STRAIT OF GEORGIA PACIFIC HERRING (*CLUPEA PALLASII*) STOCK UPDATE IN 2024

CONTEXT

Pacific Herring (*Clupea pallasii*) abundance in British Columbia is assessed using a spatially integrated statistical catch at age operating model framework, fit to spawn survey indices, fishery age composition data, and commercial catches. Simulations assess management procedure performance relative to the conservation objective and spawning stock biomass is assessed relative to biomass reference points including the limit reference point, candidate upper stock reference points, and B_{MSY}. A quota option is provided for the Strait of Georgia stock assessment region using a management procedure tuned to meet the conservation objective.

This Science Advisory Report is from the September 23, 2024 regional peer review on the Application of the Herring Operating Model for the Strait of Georgia.

SCIENCE ADVICE

Status

- The Strait of Georgia (SoG) major stock assessment region (SAR) is healthy.
- Spawning biomass is above the LRP with a 99% probability for each of the 5 OMs and above all candidate upper stock reference (USRs) points.

Trends

- The ensemble model estimates spawning biomass to be above B_{MSY} and all five candidate USRs for most of the historical time series.
- Spawning biomass has fluctuated above and below the unfished spawning biomass (B_0) for the last 10-years, since increasing from 2010.

Ecosystem and Climate Change Considerations

- An analysis of Herring data from 1988-2016 identified evidence of low biomass and low productivity states for three of five Pacific Herring stocks and these states were used to define a limit reference point (LRP) of $0.3B_0$ for all five stocks (Kronlund et al. 2018). The LRP is implemented in Herring MSE using a conservation objected which states to “avoid the LRP with a high probability” (minimum 75%). This LRP is more conservative than the default LRP identified in “DFO Sustainable Fisheries Framework” policy (DFO 2009).
- Incorporating density dependent mortality and time-varying recruitment accounts for predation mortality and other ecosystem effects that Herring experience at their trophic level.

- The SoG SAR is modelled using regional life-history traits and regional ecosystem pressures.

Stock Advice

- A quota option for 2025 of 11,570 metric tonnes is provided using the management procedure (MP) tuned to meet the conservation objective. This MP applies a 14% maximum target harvest rate to the 2025 forecast spawning biomass (Figure 2).

BASIS FOR ASSESSMENT

Assessment Details

The Pacific Herring Strait of Georgia (SoG) stock assessment region (SAR), is one of the five major SARs. Advice for the other major and the two minor SARs is presented in DFO (In Press).

Management strategies for SoG Pacific Herring are evaluated with a management strategy evaluation (MSE) process, which implements a spatially integrated statistical catch at age Herring (SISCAH) modelling framework (DFO 2023a). The modelling framework is fitted to historical time series of spawn survey indices, biological and fishery age composition data, and commercial fishery catches.

The SISCAH operating model estimates SoG Herring historical biomass time series from 1951-2023 with these features: density dependent mortality (DDM), an integrated surface and dive survey index, gear-specific commercial fishery timing, and a likelihood function with correlated age-compositions. Incorporation of density dependent natural mortality models potential ecosystem impacts (e.g., depensatory predation) on Pacific Herring stocks in line with DFO's EAFM (ecosystem approaches to fisheries management, Pepin et al. 2023).

A weighted ensemble of five differently-parameterized SISCAH operating models is used for management procedure evaluation. This approach was chosen to encompass the uncertainty around the two productivity parameters: stock recruitment steepness (h) in the Beverton-Holt stock-recruit function, which affects productivity at low stock sizes, and the lower limit on natural mortality (M_b), which represents the average mortality rate at high stock sizes. Uncertainty around h is especially high since abundance in SoG lacks sufficient contrast between high and low levels to inform the model to precisely estimate h. Details of the operating model ensemble are described in Appendix A.

The weighted ensemble of operating models simulated management procedures (MPs) over a 15-year projection period (2024-2038) and we present a MP tuned to meet the conservation objective (Section "Fishery management objectives") that is compliant with both the "DFO Sustainable Fisheries Framework" policy and "A fishery decision-making framework incorporating the Precautionary Approach" policy as per the Terms of Reference.

Year Assessment Approach was Approved

The SISCAH operating model framework implemented here for SoG Herring was reviewed and approved by CSAS in June 2023 (DFO 2023a).

Assessment Type

Full assessment, MSE process, with update to the management procedure and harvest control rule.

Most Recent Assessment Date

Last Full Assessment: this document (2024).

Assessment Approach

1. Broad category: Full MSE process using a single stock operating model ensemble.
2. Specific category: Index-based, state-space, statistical catch-at-age model, with a Beverton-Holt stock-recruitment relationship and density dependent time varying natural mortality.

This SISCAH modelling framework (Johnson et al. In Press) estimates SoG Herring stock status and quota calculations for 2024/25 season using the MP tuned to the conservation objective.

Stock Structure Assumption

The current assessment framework assumes BC has five discrete homogeneous SARs of Pacific Herring and does not consider between-area movement, potential straying, finer scale stock structure or uncertainty in stock structure. SoG Herring is one of five major BC Pacific Herring SARs (DFO 2024). Herring in SoG spawn primarily in March, over multiple locations with variable timing. Details of spawn timing and locations are described in the 2024 SoG data summary report. Post spawning, mature SoG Herring migrate to the west coast Vancouver Island (WCVI) where they share summer/ fall feeding grounds with herring that spawn on the WCVI. However adult herring are also reported in the Salish Sea throughout the summer months indicating some level of non-migratory life history. Previous genetic research has not identified finer-scale stock structure within the SoG management area, however, a new single nucleotide polymorphism (SNP) method (similar to Petrou et al. 2021) is currently being used to update genetic baseline data for SoG spawning areas and this may provide new insights into stock structure.

Reference Points

A suite of biological reference points are used to develop performance metrics for the MP evaluations. These metrics include a range of proportions of B_0 (unfished spawning biomass) and B_{MSY} (biomass at maximum sustainable yield). Figure 1 shows the relative position of biological reference points for SISCAH operating model 1 (OM 1, Appendix A).

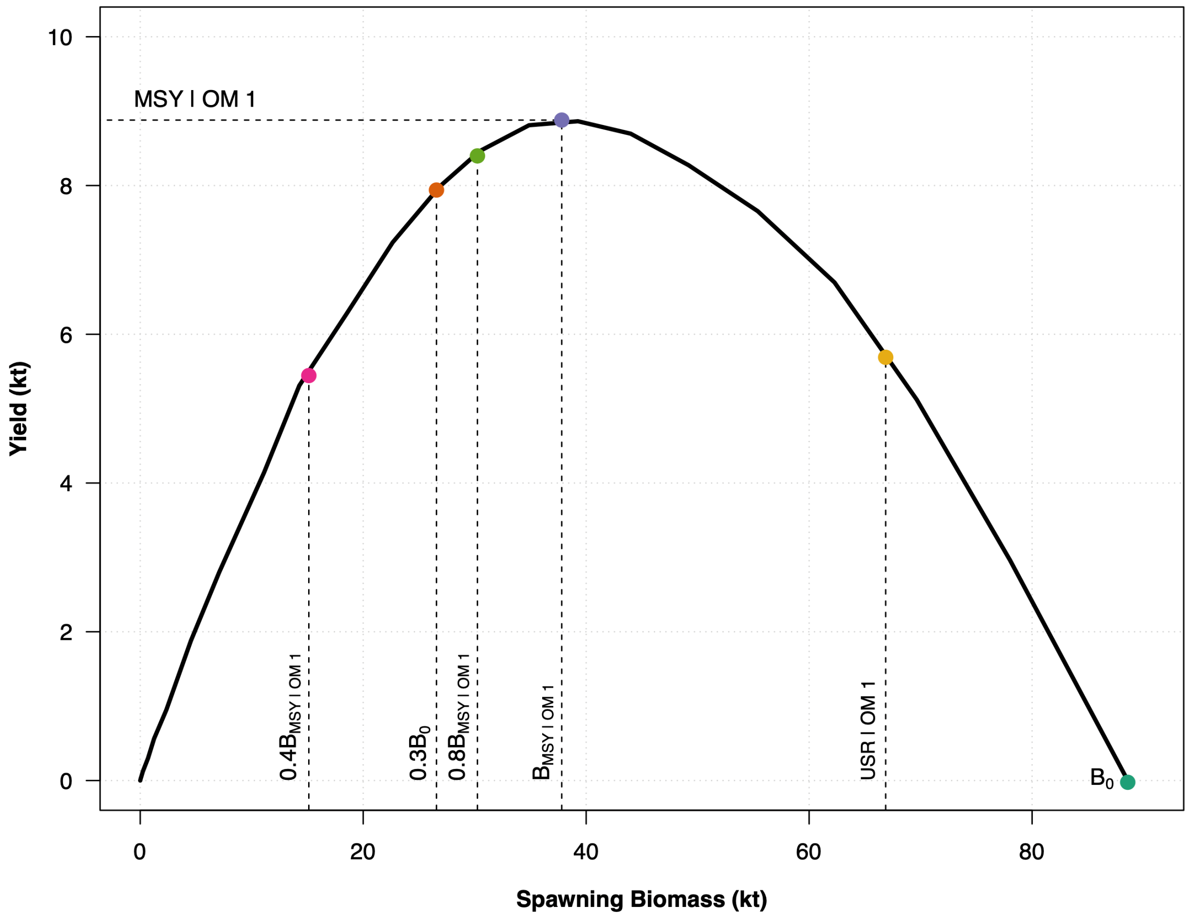

Figure 1: Strait of Georgia Herring operating model 1 (OM 1) equilibrium yield curve with respect to spawning stock biomass. The horizontal dashed line indicates OM1's estimate of maximum sustainable yield (MSY), while vertical line segments show biomass reference points including, from right to left, unfished biomass (B_0), the provisional upper stock reference (USR= 0.8$B_{1998:2007}$), optimal biomass producing MSY on average (B_{MSY}), default USR from the DFO policy (80% of B_{MSY}), the Herring limit reference point (LRP= 0.3B_0), and the default LRP from the DFO policy ($0.4B_{MSY}$).

Limit Reference Point (LRP)

The LRP for Pacific Herring is set at 0.3B_0, where B_0 is the long-term average estimated unfished spawning biomass, based on an analysis of stock productivity (Kronlund et al. 2018, Forrest et al. 2023). The LRP of 0.3B_0 for the ensemble operating model is 27.1 kt and is approximately 0.7B_{MSY} (Appendix A). This LRP is more conservative than the default LRP of 0.4B_{MSY} identified in "DFO Sustainable Fisheries Framework" (DFO 2009), as well as above the more conservative soft-limit of 0.5B_{MSY} implemented in New Zealand fisheries (Shelton and Sinclair 2008). The Herring LRP is also placed above a biomass level associated with possible serious harm (Kronlund et al. 2018) which leaves more herring available to support ecosystem processes.

Upper Stock Reference (USR)

The current provisional USR (0.8$B_{1998:2007}$), estimated using the SISCAH operating model ensemble is 67 kt. Candidate USRs were first introduced in Cleary et al. (2019) and a formal analysis of USR options was undertaken in 2022 (DFO 2023b). Following consultations, DFO Resource Management then selected and implemented $0.8B_{1998:2007}$ as a “provisional USR” for the 2022/23 IFMP where the USR was included as a performance metric in the MP evaluations. Consultations are ongoing for selection of the SoG Herring USR, therefore we include 5 USR performance metrics in this analysis: $0.8B_{MSY}$ (newly estimated this year) and all four candidate USRs presented as B_{MSY} proxies (DFO 2023b).

Target Reference Point (TRP)

TRPs have yet to be defined for SoG Herring. A biomass target objective centered on the USR has been suggested within the Herring MSE process, however final selection of a USR for SoG Herring requires additional consultations.

Removal Reference (RR)

The default maximum RR for commercially harvested fish stocks is F_{MSY} DFO (2013). RRs for SoG Herring are not currently specified because a simulation-evaluation process is instead used that directly selects an MP that meets the conservation objective, avoids the LRP with high probability, and whose harvest rate is more conservative than U_{MSY}.

Fishery Management Objectives

The primary fishery management objective (DFO 2020) is centered on the LRP and termed the conservation objective:

1. Maintain spawning biomass at or above the LRP with at least 75% probability over three Pacific Herring generations (i.e., avoid a biomass limit; $P(B_t \geq 0.3B_0) \geq 0.75$).

Three additional objectives are presented for MP evaluation once the LRP requirement is met:

1. Maintain spawning biomass at or above the USR with at least 50% probability over three Pacific Herring generations (i.e., achieve a target biomass; $P\left(B_t \geq B_{targ}\right) \geq 0.50$),
2. Maintain average annual variability (AAV) in catch below 25% over three Pacific Herring generations (i.e., minimize catch variability; AAV < 0.25), and
3. Maximize average annual catch over three Pacific Herring generations (i.e., maximize average catch).

DFO collaborates with coastal First Nations to develop area-specific objectives for Indigenous fisheries and engage with the Herring industry, government, and non-government organizations to describe broader objectives related to conservation, economics, and access.

Operating Model Stock Status

Stock status for the SoG SAR is derived from the operating model ensemble which includes five different models each representing a range of productivity levels and each with a different weighting based on previous research (Appendix A). The ensemble model stock status for 2023 is reported in Section “Assessment under MSE”.

DFO Science, Pacific Region, will be updating operating models for SoG Herring every three years, following recommendations of DFO (2023a). In 2026 SISCAH will be fit to new SoG survey and fishery data (extending the historical time series) and MPs will be re-evaluated against fishery management objectives. New objectives and performance metrics may also be added to the MSE process at this time.

In the interim years (2024 and 2025), the operating model remains constant. The estimation model is used to generate interim estimates of unfished spawning biomass, the current spawning biomass, and the one-year-ahead spawning biomass projection which are all required as inputs to the MP HCR which is used to calculate an annual quota or total allowable catch (TAC).

Harvest Decision Rule

Herring MSE presents sustainable harvest advice for SoG Herring using simulation tested MPs which identify the maximum target harvest rate for a MP tuned to meeting the established conservation objective. MPs are evaluated using a 15-year projection period and simulated performance is reported against a suite of biological reference points and fishery metrics. See Section "Projections" for a full description.

The harvest control rule component of each simulation-test MP is a "hockey-stick" shaped function defined by lower and upper control points, and a maximum target harvest rate (Cox et al. 2013). Three shapes which differ in their control points and maximum target harvest rates (Figure 2) are presented. These options were chosen because previous results showed the harvest rate as the key factor governing conservation performance for Herring. A ramp to ensure that removals are progressively reduced in order to avoid reaching the LRP is implemented, as per DFO (2009). Sustainable harvest advice for SoG Herring for 2024/25 is presented using the MP tuned to meeting the conservation objective which has lower and upper control points at 30% and 60% of unfished spawning biomass, respectively, and a maximum target harvest ($maxTHR$) of 14% (green solid line, Figure 2).

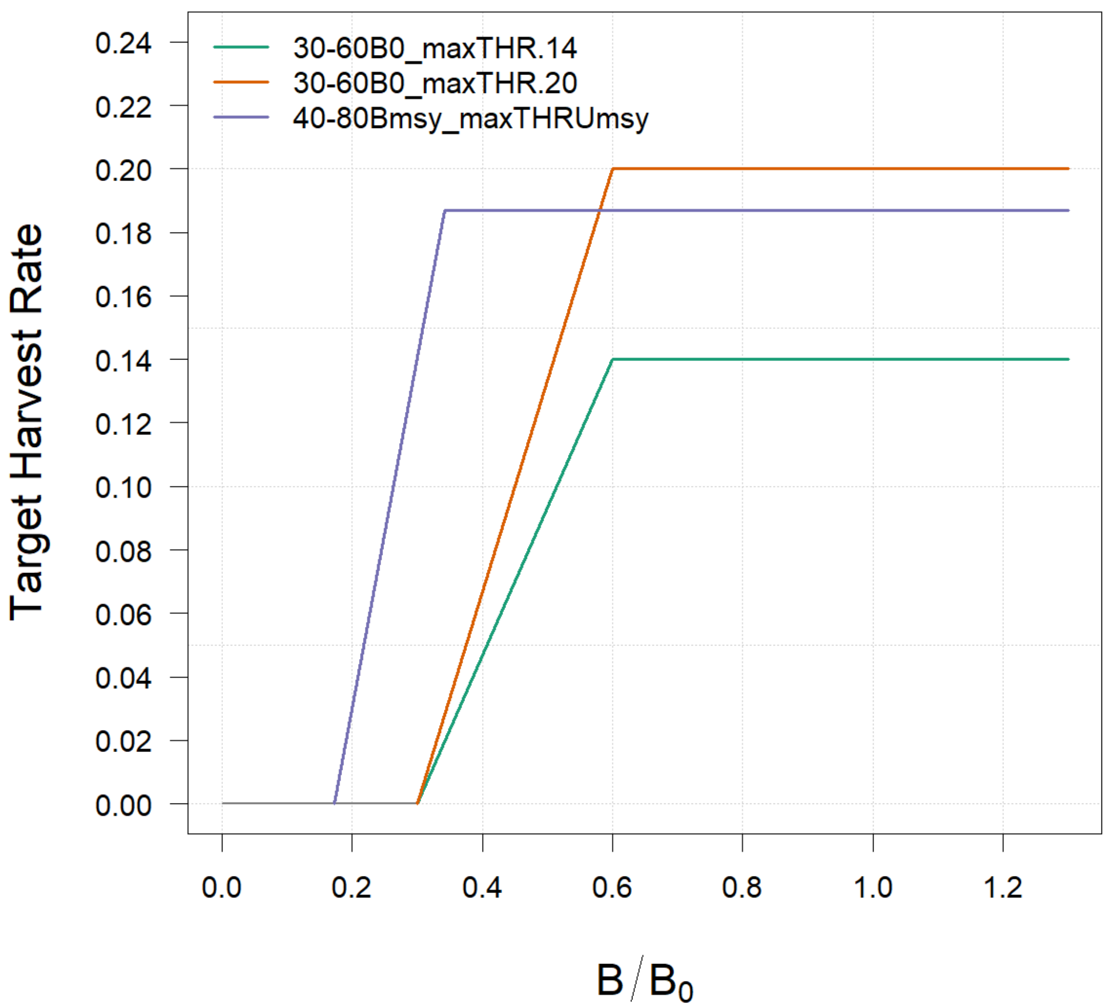

Figure 2: Three harvest control rule components of SoG management procedures (MPs). The green line represents the MP tuned to meet the conservation objective over the 15-year projection period for the ensemble operating model (with density dependent natural mortality) and maximum target harvest rate, $maxTHR$, of 14%. The red line denotes an additional hockey-stick shaped rule with the previously used 20% maximum target harvest rate and the purple line shows the DFO default harvest control rule with maximum target harvest rate set at U_{MSY} and control points at $0.4\ B_{MSY}$ and $0.8\ B_{MSY}$.

Performance Evaluation for Interim Years and Exceptional Circumstances

For each interim year three indicators: the realized catch, survey index, and estimation-model-derived spawning biomass, will be examined and compared to the range of values simulated in the ensemble operating model in order to identify exceptional circumstances. Any unusual deviations from the ensemble operating model range of uncertainty is investigated for severity and potential impacts on the performance of the MP, and consideration given to reexamining operating models and reevaluating MPs through simulation in interim years. For example, if the previous year's realized catch far exceeds the TAC prescribed by the MP or if the survey index is far below the projected index, then these results are an indication of an exceptional circumstance requiring consideration. Additional criteria for exceptional circumstances will be considered on a case by case basis. For example, if the data required to implement the MP are not available in a given year, then this would also be a form of exceptional circumstances that would need to be examined.

Data

There are three types of input data used for the Pacific Herring stock assessment: catch data, biological data, and a fishery independent survey index. The survey index is made up of two classes of surveys, surface and dive. Combining the surveys into a blended index properly accounts for years in which these survey types co-occur and is a feature of the new SISCAH model. SoG data are described in full in the 2024 SoG data summary report.

ASSESSMENT UNDER MSE

Stock status and trends for SoG Herring are represented by the ensemble operating model, using the historical time series (1951-2023) and 6 indicators (Figure 3). Ensemble operating model trends are similar to those presented for SoG Herring in previous stock assessments (e.g., DFO (2024)), with near-identical data sources and choice of indicators. Step wise comparisons are found in Johnson et al. (In Press).

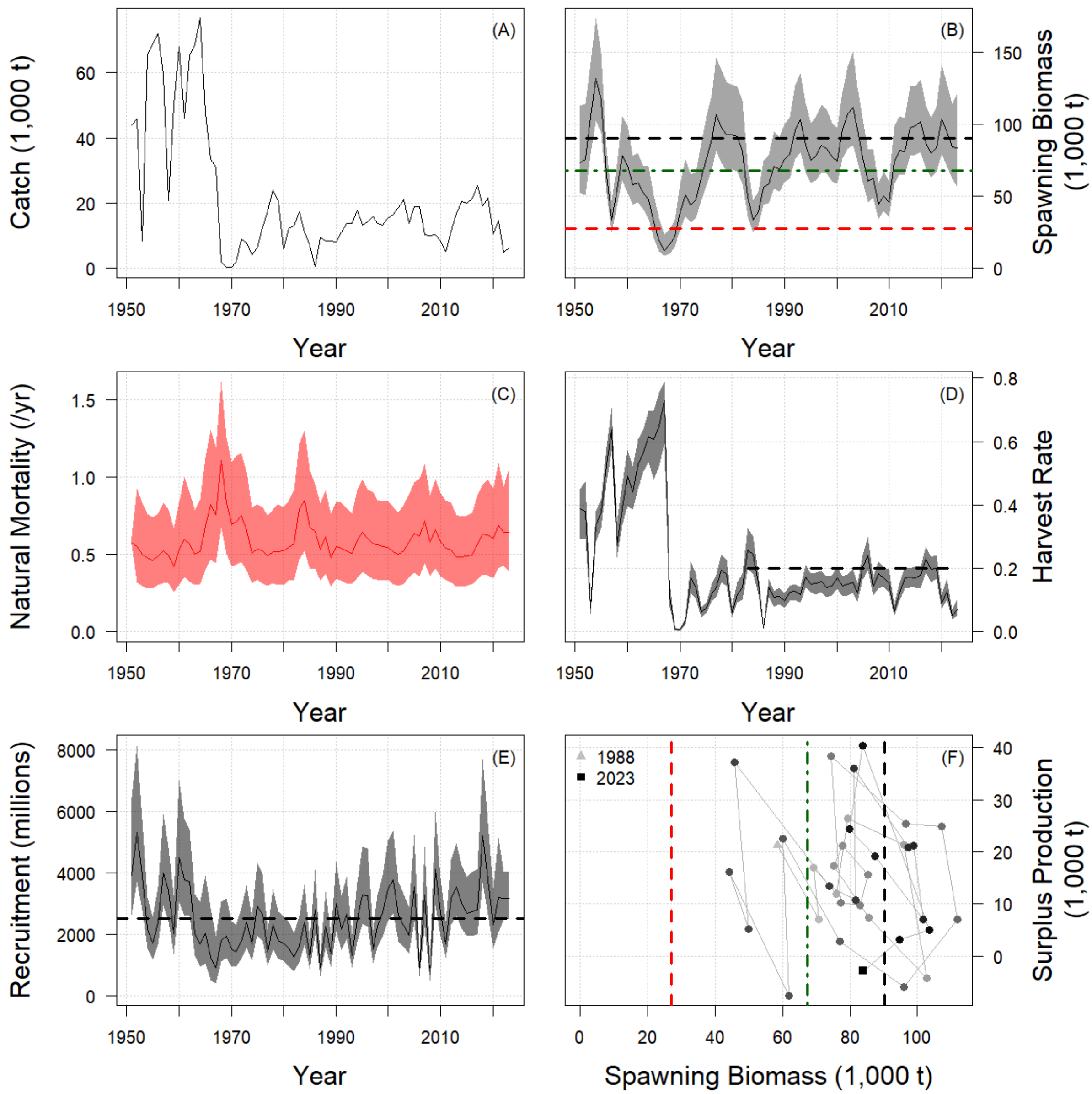

Figure 3: Estimated stock status indicators for Pacific Herring in the Strait of Georgia (SoG) major stock assessment region (SAR) from 1951 to 2023, as estimated by the ensemble operating model. All lines indicate weighted ensemble posterior median values, and where applicable, shading indicates 95% credibility intervals. (A) Catch (x 1,000 t). (B) Estimated spawning stock biomass (x 1,000 t) with limit reference point (LRP; dashed red line), productive period upper stock reference (USR; dashed green line), and unfished spawning biomass (B_0; dashed black line). (C) Estimated natural mortality rate (M /yr; red line). (D) Estimated harvest rate (U_t, black trend line), with dashed horizontal line at 20% for 1983-2022. (E) Recruitment of age-1 fish, with historical average shown as a black dashed line. (F) Estimated surplus production (vertical axis) vs. spawning biomass (horizontal axis) for 1988 (triangle) though 2023 (square) with lighter points representing earlier years. Vertical dashed lines (left to right): LRP (red), productive period USR (green), and B_0 (black).

Historical and Recent Stock Trajectory and Trends

Spawning Biomass and Status Relative to Reference Points

The estimated spawning biomass in 2023 (B_{2023}) is 84.3 kt, the unfished spawning biomass (B_0) is 90.23kt, and the stock status (B_{2023}/B_0) is 0.93 (weighted posterior medians). Spawning biomass in 2023 is estimated to be above the LRP with a 99% probability in each of the 5 OMs.

The ensemble model estimates spawning biomass to be above B_{MSY} and all candidate USRs for the majority of the historical time series (Figure 3A). Additionally, median posterior estimates of spawning biomass have remained above the LRP in all years since 1970.

Recruitment and Natural Mortality

Most of the fluctuations in estimated spawning biomass have been attributed to estimated recruitment, with lower than average age-1 recruitment in the 1970s, 1980s, and in 2007 and 2009, all of which mirror dips in spawning biomass. Above average recruitment occurred in the intervening times corresponding to biomass peaks (Figure 3E). While 2020 is one of the three highest peaks in estimated spawning biomass (since 1970), rising estimates of natural mortality (Figure 3C) since 2015 has moderated impacts of above average recruitment. Finally, opposing fluctuations in estimated recruitment and natural mortality likely contribute to increased uncertainty in spawning biomass and forecast biomass.

Spawn Biomass Production

Estimated spawning biomass production was high in 2019, indicating surplus production, and then declined each of the next three years to 2023 (Figure 3F), despite spawning biomass remaining fairly constant. This is likely due to the increasing trend in natural mortality estimates (Figure 3C).

Ecosystem and Climate Change Considerations

Ecosystem considerations are taken into account in the model in a number of ways:

1. Different than most fisheries, the biological LRP is set to a higher value than what is recommended by default (0.4B_{MSY}, DFO 2009) and 0.5B_{MSY} which is implemented in New Zealand fisheries (Shelton and Sinclair 2008). Herring's position in the lower to mid-trophic levels of the ecosystem drives some of the high variability observed in their recruitment and productivity, along with small body size and rapid growth. The higher LRP allows for a certain amount of herring to remain for predators, such as salmon and whales.
2. While predators, prey and other ecosystem indicators are not directly incorporated into models, they are modelled implicitly via time varying natural mortality and recruitment. The new density dependent mortality feature of the new operating model, SISCAH, better represents the underpinning ecosystem interactions.
3. BC Pacific Herring are managed as five stock assessment regions such that stock specific life history and abundance information are fed into the models.
4. Candidate USRs (DFO 2023b), which incorporate area specific ecosystem considerations, have been introduced to the MSE process and IFMP for consideration as (1) a biomass target objective and (2) the lower boundary of the Healthy zone. Ongoing research incorporating spatial, and other ecosystem indicators highlights DFO's commitment to an ecosystem approach to fisheries management. A summary of recent research can be found in DFO (2024).

History of Management

A maximal harvest rate of 20% has been implemented since 1983 for the SoG Herring SAR. The realized harvest rate has mostly hovered below this rate since then with reduced harvest rates applied for the past few years (Figure 3, panel D). Since 2015 the selection of annual harvest rates has been informed by MP simulation testing.

Projections

Interim Year Update for 2024

For 2024, the estimation model estimates spawning biomass, $\hat{B}_{2024}$, = 81.02 kt (maximum likelihood estimate), with stock status ($\hat{B}_{2024}/\hat{B}_0$) = 0.78. The time series of maximum likelihood estimates from the estimation model are presented in Figure 8.

Application of MP for 2025

We simulation tested three MPs, each with hockey-stick shaped harvest control rules (Figure 2). The MP with lower and upper control points at 30% and 60% of unfished spawning biomass, respectively, and a maximum target harvest rate of 14% meets the conservation objective and is compliant with both the “DFO Sustainable Fisheries Framework” policy and the “Precautionary Approach” (DFO (2009)), as per the Terms of Reference.

In the absence of fishing, spawning biomass in 2025 is estimated to be $\hat{B}_{2025} = 82.6$ kt (maximum likelihood estimate), with stock status ($\hat{B}_{2025}/\hat{B}_0$) = 0.79. Given that the spawning biomass is above the harvest control rule’s upper control point of $0.6B_0$, the maximum target harvest rate of 14% is recommended by the MP, resulting in a total allowable catch of 11.57 kt. This is shown graphically in Figure 4.

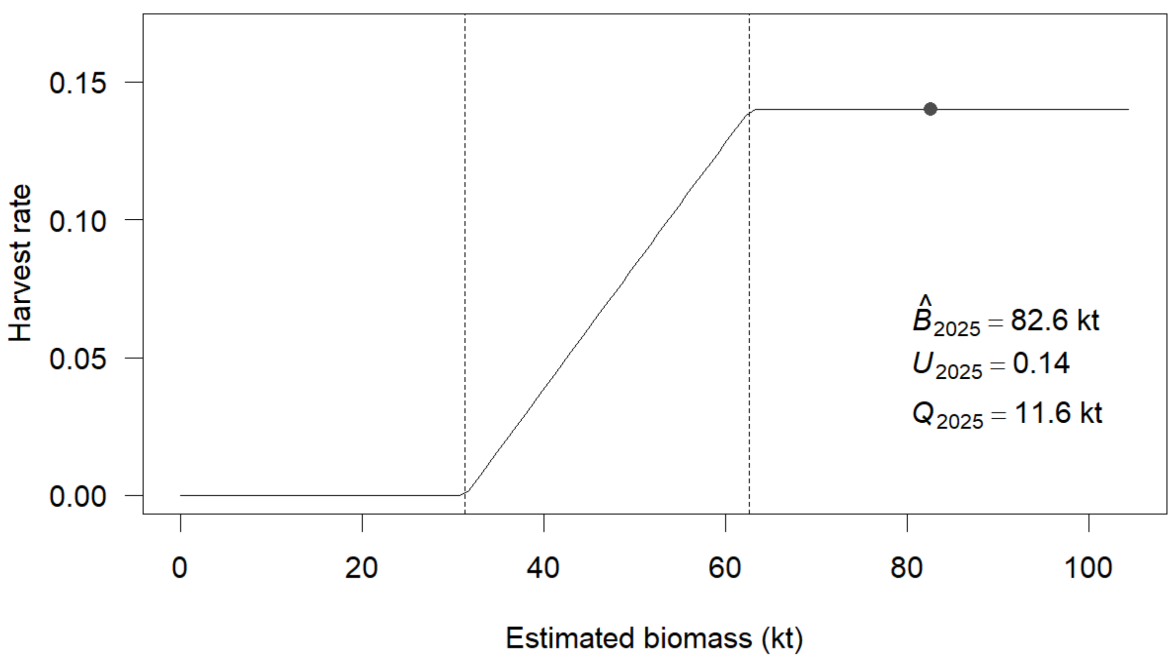

Figure 4: Strait of Georgia (SoG) Pacific Herring management procedure harvest control rule (HCR; line), showing forecast spawning biomass (kt) in 2025 ($\hat{B}_{2025}$, point), and associated harvest rate U_{2025} and total allowable catch (TAC (kt); Q_{2025}).

Performance Evaluation for Interim Years and Exceptional Circumstances

All routine forms of Herring fishery monitoring data were collected in 2024 and show the population is behaving within operating model expectations. The most recent spawn index falls within the range of uncertainty that was simulated in the MSE projections (Figure 5). Also, catch in 2024 was considerably lower than the simulated catch in the MSE projections (i.e., from the MP tuned to meet the conservation objective) due to quota being set using a 10% harvest rate for 2023/24 season.

Model mis-specification is evaluated visually by comparing catch and spawn index values within the central 95% of the 2023 ensemble operating model simulations. There is no indication of operating model mis-specification (Figure 5).

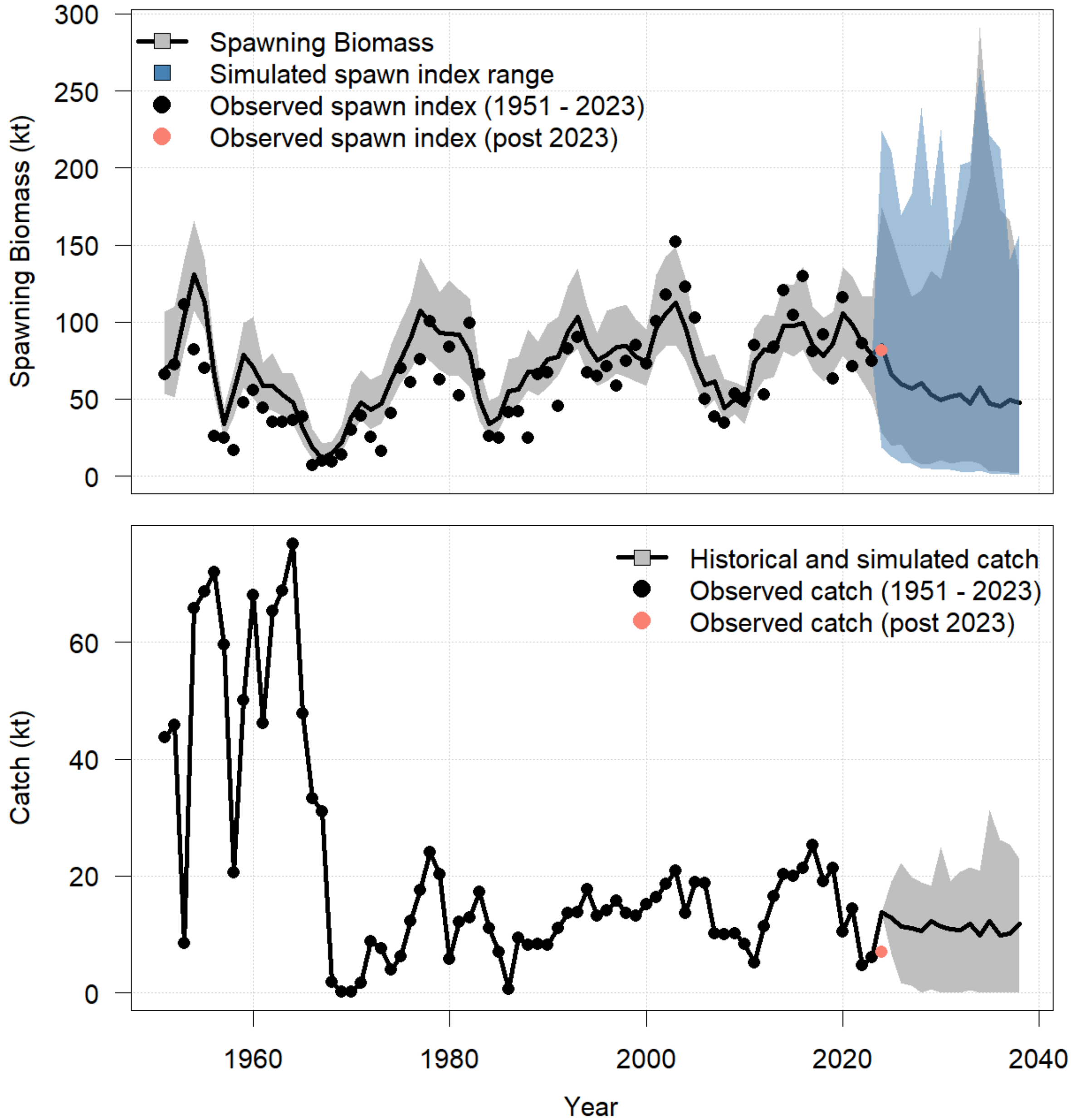

Figure 5: Evaluation of exceptional circumstances and operating model mis-specification: graphical comparison of simulation envelopes from the ensemble model (1951-2023) and catch and spawn index data from interim year (2024). Panels show the central 95% of projected simulated data, including spawn index data (top) and catch (bottom) from the 2023 weighted ensemble SoG operating model. Forward projections in time (15-years) represent the maxTHR0.14 MP. Realised data are overlaid as points for the history (black) and projection years (red).

BYCATCH

Some fisheries and aquaculture activities in BC cause incidental mortality to Pacific Herring. Similar to FSC, and recreational catch, data on incidental mortality is not directly included in the assessment process however it is indirectly accounted for in the annual estimates of natural mortality and is considered minor relative to commercial harvest.

PROCEDURE FOR INTERIM YEAR UPDATES

Once a harvest control rule is chosen through the MSE process, that harvest control rule defines the maximum possible removal rate given the objective(s) until the next MSE cycle. The recommended MP for the SoG SAR is model-based with a harvest control rule that depends on annual estimates of projected spawning biomass ($\hat{B}_{Y+1}$) and unfished spawning biomass ($\hat{B}_0$). These estimates are obtained using an estimation method (EM) and for SoG Herring, the EM is a spatially integrated statistical catch at age Herring (SISCAH) model with density independent M (DIM SISCAH). This EM was selected because it's performance was similar to the DDM formulation and it is less computationally intensive for interim updates.

SOURCES OF UNCERTAINTY

Sources of uncertainty include those surrounding both the data and the model estimations. That being said, Herring operating models are built on a data rich environment and uncertainty is well-accounted for in the model.

Research Recommendations

The parameters of the SoG ensemble model are currently calculated as a weighted average of the five operating models. Future work could involve generating a single weighted posterior from the five OMs from which model parameters can be calculated. This approach would support a shift to reporting management outputs as median posterior density values, rather than currently used maximum likelihood estimates.

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Bryan Rusch	DFO Resource Management	Subcommittee member
Sarah Hawkshaw	DFO Science	Reviewer
Chris Rooper	DFO Science	Chair
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APPENDIX A

This appendix summarises closed loop simulations evaluating candidate management procedures for the Strait of Georgia (SoG) Herring fishery. SoG Herring is the first BC Herring fishery to use the new Herring operating model framework, named the Spatially Integrated Statistical Catch-at-Age Herring Operating Model (SISCAH-OM). Although there are several differences between SISCAH and the previous Herring assessment and operating models, the main difference in SISCAH-OM is the ability to model density dependent mortality (DDM), where natural mortality is higher when biomass is lower (Johnson et al. In Press).

Results from an ensemble of five SISCAH-OMs were weighted to incorporate uncertainty in future productivity while evaluating candidate MPs identified in the Herring management strategy evaluation (MSE) process. We first summarise the simulation approach, and then present results with some brief discussion of the management implications.

Simulation Approach

Operating models

To take into account uncertainty in productivity at high and low stock sizes five SoG Herring operating models where chosen. Productivity at high stock size is influenced by the M_b parameter, which represents the average mortality rate at very high biomass (generally above unfished levels). At low stock size, productivity is more influenced by the stock-recruit relationship's steepness parameter h, which is the ratio of recruitment at 20% of unfished biomass to the unfished recruitment R_0. Overall h is better estimated for stocks where the history includes recovery from very low stock sizes. Since this isn't the case for SoG, we capture some of the uncertainty around M_b and h by considering operating models with different values for those parameters. First we used an established value of $h = 0.70$ (Cleary et al. 2019) and then used a likelihood profile approach to estimate operating model parameters across a grid of a M_b values. A likelihood profile is obtained by plotting negative log likelihood values estimated by SISCAH at each grid point, which shows the minimum value (i.e., the value most in agreement with the data) occurs when $M_b = 0.562$ (Figure 6). The same likelihood profile is used to choose the outer range of $M_b = 0.532$ and $M_b = 0.584$, which have equal likelihood values and bound the minimum of $M_b = 0.562$ (Figure 6). Finally, two additional operating models are obtained using the optimal $M_b = 0.562$ value and varying stock-recruit steepness to a lower level of $h = 0.65$ and an upper level of $h = 0.75$, based on ranges observed in forage fishes (Myers 2001; Hsu et al. 2024).

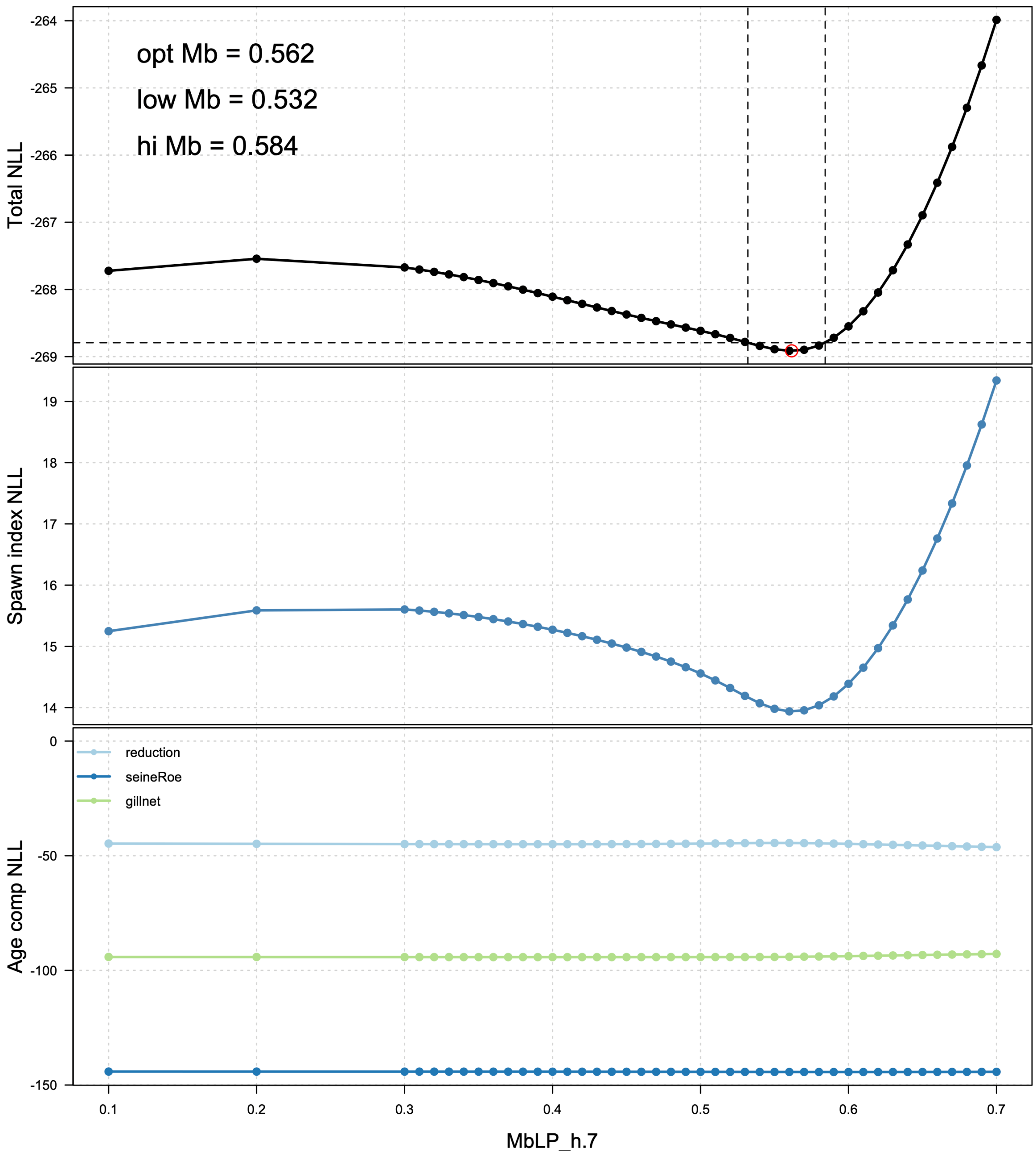

Figure 6: Fishery monitoring data likelihood function profiles relative to a range of natural mortality asymptotic lower limit (M_b) parameter values. The red point shows the most likely value, while the two vertical dashed lines show two values with equal likelihood chosen to bound the central OM1. All SISCAH model fits here have a steepness value of $h = 0.7$.

The above process creates a cross design (Table 1) of operating models. The ensemble of operating models is then combined via weighted averaging to estimate biomass, fishery reference points, and current stock status relative to those reference points. The central OM (called OM1, $M_b = 0.562$ and $h = 0.7$) is given the highest weighting of 0.34, since it is believed to be the most likely and the remaining weight of 0.66 is equally split among the other operating models (OM2 - OM5) giving a weight of 0.165 for the remaining models. Then, model parameters θ and derived quantities are found via a weighted average, e.g.,

$$\theta_{ens} = 0.34 \cdot \theta_{OM_1} + 0.165 \cdot \sum_{k=2}^{5} \theta_{OM_k},$$

where θ_{ens} is the ensemble weighted average of the parameter values θ_{OM_k} from operating model $k = 1,\ldots,5$.

For all operating models, we report leading OM parameters, current biomass, current stock status relative to unfished biomass, and MSY based reference points (Table 1). The final column also gives the weighted ensemble value of the posterior mean values from each OM.

Table 1: SISCAH-OM life-history and management parameter values from the 5 operating models (OMs 1 - 5) for stock-recruit steepness (h), asymptotic lower limit on depensatory M (M_b, /yr), unfished biomass (SB_0, kt), unfished recruitment (R_0, 1e6), unfished mortality (M_0, /yr), mortality depensation rate (m_1), time-averaged mortality ($\overline{M}$, /yr), surface survey design catchability (q_s), spawning biomass in 2023 (SB_{2023}/SB_0), stock status ($P(SB_{2023} > 0.3SB_0)$), spawning biomass at maximum sustainable yield (SB_{MSY}, kt), harvest rate targeting maximum sustainable yield (U_{MSY}), maximum sustainable yield (MSY), upper stock reference (USR, kt), harvest rate targeting the upper stock reference (U_{USR}), equilibrium yield at the upper stock reference (Y_{USR}), harvest rate associated with negative production and higher risk of extirpation (U_{Crash}). Uncertainty is shown as the 95% credible interval where estimates could be drawn from posterior samples (indicated by two parenthetical values), or half the interquartile range where estimates were drawn from 200 year simulations (one parenthetical value).

	OM 1	OM 2	OM 3	OM 4	OM 5	Ensemble
h	0.70	0.65	0.75	0.70	0.70	0.70
M_b	0.562	0.562	0.562	0.532	0.584	0.560
M_0	0.58 (0.56, 0.65)	0.58 (0.56, 0.66)	0.58 (0.56, 0.64)	0.57 (0.53, 0.66)	0.6 (0.58, 0.66)	0.58
m_1	4.52 (2.43, 7.42)	4.58 (2.33, 7.85)	4.52 (2.52, 7.77)	3.92 (2.03, 6.78)	4.84 (2.64, 8.01)	4.48
$\overline{M}$	0.6 (0.57, 0.63)	0.6 (0.57, 0.64)	0.6 (0.57, 0.64)	0.59 (0.56, 0.63)	0.61 (0.58, 0.64)	0.6
q_s	0.7 (0.57, 0.86)	0.7 (0.56, 0.86)	0.71 (0.57, 0.85)	0.72 (0.58, 0.88)	0.69 (0.55, 0.84)	0.7
q_d	1 (1, 1)	1 (1, 1)	1 (1, 1)	1 (1, 1)	1 (1, 1)	0.99
q_{blend}	0.86 (0.79, 0.93)	0.86 (0.79, 0.93)	0.86 (0.8, 0.93)	0.87 (0.8, 0.94)	0.85 (0.78, 0.92)	0.86
R_0	2145.64 (1671.28, 2753.85)	2150.36 (1677.67, 2750.14)	2120.51 (1684.48, 2658.85)	2001.35 (1579.99, 2519.71)	2263.97 (1777.08, 2874.07)	2137.99
B_0	88.58 (36.93)	88.25 (40.18)	92.51 (37.14)	91.54 (42.55)	92.05 (36.67)	90.23
B_{2023}	84.54 (55.46, 122.08)	84.35 (56.53, 122.32)	84.64 (54.64, 121.94)	84.56 (56.45, 119.75)	83.36 (54.37, 118.02)	84.33
B_{2023}/B_0	0.95 (0.63, 1.38)	0.96 (0.64, 1.39)	0.91 (0.59, 1.32)	0.92 (0.62, 1.31)	0.91 (0.59, 1.28)	0.93
$P(B_{2023} > 0.3B_0)$	0.99	0.99	0.99	0.99	0.99	0.99

	OM 1	OM 2	OM 3	OM 4	OM 5	Ensemble
B_{MSY}	37.81 (13.27)	44.71 (17.15)	34.48 (12.89)	43.68 (18.23)	36.35 (15.32)	39.13
U_{MSY}	0.185 (0.077)	0.122 (0.066)	0.261 (0.079)	0.145 (0.063)	0.229 (0.072)	0.19
MSY	8.876 (6.578)	6.480 (5.560)	12.537 (8.005)	7.626 (6.113)	11.329 (7.497)	9.28
U_{USR}	0.078 (0.102)	0.060 (0.084)	0.099 (0.123)	0.077 (0.098)	0.096 (0.117)	0.08
USR	67.18 (60.08, 75.49)	67.37 (60.38, 76.1)	67.46 (60.7, 75.8)	66.29 (59.15, 75.4)	68.4 (61.21, 77.83)	67.31
Y_{USR}	5.774 (7.848)	4.390 (6.444)	7.511 (10.040)	5.627 (7.455)	7.402 (9.393)	6.08
U_{Crash}	0.279 (0.097)	0.166 (0.115)	0.419 (0.095)	0.261 (0.074)	0.316 (0.112)	0.29

Management Procedures

Management procedures are evaluated using three components: data, the SISCAH ensemble operating model, and the particular harvest control rule. Fifteen year simulations are used to produce performance metrics which are used to evaluate the MP. This procedure is recommended to occur every three years, or sooner if required under an exceptional circumstance.

For interim years, a simpler estimation model (EM) using a density-independent M (DIM) random walk formulation is used to estimate the input signal to the HCR and then calculate the annual TAC (DFO 2023b).

The DIM EM is similar to the previous model used for Herring assessments and setting TACs prior to 2023, except that the previous model used a spline with 16 nodes instead of a simple random walk to estimate time-varying M. The EM provides annual estimates of unfished spawning biomass and a 1-year ahead forecast of spawning biomass. It is worth noting that when using a model-based approach for the EM it should not be treated as a full stock assessment, and rather, it should be considered as an algorithm that generates the input signal to the HCR.

Using a DIM EM is appropriate for setting up the MSE as it allows more computational resources to be focused on evaluating population dynamic complexities in the OM, with a simpler EM focused on generating annual TACs.

SoG Herring, a “hockey-stick” shaped function defined by lower and upper control points, and a maximum target harvest rate was used in the MP (Cox et al. 2013). When biomass is estimated to be below the lower control point the rule sets the harvest rate to zero. Between control points, the harvest rate is a linear ramp from zero to the maximum harvest rate, and above the upper control point the rule sets harvest rates to the maximum target harvest rate, called $maxTHR$. This report shows results for three MPs with the maximum target harvest rate set to either the currently recommended 14% (tuned to meet the conservation objective), the formerly recommended 20%, or U_{MSY} (DFO 2009,Figure 2, Table 2).

Finally, after the three year cycle (e.g., in 2026) the operating model is fully updated with new data and comprehensive performance evaluation of MPs is again undertaken.

Performance metrics

First, MPs are quantitatively evaluated against the conservation objective (the primary management objective):

1. $P(B_t > 0.3B_0) \geq 0.75$, or avoid the limit reference point (LRP) with high probability over three Herring generations.

Next, MP performance is examined using additional metrics of biomass and yield, which reflect three additional objectives described in Section “Fishery management objectives”.

To help fishery managers understand trade-offs among biomass and yield, additional quantitative performance metrics are estimated. These metrics do not have a minimum or target value like objectives, but give greater detail on biomass and yield outcomes of each MP over the 15-year simulation.

1. $P(B_t > B_{MSY})$: The probability that biomass is above B_{MSY}.
2. $P(B_t > 0.6B_0)$: The probability that biomass is above $(0.6B_0)$
3. $P(B_t > \overline{B}_{prod})$: The probability that biomass is above $(\overline{B}_{prod})$, also called the provisional USR.
4. $P(U_t > U_{MSY})$: The probability that the effective harvest rate is above U_{MSY}.
5. $\overline{C}$: Median (over replicates) of the average (over years) total landings.
6. AAV: Average annual variation in catch, or the mean percentage difference in catch from year-to-year.
7. $\overline{B_t/B_0}$: Average biomass depletion from 2024 - 2038.
8. B_{2038}/B_0: Median biomass depletion in 2038.
9. B_{2038}: Median biomass in 2038.

Performance metrics are estimated via the following closed loop feedback simulation algorithm:

1. For each operating model, initialize a pre-conditioned simulation model for the period 1951 to 2023 based on a random draw from the operating model posterior distribution;
2. Project the SoG Herring DDM operating model into the future one year at a time. For each year in the projection, apply the following:
    a. Update the time series of commercial catch, catch-at-age, and blended spawn survey data up to time-step t for the stock assessment component of the MP;
    b. Use an estimation model (a statistical catch age model with density independent M) to produce a 1-year ahead forecast of spawning biomass depletion;
    c. Determine the target harvest rate associated with the forecast depletion using a harvest control rule;
    d. Using this target harvest rate calculate the total allowable catch from the 1-year ahead biomass forecast;
    e. Update the simulated DDM operating model Herring population with incoming recruitment from the DDM stock-recruit curve with recruitment process errors; density dependent natural mortality; and fishing mortality corresponding to the total allowable catch in the previous step.

f. Repeat steps 2.i - 2.v until the projection period ends (2038).

3. Repeat Step 1. and Step 2. 99 more times;
4. Calculate quantitative performance statistics across all 100 replicates.

Discussion

Selecting a MP by tuning to meet the conservation objective leads to a recommended harvest control rule with a 14% maximum target harvest rate. If applied annually, the average yield, using recent 20-year average allocation among gear types, is 10 - 12 kt (Table 2, Figure 7). Selecting an MP with a maximum target harvest rate at or below 14% will achieve the conservation objective.

Although additional fishery objectives are presented in Section “Fishery management objectives”, these are not a full suite of objectives for SoG Herring and are not currently used for further MP tuning. If this was undertaken, for example, tuning the MP to meeting a biomass target of $0.6B_0$, the maximum target harvest rate and average annual catch would be lower.

Table 2 includes additional MPs with maximum target harvest rates of 20% and U_{MSY}, which reflect previously implemented harvest rate and the maximum reference removal (RR) defined in DFO (2009).

However, when tested using an operating model that implements a density dependent formulation of time-varying natural mortality, neither of these harvest rates meets the conservation objective when included in a ramped harvest control rule. Thus probabilities and performance statistics do not appear in the Table 2. See Figure 2 for HCR shape for these additional simulation tested MPs.

Simulation-evaluation of MPs show that harvest rates need to be lower than U_{MSY} to avoid the LRP with high probability (75% or more). This is due to the LRP being set at a higher level, roughly 70% of B_{MSY} estimated from the ensemble operating model (Table 1, Figure 7). For comparison, the default LRP in Canadian fisheries policy (DFO (2009)) is 40% of B_{MSY} or some proxy, although this is largely applied to longer lived groundfish species with less variable recruitment and lower predation pressures.

The EM implements a density independent M model and appears to overestimate biomass in the 1-year ahead forecast. This positive bias can result in an effective harvest rate that exceeds the maximum target harvest rate (Figure 7, bottom row). However this is accounted for in the simulation. Harvest that occurs as a result of the overestimated projected biomass is subtracted from the simulated actual biomass. Thus the MP is simulation-tested with this known positive bias and the probabilities reflect the likelihood of the MP being able to meet the conservation objective.

Table 2: Performance statistics for MPs differing by maximum target harvest rates indicated in column 1. Objectives that are met by an MP are indicated by 'Y', otherwise 'N'. $\overline{B}$ is the average biomass from 1951 to 2023. Subscript t indicates the years 2024 - 2038. Biomass B and Harvest Rate U metrics (columns 2 - 8) are the probability that B_t or U_t respectively is greater than the value indicated in the header. Average catch $\overline{C_t}$ and final biomass B_{2038} are in biomass units (kt), and final year B_{2038}/B_0 and average projection year $\overline{B_t/B_0}$ stock status is biomass depletion relative to unfished biomass. For SoG, B_{prod} is calculated as 80% of the average spawning biomass during the productive period, $0.8B_{1998:2007}$. Note: The bottom two rows are included to show these MPs do not meet the conservation objective.

Max HR	$0.3B_0$	B_{MSY}	$0.4B_0$	$0.5B_0$	$0.6B_0$	$\overline{B}_{prod}$	$\overline{B}$	U_{MSY}	$\overline{C_t}$	AAV	$\overline{B_t/B_0}$	B_{2038}/B_0	B_{2038}
0.14	Y	0.63	0.66	0.56	0.47	0.35	0.31	0.37	11.83	29.38	0.66	0.61	55.18
U_{MSY}	N	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
0.20	N	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

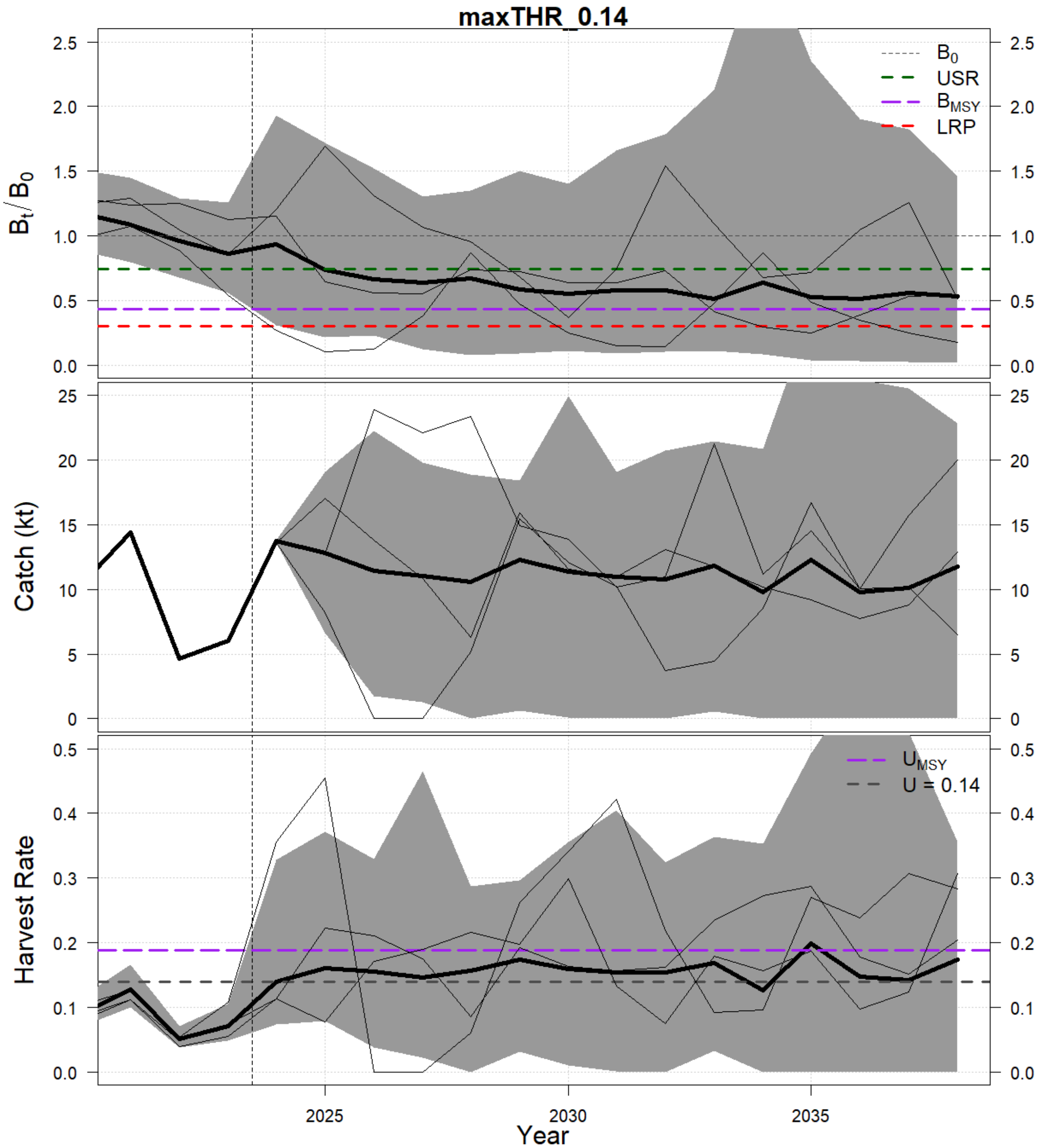

Figure 7: Simulated time series of projected spawning biomass (top), catch (middle), and harvest rate (bottom) for the MP tuned to the conservation objective (HS30-60_HR 0.14). Median values are shown by the thick black lines, the grey shaded region shows the central 95% of each simulation envelope, and three randomly selected individual replicate traces are shown as thin black lines. The dashed vertical line represents the last year of the historical data, 2023, and the dashed horizontal line in the bottom panel represents 14% maximum target harvest rate.

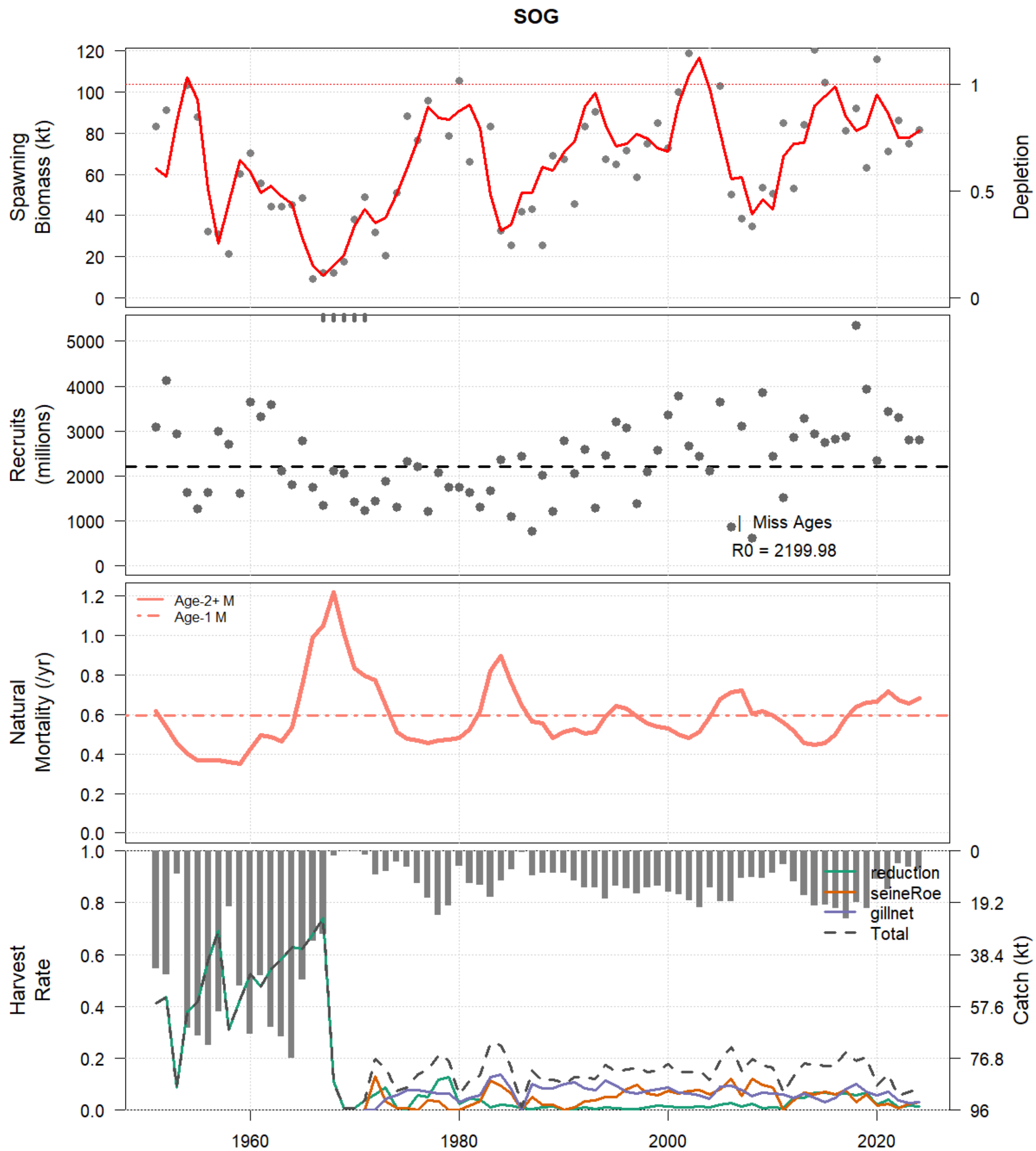

Figure 8: Time series (1951-2024) of maximum likelihood estimates from the estimation model (top to bottom): blended spawn index (circles, kt) and spawning biomass (kt) and depletion (red trend), recruitment in millions of fish (Miss Ages denotes years with no age composition data), estimated natural mortality (density independent formulation), and harvest rate (trend lines), and catch (kt, vertical bars).

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ISSN 1919-3769
ISBN 978-0-660-74684-5 Cat. No. Fs70-7/2024-041E-PDF

Correct Citation for this Publication:

DFO. 2025. Strait of Georgia Pacific Herring (*Clupea pallasii*) Stock Update in 2024. DFO Can. Sci. Advis. Sec. Sci. Resp. 2024/041.

Aussi disponible en français :

*MPO. 2025. Mise à jour de l’évaluation du stock de hareng du Pacifique (*Clupea pallasii*) du détroit de Georgia de 2024. Secr. can. des avis sci. du MPO. Rép. des Sci. 2024/041.*