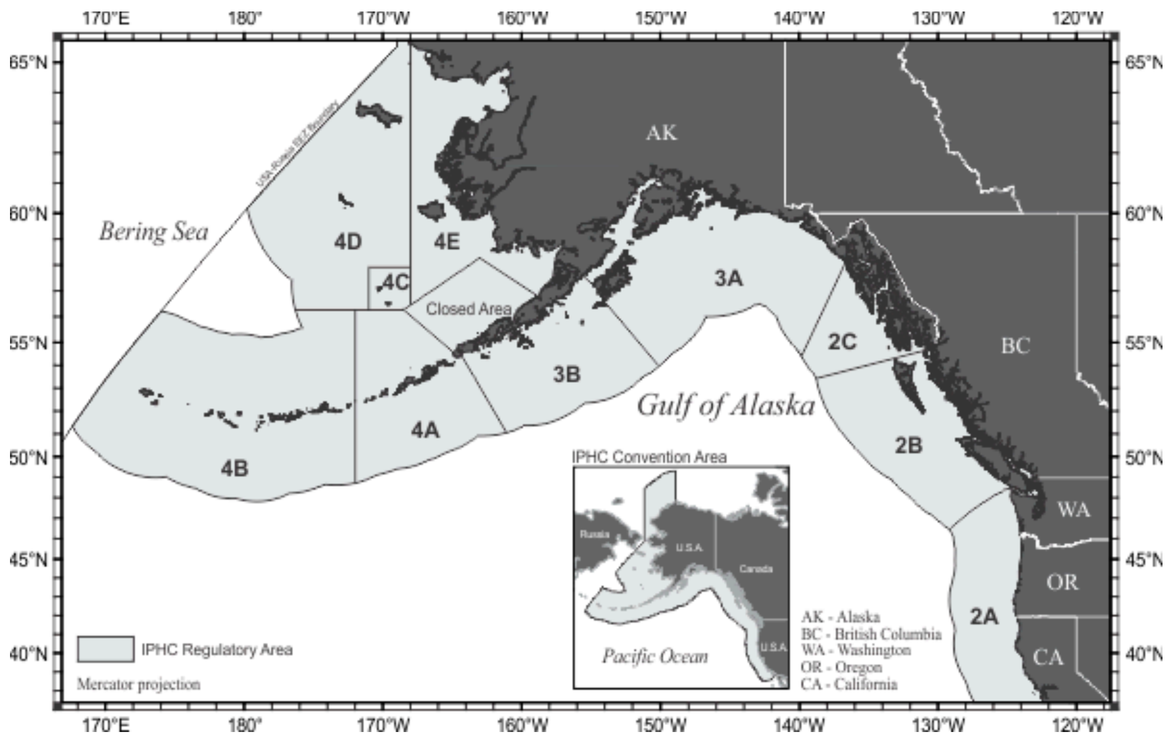

Figure 1. Map of International Pacific Halibut Commission management areas. Figure from www.iphc.int.

Model Structure

Recruitment

Pacific halibut recruitment is represented as a Beverton-Holt stock-recruitment relationship with a steepness of $h = 0.75$ and apportioned among model areas:

(1) $$R_{l,y} = \delta_l \frac{SSB_y 4hR_0}{SSB_0(1-h) + SSB_y(5h-1)} e^{\varepsilon_y - \frac{\sigma_r^2}{2}}$$

where SSB_y is the coast-wide spawning stock biomass in year y and δ_l is the proportion of recruits to each area l.

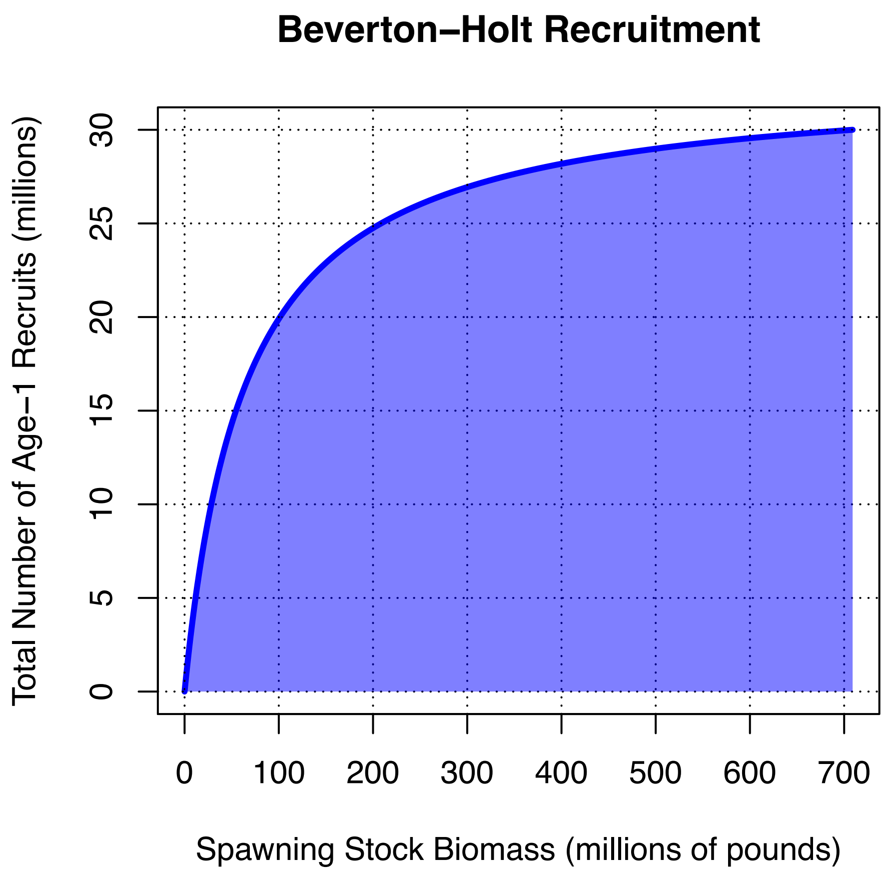

Figure 2. Total Beverton-Holt recruitment across model areas as a function of spawning stock biomass.

Random process variation in recruitment is log-normal with standard deviation of $\sigma_r = 0.6$:

(2) $$\varepsilon_y \sim Normal\left(0, \sigma_r\right)$$

Recruitment parameters were taken from the 2015 International Pacific Halibut Commission (IPHC) Coastwide Long (1888-2015) assessment model (Stewart & Martell 2016), as described in the appendix to the 2015 assessment. Spawning stock biomass is product of female biomass at age and maturity at age, summed across both areas and ages:

(3) $$SSB_y = \sum_l \sum_a N_{l,s,y,a} w_{s,a} m_{s,a} = \sum_l \sum_a B_{l,s,y,a} m_{s,a}$$

where $w_{s,a}$ and $m_{s,a}$ are the weight and maturity for each sex s at each age a, and equivalently $B_{l,s,y,a}$ is biomass at age.

A key uncertainty to be addressed is how to allocate the coast-wide halibut recruitment between the two areas, through specification of δ_l. Sensitivities to δ_l are presented at the bottom of this document.

Survival

Cohorts of halibut are tracked forward in time across ages within areas, subject to both sex-specific natural mortality M_s and annual fishing mortality by area, year, and fishing sector or gear type g. Currently two gear types are specified representing the directed fishery and PSC harvest sectors, although the PSC sector will be split between trawl and longline. Total instantaneous mortality is:

(4) $$Z_{l,s,y,a} = M_s + \sum_g v_{g,s,a} F_{l,g,y}$$

where $v_{g,s,a}$ is the gear, sex, and age-specific selectivity for fishing gear, and $F_{l,g,y}$ is the annual (y) fishing mortality by gear g and area l. Natural mortality rates (M_s) are age-independent and equal to 0.15 for females and 0.13 for males.

Halibut numbers at age are updated based upon annual recruitment and age-specific survival, with numbers at $a = 1$ calculated as:

(5) $$N_{l,s,y,a=1} = 0.5 R_{l,y-1}$$

Numbers at age for all ages $1 < a < A$ are updated by:

(6) $$N_{l,s,y,a} = N_{l,s,y-1,a-1} e^{-Z_{l,s,y-1,a-1}}$$

where A is the plus age group and equal to age 30. The plus age group in year y is equal to the surviving individuals at age A, plus surviving entrants into the plus age group:

(7) $$N_{l,s,y,a=A} = N_{l,s,y-1,a=A} e^{-Z_{l,s,y-1,a=A}} + N_{l,s,y-1,a-1} e^{-Z_{l,s,y-1,a-1}}$$

Harvest

Age-specific total catch in numbers by year is calculated as:

(8) $$C_{l,s,y,a} = \left(\frac{f_{l,s,y,a}}{Z_{l,s,y,a}}\right) N_{l,s,y,a} \left(1 - e^{-Z_{l,s,y,a}}\right)$$

with $f_{l,s,y,a} = \sum_g v_{g,s,a} F_{l,g,y}$ being the sum of fishing mortality across gear types. The gear-specific annual catch is:

(9) $$c_{l,s,y,a,g} = \left(\frac{v_{g,s,a} F_{l,g,y}}{Z_{l,s,y,a}}\right) N_{l,s,y,a} \left(1 - e^{-f_{l,s,y,a}}\right)$$

Harvest in units of biomass by gear type is the product of gear-specific catch and weight at age, summed across sexes and ages:

(10) $$H_{l,y,g} = \sum_s \sum_a c_{l,s,y,a,g} w_{s,a}$$

Movement

Movement of halibut is currently assumed to occur after removals from both natural and fishing mortality. Within the current simulation framework movement rates are implemented as age-specific transition probabilities between areas. In this way a fixed proportion of individuals of each age move from one model area to another in each year. The simulation model currently includes two areas, the Being Sea and Aleutian Islands (4ABCDE) and the remaining west coast range of Pacific halibut. The number of migrants from area i to area j in each year is:

(11) $$\tau_{i,j,s,y,a} = N_{l=i,s,y,a} \pi_{i,j,a}$$

where $\pi_{i,j,a}$ is the transition probability at age. Once the number of annual migrants is calculated, numbers in each area, of each sex and age, is updated to by adding the number of immigrants into an area less emigrants out of an area:

(12) $$N_{l,s,y,a} = N_{l,s,y,a} + \sum_{k \in areas} \tau_{i=k,j=l,s,y,a} - \sum_{k \in areas} \tau_{i=l,j=k,s,y,a}$$

Management Process

The fishing mortality rate for each gear type in each year will be approximated given the established IPHC harvest control rule and established allocation procedure across sectors and areas for the directed fishery and various alternative ABM control rules for each PSC gear type. Currently, spawning stock size is assumed to be known without error, however in future a simple assessment model to be used to add outcome uncertainty to the implementation of the current fishery management structures for both directed and PSC gear types.

Forward Simulation

Population dynamics of Pacific halibut within the two model areas are simulated over time, replicated across simulations with different random recruitment deviations. The simulation model is conditioned with a starting biomass $Bstart$ and initial biomass proportions at age in each area. In each simulation the numbers at age in the first year are calculated as:

$$N_{l,s,y=1,a} = B_{start} p_{l,s,a} / w_{s,a} = B_{l,s,y=1,a} / w_{s,a} \quad (13)$$

During each year of each simulation fishing mortality rates will be calculated based on the management process described above, based on relative stock status for the directed fishery and the values of the simulated indices used in the ABM control rules. As such fishing mortality rates by gear type differ among both years and simulations.

Key Uncertainties

At present several uncertainties remain regarding the value of specific simulation model parameters that will need to be addressed prior to implementation. The first uncertainty is the annual movement rates between the model areas ($\pi_{i,j,a}$) and whether these movement rates change across ages as fish mature and migrate. While IPHC tagging data suggest little to no movement of halibut into the BSAI area, movement rates out of the BSAI area will need to be specified. The second key uncertainty is how total recruitment is allocated between the two model areas (δ_l). Together these two quantities dictate the distribution of halibut biomass and the age structure of individuals across areas. Below we provide a several examples illustrating the sensitivity of outcomes to these two parameters, assuming no directed fishery or PSC mortality.

To explore the interaction between the assumed proportion of annual recruitment allocated among model areas and the annual movement probability out of the BSAI area we simulated hypothetical outcomes over time with random variation in recruitment and at equilibrium. Figure 3 illustrates the predicted female spawning stock biomass at age over a 100-year interval, with the same random recruitment deviations in each scenario and all recruitment allocated to the BSAI area ($\delta_{l=BSAI} = 1$). Left panels describe female spawning stock biomass at age over time with an annual movement rate out of the BSAI area of 0.01 and no movement into the BSAI, while right panels show these same simulations with an annual movement rate out of the BSAI of 0.05. Movement rates were specified as constant across ages and sexes. Simulation results indicate that the distribution of spawning stock biomass among areas is highly sensitive to the assumed movement rate out of the BSAI area.

Proportion of Recruitment to BSAI	1.0
Movement rate **out** of BSAI	0.01
Movement rate **into** BSAI	0.0

Proportion of Recruitment to BSAI	1.0
Movement rate **out** of BSAI	0.05
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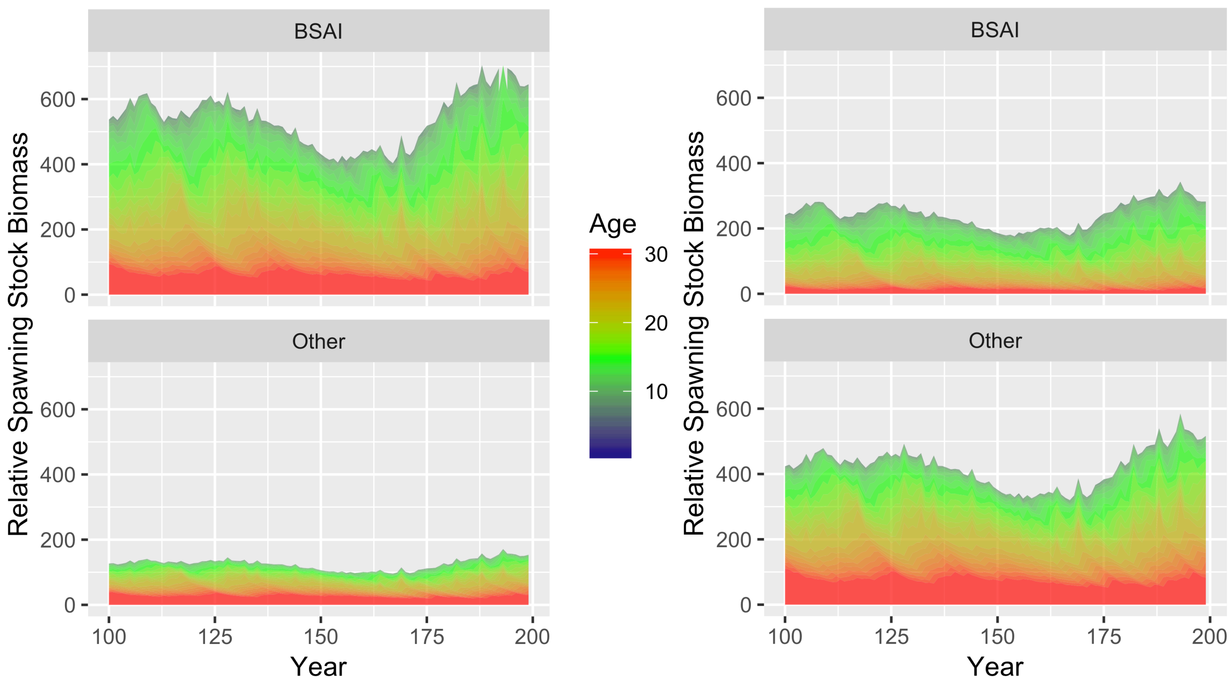

Figure 3. Simulated female spawning stock biomass at age over time under two movement scenarios, with no fishing mortality and all recruitment allocated to the BSAI area. Annual movement rates are constant across ages and sexes.

In order to illustrate the interaction between recruitment allocation and movement rates, equilibrium biomass was simulated assuming the proportion of recruitment allocated to the BSAI area was 1.0, 0.7, and 0.5, and annual movement rates out of the BSAI area of 0, 0.01, and 0.05 for both sexes and all ages (Figure 4). Simulations suggest that the equilibrium distribution of biomass among regions and the age distribution of halibut in the two areas is highly sensitive to both recruitment allocation and movement rates. With all recruitment allocated to the BSAI area and the higher movement rate (0.05 out of BSAI) total biomass is comprised of a higher proportion of younger age classes in the BSAI area compared with the remaining West Coast area.

Together these examples highlight the sensitivity of simulation outcomes to these two input parameters and suggest that the distribution of recruitment across areas and annual movement rates should be clearly defined, or a range of reasonable scenarios identified, before simulating ABM alternatives.

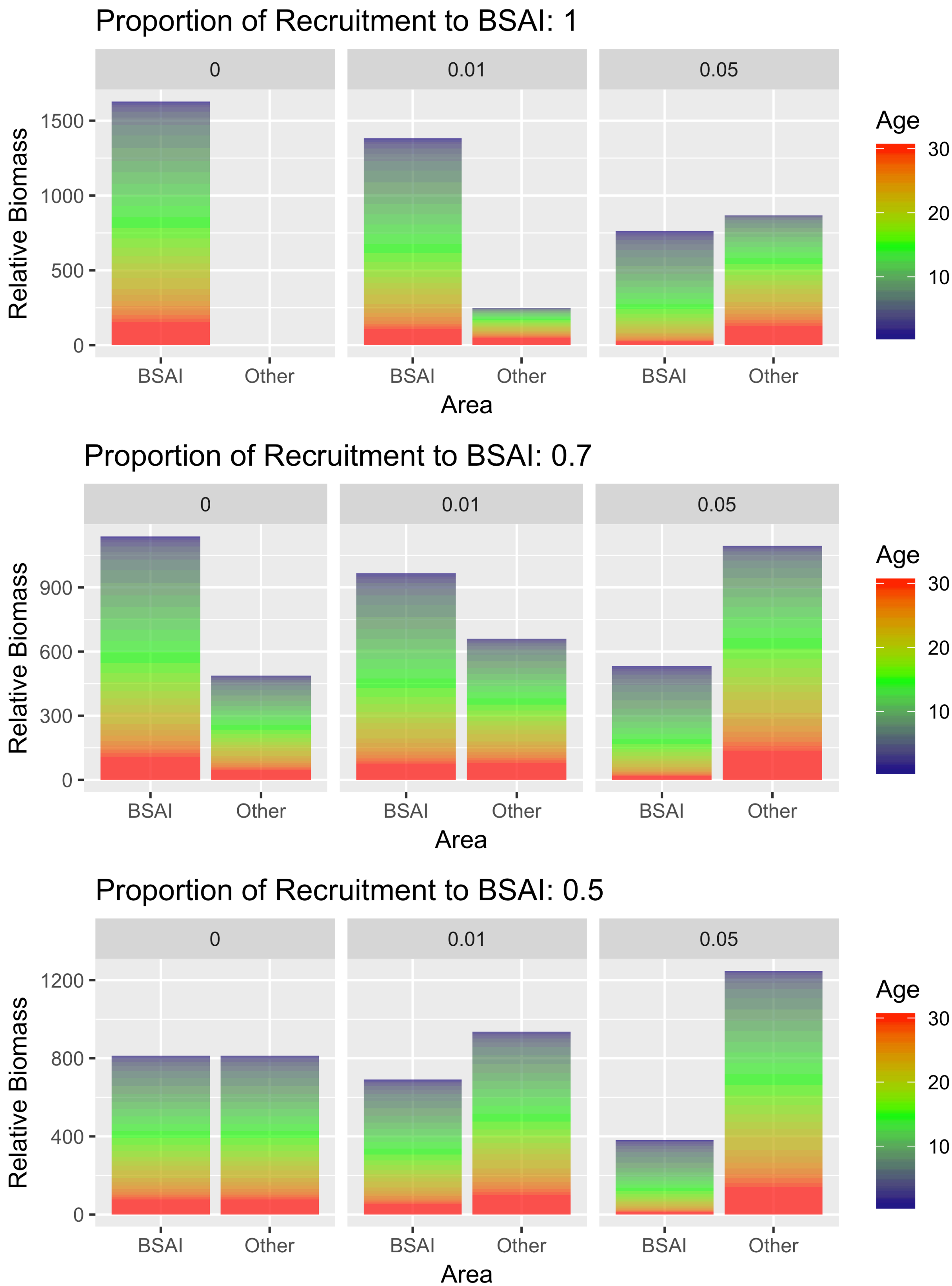

Figure 4. Equilibrium biomass at age in each model area, as a function of the proportion of recruitment allocated to the BSAI area and annual movement rates out of the BSAI. The value heading at the top of each individual panel is the assumed movement rate out of the BSAI.

Model Components

Symbols

Symbol	Description
$\boldsymbol{l}$	Area or location (Bering Sea and Aleutian Islands and remaining West Coast halibut range)
$\boldsymbol{y}$	Year
$\boldsymbol{s}$	Sex
$\boldsymbol{a}$	Age
$\boldsymbol{g}$	Gear type or fishing sector
$\boldsymbol{i}$	Area migrating **from**
$\boldsymbol{j}$	Area migrating **to**

Derived Parameters

Parameter	Description
$\boldsymbol{R_{l,y}}$	Recruitment
$\boldsymbol{SSB_y}$	Spawning stock biomass
$\boldsymbol{N_{l,s,y,a}}$	Numbers at age
$\boldsymbol{B_{l,s,y,a}}$	Biomass at age
$\boldsymbol{Z_{l,s,y,a}}$	Total mortality
$\boldsymbol{F_{l,g,y}}$	Fishing mortality rate
$\boldsymbol{f_{l,s,y,a}}$	Age and sex-specific fishing mortality rate
$\boldsymbol{C_{l,s,y,a}}$	Total catch in numbers
$\boldsymbol{c_{l,s,y,a,g}}$	Catch in numbers by gear type
$\boldsymbol{H_{l,y,g}}$	Harvest in biomass by gear type

Input Parameters

Parameter	Description
$\boldsymbol{M_s}$	Natural mortality by sex
$\boldsymbol{w_{s,a}}$	Weight at age by sex
$\boldsymbol{m_{s,a}}$	Maturity at age (note this is equal to zero for males)
$\boldsymbol{v_{g,s,a}}$	Selectivity
$\boldsymbol{B_{start}}$	Initial biomass
$\boldsymbol{p_{l,s,a}}$	Initial biomass proportions at age by area