Fisheries and Oceans Canada / Pêches et Océans Canada
Ecosystems and Oceans Science / Sciences des écosystèmes et des océans

Pacific Region

Canadian Science Advisory Secretariat
Science Response 2026/003

STRAIT OF GEORGIA PACIFIC HERRING (*CLUPEA PALLASII*) STOCK UPDATE IN 2025

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 Response Report results from the September 22, 2025, regional peer review on the Strait of Georgia Pacific Herring Stock Status in 2025.

SCIENCE ADVICE

Status

- Spawning biomass, as represented by the operating model, is above the LRP with a 99% probability and has remained above the productive period candidate upper stock reference (USR) point of around 67.31 kt (Table 1) since the early 2010s.
- The Strait of Georgia (SoG) major stock assessment region (SAR) is healthy.

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 in 2010.

Ecosystem and Climate Change Considerations

- An analysis of Herring data from 1988-2016 identified evidence of low biomass and low productivity states for 3 of 5 Pacific Herring major stocks and these states were used to define a limit reference point (LRP) of $0.3B_0$ for all 5 stocks (Kronlund et al. 2018). This LRP is implemented in Herring MSE using a conservation objective which states to “avoid the LRP with a high probability” (minimum 75%). For all 5 stocks, this LRP is more conservative than the default LRP of $0.4 \cdot B_{MSY}$ identified in “DFO Sustainable Fisheries Framework” policy (DFO 2009).
- The Herring management framework incorporates density dependent mortality and time-varying recruitment into the Herring operating model ensemble, mechanistically accounting for predation mortality and ecosystem effects experienced by this mid-trophic

level pelagic species. These effects are also included when simulating reference points and in evaluating management procedure performance.

- Additionally, each major SAR is modelled using regional life-history traits and regional ecosystem pressures.

Stock Advice

- A quota option for 2026 of 13,054 metric tonnes is provided using the management procedure (MP) tuned to the conservation objective. This MP applies a maximum target harvest rate of 14% to the 2026 forecast spawning biomass.

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 a.) and DFO (In press b.)

Harvest strategies for SoG Pacific Herring are developed within a management strategy evaluation (MSE) process, intending to bring together First Nations and fishery stakeholders, their objectives, monitoring data, and quantitative models to generate harvest advice via repeatable and transparent decision rules. The technical core of an MSE is simulation testing which evaluates the performance of management procedures (MPs) against fishery management objectives. Simulations for SoG Herring are generated by the SoG Herring operating model (OM) implemented using the spatially integrated statistical catch-at-age Herring (SISCAH) modelling framework (DFO 2023a).

The SISCAH OM estimates SoG Herring biomass from 1951-2023 based on historical time series of spawn survey indices (Figure 1), biological and fishery age compositions, and commercial fishery data. Key operating model assumptions include: density dependent mortality (DDM), a spawn survey index that integrates (blends together) surface and dive survey observations, gear-specific commercial fishery timing and catch (Figure 2), and a likelihood function with correlated errors within age-composition data. Science advice supporting DFO's Ecosystem Approach to Fisheries Management (EAFM) is represented via density-dependent natural mortality and time-varying recruitment which aim to capture the net effect of ecosystem impacts on Pacific Herring mortality that are not directly observable (e.g., depensatory predation).

A weighted ensemble of five SISCAH operating models is used for management procedure evaluation. This approach was chosen to encompass future uncertainty around the two productivity parameters: stock recruitment steepness (h), 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 has rarely decreased low enough to give the model a strong indication of what h should be. Details of the operating model ensemble are described in Appendix A.

The ensemble operating model simulates herring population dynamics under candidate MPs over a 15-year projection period (2024-2038) to generate distributions of biomass and fishery yield outcomes and performance statistics related to fishery management objectives (Section "Fishery management objectives"). Here, we present an MP that is tuned to meet the conservation objective (i.e., $P(B_t \geq 0.3B_0) \geq 0.75$) to ensure MP compliance with the Herring LRP objective and with 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

1. Last Full Assessment: this document (2025).

Assessment Approach

1. Broad category: Full MSE process using a single stock ensemble operating model, every three years.
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 prep[1]) estimates SoG Herring stock status and quota calculations for the 2025/2026 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. This assumption is consistent with the findings of (Beacham et al. 2008) which assessed population structure using microsatellite variation and found little evidence for genetic sub-structure within the SAR.

More recent analysis of genomics data by (Petrou et al. 2021) show reproductive timing drives population structure in Pacific Herring and further research is now underway to further investigate spatial and temporal structure of BC Herring populations.

The current framework does not consider potential straying or movement between SARs, finer scale stock structure, or uncertainty in stock structure, however the finer scale dynamics of herring stock structure are considered at an operational level in the on-grounds management of commercial fisheries, i.e., through gear restrictions and/or area closures (as described in the annual IFMP).

Herring in SoG spawn primarily in March, over multiple locations with variable timing (Figure 1). Details of spawn timing and locations are described in the 2025 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 in the WCVI region. There also appears to be indications of non-migratory life-history, with adult herring also reported in the

[1] Johnson, S.D.N., Cox, S.P., Cleary, J.S., Benson, A.J., Power, S.J.H., and Rossi, S.P. In prep. Application of a New Modelling Framework for the Assessment of Pacific Herring (*Clupea pallasii*) Major Stocks and Implementation in the Management Strategy Evaluation Process. DFO Can. Sci. Advis. Sec. Res. Doc.

Salish Sea throughout the summer months. Previous genetic research has not identified finer-scale stock structure within the SoG management area (Beacham et al. 2008), however, a new single nucleotide polymorphism (SNP) analysis (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.

Figure 1. Top: Spatial distribution of Herring spawn (spawn biomass adjusted) in 1951 - 2025. Diamonds indicate presence of incomplete spawn biomass. Bottom: Spatial distribution of herring catch records in 1951 – 2025, where tonnes denotes catch from reduction, roe herring, food& bait, special use fisheries. Rows denote Herring Sections.

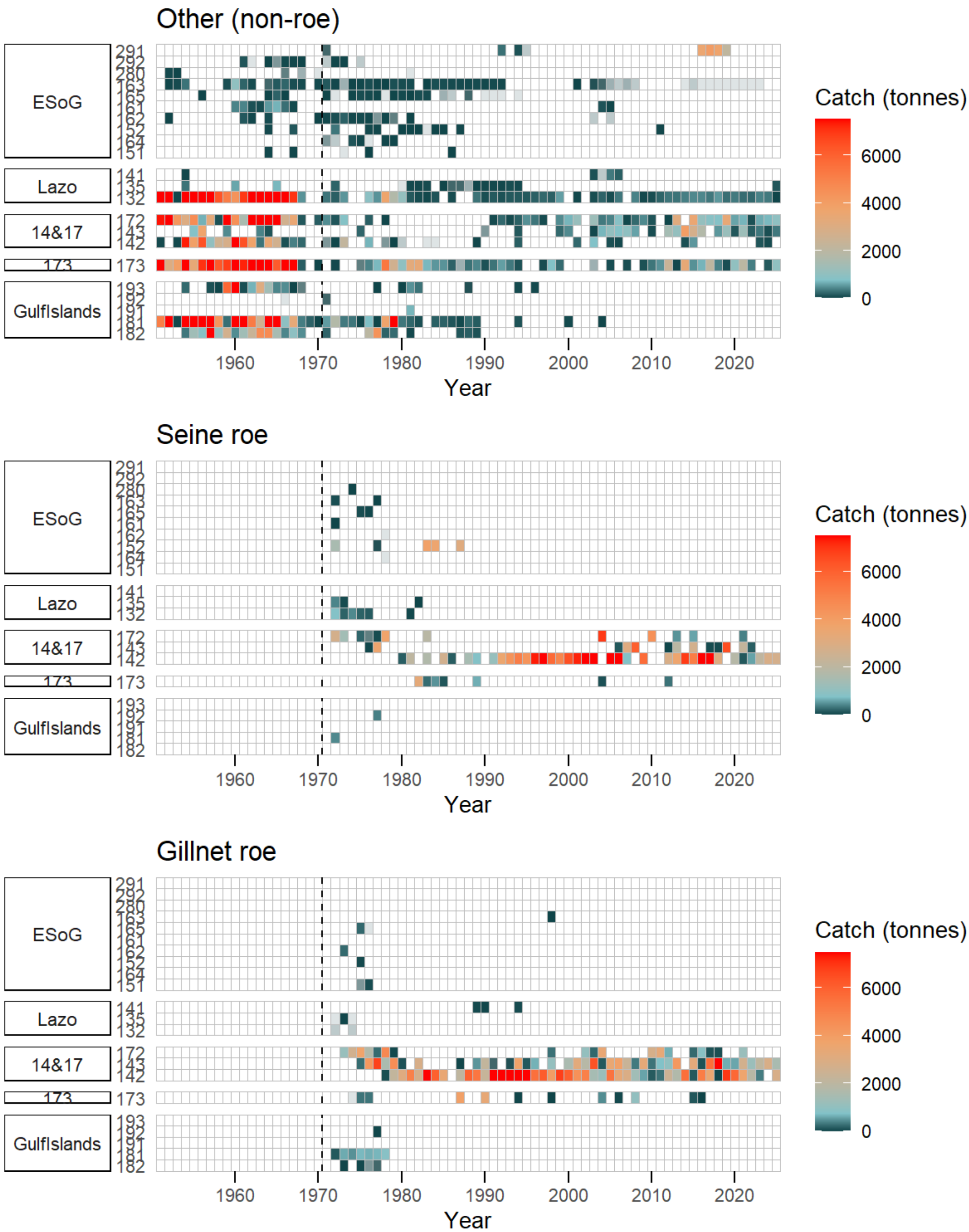

Figure 2. Spatial distribution of herring catch records in 1951 – 2025, where tonnes denotes catch from reduction and FB/SU (top), seine roe (middle), and gillnet roe (bottom).

Reference Points

Biological reference points are used as the basis of some fishery objectives, and as performance metrics for MP evaluations. These include a range of proportions of B_0 (unfished spawning biomass) and B_{MSY} (biomass at maximum sustainable yield). Figure 3 shows the relative position of biological reference points for SISCAH operating model (Appendix A). The equilibrium yield curve assumes that yield is split among fisheries (i.e., seine, gillnet, food and bait, and/or spawn-on-kelp) using the average proportion of total catch landed by each fishery over the last 20 years with fishing. For areas with spawn-on-kelp fisheries (i.e., PRD), the catch is converted to whole fish equivalents (Johnson et al. In prep[1]).

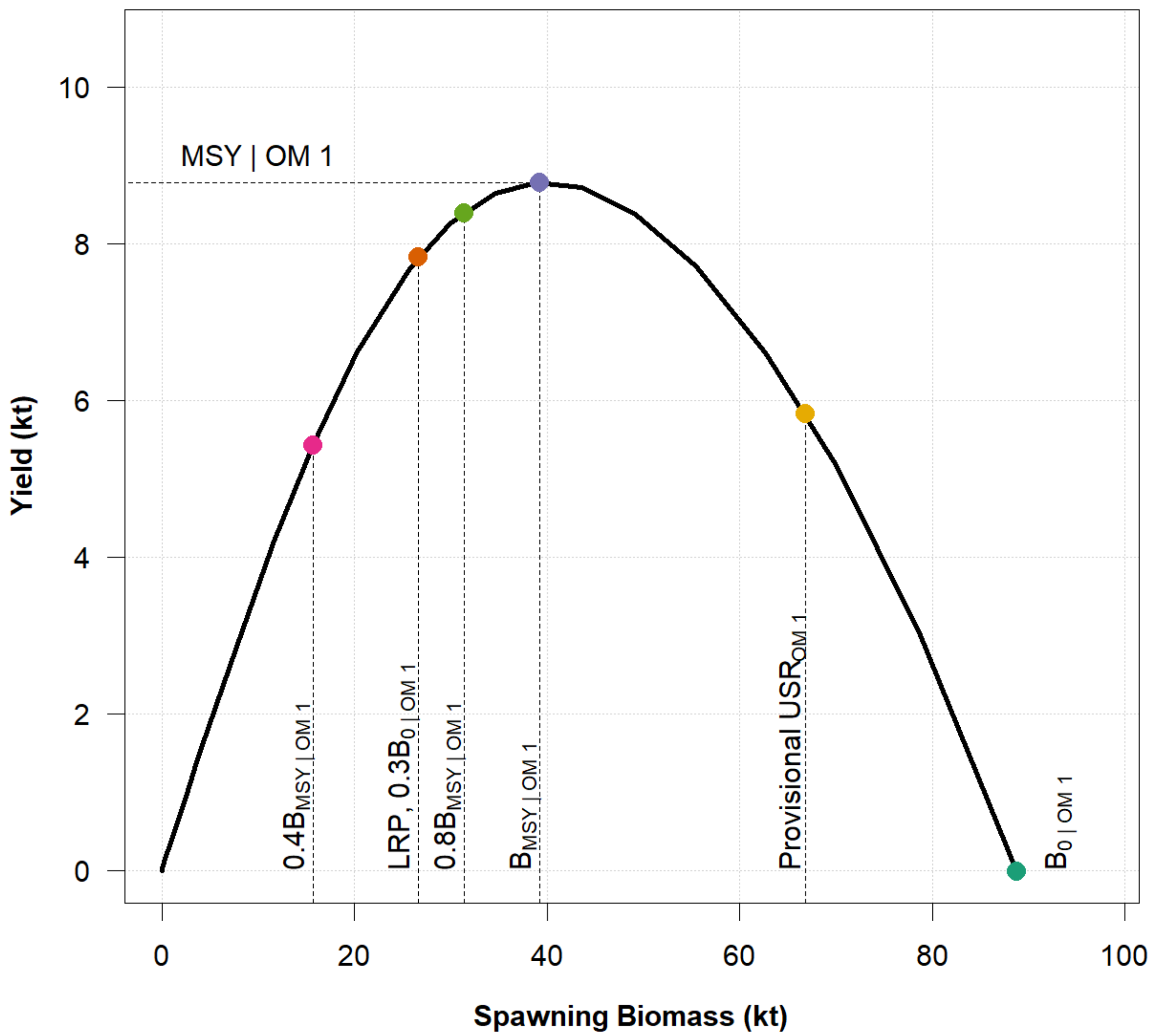

Figure 3. Strait of Georgia Herring operating model equilibrium yield curve with respect to spawning stock biomass. The horizontal dashed line indicates the OM's estimate of maximum sustainable yield (MSY), while vertical line segments show biomass reference points including, from right to left, unfished biomass (B_0), the provisional upper stock reference ($0.8\bar{B}_{1998:2007}$), optimal biomass producing MSY on average (B_{MSY}), default USR from the DFO policy (80% of B_{MSY}), the Herring limit reference point (LRP = $0.3\ B_0$), and the default LRP from the DFO policy ($0.4B_{MSY}$).

- Limit Reference Point (LRP): The current LRP ($0.3\ B_0$), estimated using the SISCAH ensemble operating model, is 27.1 kt, where B_0 is the estimated long-term average unfished spawning biomass (Kronlund et al. 2018; Forrest et al. 2023) (Appendix A). This LRP is higher than the default LRP of $0.4\ B_{MSY}$ identified in “DFO Sustainable Fisheries Framework” policy (DFO 2009), and is a more conservative choice of limit.
- Upper Stock Reference (USR): The current provisional USR ($0.8\bar{B}_{1998:2007}$), estimated using the SISCAH operating model is 67 kt (Table 1; Figure 3). 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 $0.8\bar{B}_{1998:2007}$ as a “provisional USR” beginning with 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). For SoG Herring, a maximum RR is not currently specified because the MSE process is used to select an MP that meets the conservation objective of avoiding the LRP with high probability, with a harvest rate at or below U_{MSY}.

Ecosystem Reference Points

Ecosystem considerations are incorporated into the conservation objective for SoG Herring through:

1. A LRP of $0.3\ B_0$ based on an analysis of stock productivity (Kronlund et al. 2018). The LRP of $0.3\ B_0$ for the SoG ensemble operating model is approximately $0.7\ B_{MSY}$ (Appendix A). This is above the default LRP of $0.4\ B_{MSY}$ (DFO 2009) and incidentally is above the conservative soft-limit of $0.5\ B_{MSY}$ implemented in New Zealand fisheries (Shelton and Sinclair 2008).
2. Including time-varying recruitment to account for changes in year-class strength and size-at-age.
3. Incorporating density dependent mortality to model predation mortality, representing the trophic level of Herring as a forage species.

Additional research is underway to identify evidence-based ecosystem indicators for BC Herring stocks for inclusion in the operating model framework (Boldt et al. 2025).

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, or 15 years (i.e., avoid a biomass limit; $P(B_t \geq 0.3B_0) \geq 0.75$).
2. Three additional objectives are presented for consideration, once the LRP requirement is met:

a. Maintain spawning biomass at or above the USR with at least 50% probability over three Pacific Herring generations (i.e., achieve a target biomass; $P(B_t \geq B_{targ}) \geq 0.50$),

b. Maintain average annual variability (AAV) in catch below 25% over three Pacific Herring generations (i.e., minimize catch variability; AAV < 0.25), and

c. Maximize average annual catch over three Pacific Herring generations (i.e., maximize average catch).

3. DFO is also collaborating with coastal First Nations to develop area-specific objectives for Indigenous fisheries, and engages 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 SISCAH ensemble operating model, represented as a single operating model with uncertainty representing a range of productivity levels based on previous research (Appendix A).

The ensemble operating model stock status for 2023 is reported in Section “Assessment under MSE”.

DFO Science, Pacific Region, will be updating the operating model for SoG Herring every three years, following recommendations of DFO (2023a), and as described in Table 3. In 2027 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 under the revised operating model(s). New hypotheses, objectives and performance metrics may also be added to the MSE process at this time.

In the interim years (2024, 2025, and 2026), the operating model and any values derived from it remain 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 used to calculate an annual quota or total allowable catch (TAC).

Harvest Decision/Control Rule

The Herring MSE produces sustainable harvest advice for SoG Herring using simulation tested MPs. Those simulations are used to identify the maximum target harvest rate for a MP that will meet the established conservation objective. MPs are evaluated using a 15-year projection period (three Pacific Herring generations) and simulated performance is measured against a suite of fishery metrics based on biological reference points and harvest outcomes. See Section “Projections” for a full description.

The harvest control rule (HCR) 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 control rules which differ in their control points and maximum target harvest rates (Figure 4) are presented. These were chosen based on previous research which showed the harvest rate as the key factor governing conservation performance for Herring (Cleary et al. 2010).

Each rule is a ramp from no fishing at lower biomass levels to the maximum target harvest rate at higher biomass levels. The ramp progressively reduces target harvest rates as biomass declines in order to gradually close the fishery as biomass declines, intending to reduce the probability of declining below the LRP. Similarly, the ramp will gradually open the fishery as biomass increases, controlling fishing to be at low levels until stock biomass is higher. The ends of the HCR ramp are the lower and upper control points (LCP and UCP, respectively), which are biomass levels where the target harvest rate changes to the fixed values. At the LCP, SoG Herring HCRs have a 0% target harvest rate, and at the UCP the target harvest rate is set to the maximum level.

Sustainable harvest advice presented for SoG Herring for 2025/2026 is derived using the MP tuned to meeting the conservation objective. The HCR component of the MP has lower and upper control points at 30% and 60% of unfished spawning biomass, respectively, and a maximum target harvest rate (HR) of 14% for the selected MP (Figure 4); note that the maximum target harvest rate may be different for different MPs. HCR control points have been explored in the MSE process beginning in 2018, prior to defining provisional USRs for each SAR. The upper control point is not intended to represent the USR. The performance of MPs using the two alternative rules are presented in Appendix A for comparison.

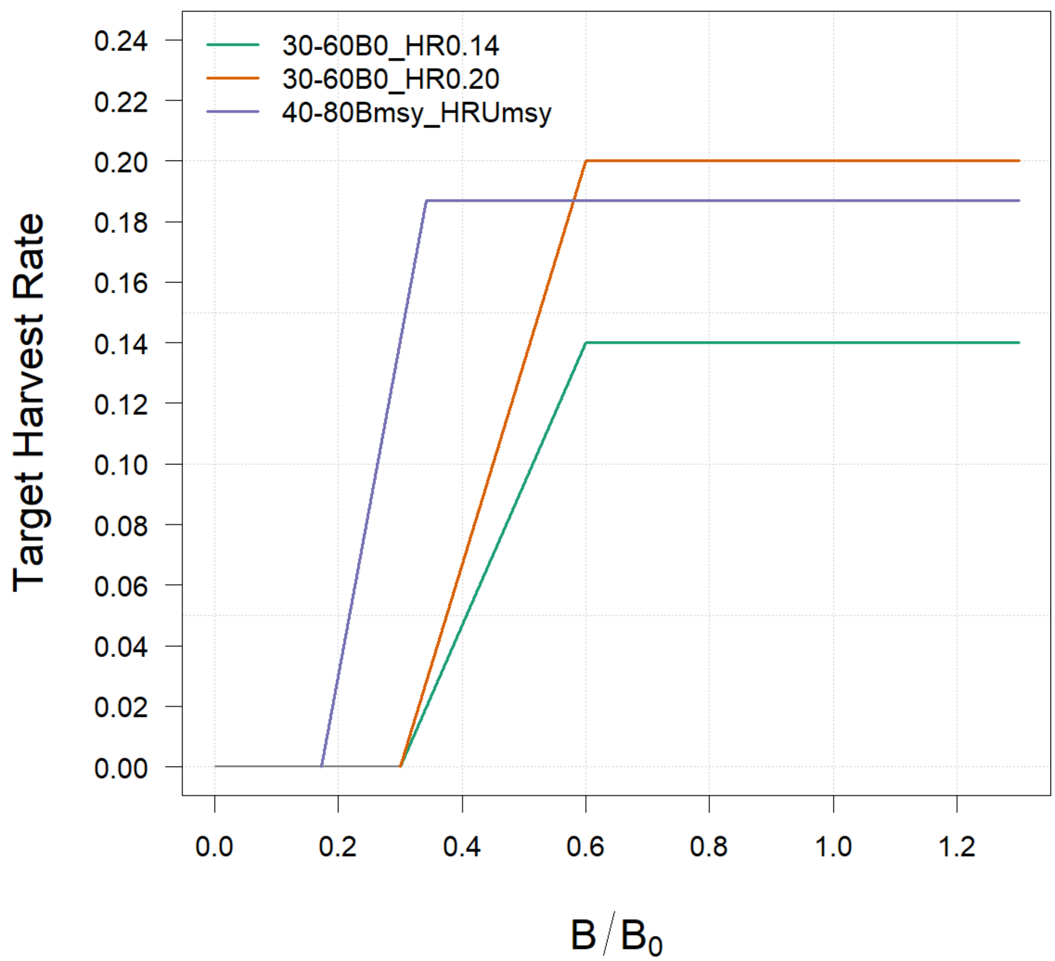

Figure 4. Three harvest control rules for SoG management procedures (MPs). The green line represents the MP tuned to meet the conservation objective over a 40-year projection period for the operating model (with density dependent natural mortality) and maximum target harvest rate (HR) of 14%. The orange line denotes an additional hockey-stick shaped rule with the previously applied effective 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 $0.4B_{MSY}$ and $0.8B_{MSY}$.

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 would be investigated for severity and potential impacts on the performance of the MP, and consideration given to re-examining 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 this would be 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 survey data required to implement the MP are not available in a given year 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 2025 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 5). Operating model trends are similar to those presented for SoG Herring in previous stock assessments (DFO 2025), with near-identical data sources and choice of indicators.

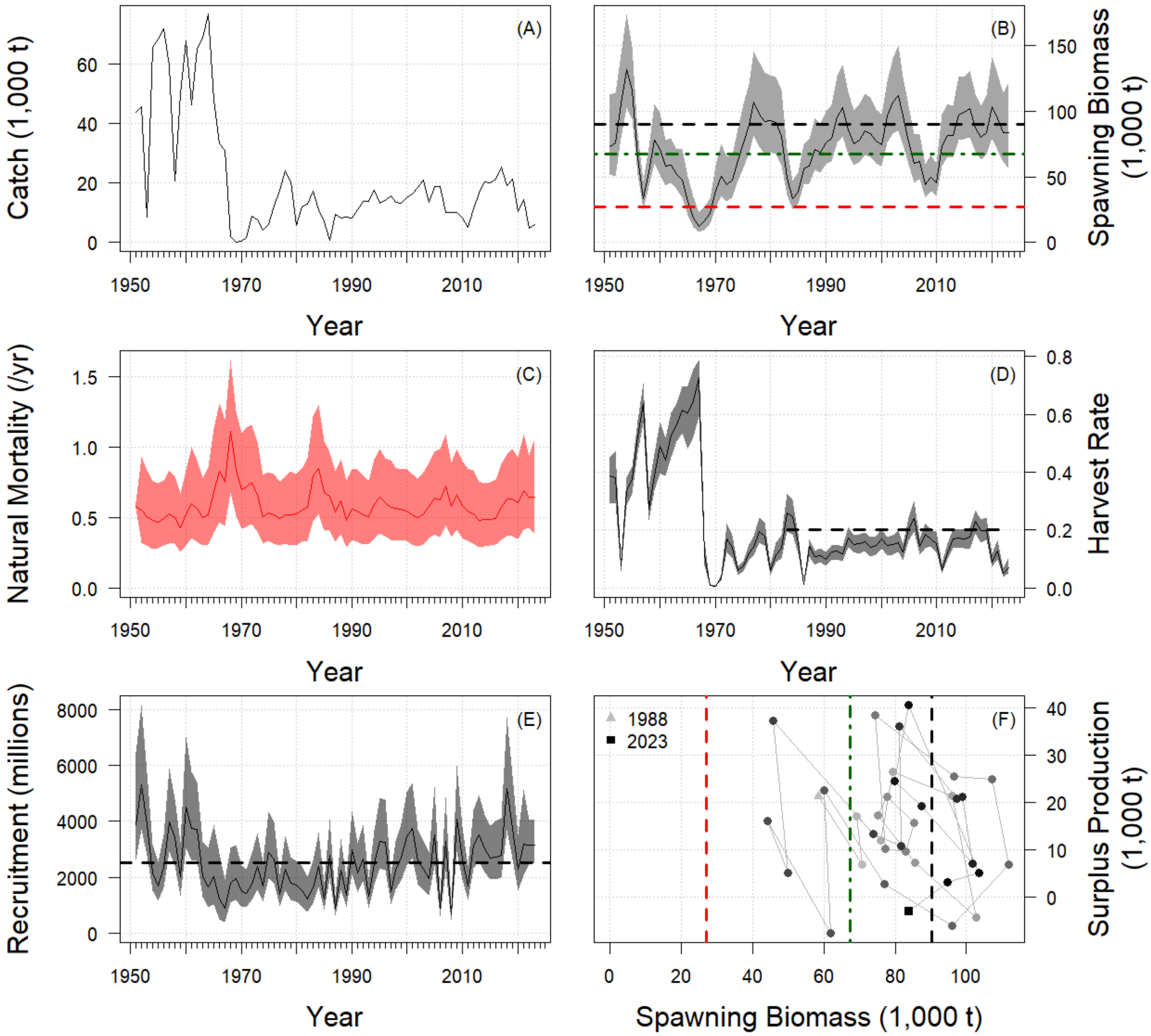

Figure 5. Estimated stock status indicators for Pacific Herring in the Strait of Georgia (SoG) major stock assessment region (SAR) from 1951 to 2023, as estimated by the ensemble operating model. All lines indicate posterior median values, and where applicable, shading indicates 95% credibility intervals. (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).

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 90.23 kt, 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 % probability in each of the 5 OMs.

The ensemble operating model estimates spawning biomass to be above B_{MSY} and all candidate USRs for the majority of the historical time series (Figure 5A). 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 5E). While 2020 is one of the three highest peaks in estimated spawning biomass (since 1970), rising estimates of natural mortality (Figure 5C) 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 and then declined each of the next three years to 2023 (Figure 5F), despite spawning biomass remaining fairly constant. This is likely due to the increasing trend in natural mortality estimates since 2015, reducing the survival of young fish despite lower recent harvest rates and higher than average recruitment (Figure 5C-E).

Ecosystem and Climate Change Considerations

Stock assessment models for Pacific Herring incorporate ecosystem and climate change indirectly via estimates of time-varying natural mortality (M) and recruitment, which are the foundations of historical stock productivity. This implicit approach allows productivity estimates to reflect a changing climate and/or ecosystem without needing to describe the exact ways in which those changes affet recruitment and mortality, as many of those pathways are not directly observable.

Over the years, scientists and First Nations expressed the need to examine the role of ecosystem changes in driving variation and trends in these processes, especially considering the importance of future productivity in evaluating harvest management procedures (i.e., as part of the MSE process). This also aligns with DFOs commitment to advance Ecosystem Approaches to Fisheries Management.

First Nations-led research conducted since 2020 in WCVI examining ecosystem impacts on Pacific Herring productivity found relatively large changes in predator populations since the 1990s. The direction and magnitude of potential consumption of Pacific Herring by these predators generally align with natural mortality trends estimated in stock assessment models.

Although the role of predation and ecosystem change varies among Pacific Herring stock assessment regions, there are shared processes and commonalities among regions in how ecosystems and climate affect productivity. The following section summarizes insights from these studies and their implications for future management of SoG Pacific Herring fisheries, and explains how this research supports/further corroborates the use of a depensatory function to model natural mortality for SoG Herring.

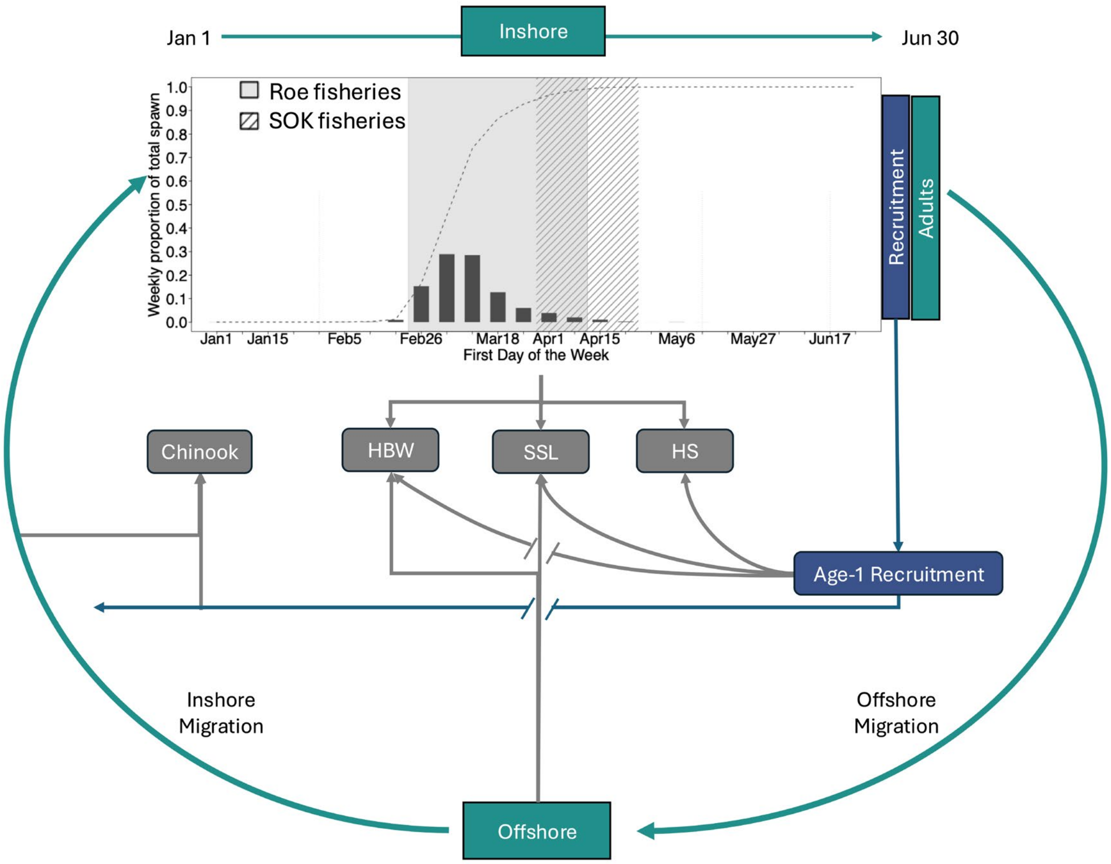

Figure 6. Conceptual model of the annual life cycle of Pacific Herring, including predation mortality in inshore and offshore regions, spawn timing (January–June), recruitment, and fisheries. Arrows to predator boxes (grey) indicate losses due to predation mortality from Humpback Whales (HBW), Steller Sea Lions (SSL), Harbour Seals (HS), and Chinook Salmon (Chinook). Spawning occurs at the end of each year on June 30th. Arrows from recruitment boxes (blue) to indicate recruitment of juveniles hatched from eggs deposited during the previous year's spawning events. Recruits do not migrate offshore during the feeding season but are subject to inshore predation before mixing with age-2+ herring returning from the offshore (green arrow on far left) during the spawning season. The top panel shows average weekly (vertical bars) and cumulative (dashed line) proportion of spawn for inshore spawning grounds, along with timing for roe and SOK fisheries.

Changing predation regimes

Ecosystem effects are included in Herring population dynamics models by linking historical (and future) predator consumption estimates to observed natural mortality (Doherty et al. 2024). Predators in the SoG include Humpback Whales (*Megaptera novaeangliae*), Harbour Seals (*Phoca vitulina*), Steller Sea Lions (*Eumetopias jubatus*), and Chinook Salmon (*Onchorynchus tshawytscha*) that all prey on multiple life stages of Herring during most of their annual life cycle (Figure 6). Consumption of Pacific Herring by each predator is estimated via bio-energetics modeling (Chasco et al. 2017; Doherty et al. 2024), accounting for predator body size, estimated predator abundance, size selectivity, foraging days, diet composition, and the energy content of Pacific Herring (Doherty et al. 2024). Estimates of stock biomass and historical total natural mortality derived from these ecosystem based models are consistent with corresponding estimates from this stock assessment (Figure 7).

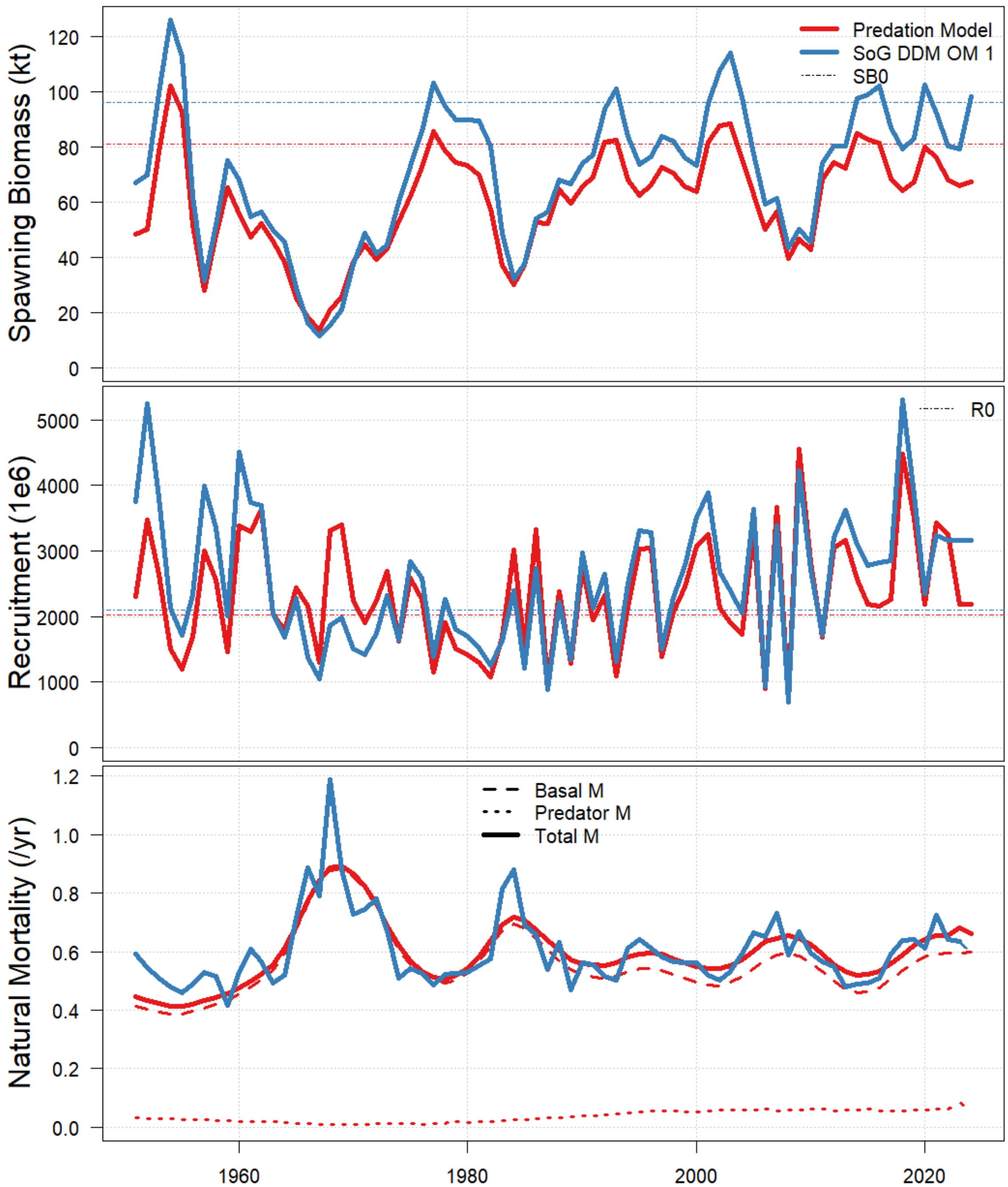

Figure 7. Comparison of Strait of Georgia (SoG) maximum likelihood estimates of spawning stock biomass (top), age-1 recruitment (middle), and age-2 natural mortality rate (bottom) from the Predation Model (red) and SoG SISCAH Density Dependent Mortality Operating Model (DDM OM) 1 (blue).

While estimates of historical biomass, mortality, and recruitment derived from predation models are similar to corresponding estimates from the SISCAH framework used in this assessment, expectations for future biomass and productivity differ because of expected future changes in predation regimes. For example, over the last 20 years consumption of herring by predators has increased by around 25%, driven primarily by growth in Humpback Whales and Steller Sea Lions within the SoG SAR, and to some degree by Chinook Salmon depending on the run size (Figure 8). The latter contributed to peak predator consumption of nearly 14 kt in year 2023 due to larger Chinook returns. Estimates of unfished biomass levels based on these more recent predation mortality rates are about 10% lower than estimates from time-varying M models, suggesting that future productivity may be negatively impacted by predator consumption.[2]

The key difference between the time-varying M approach and explicitly modeling M via predation lies in their implications for future trends in natural mortality. Projecting M via the implicit approach requires strong assumptions about the trends in M, while the predation approach involves modeling future trends in predator populations for which we have reasonable data and models. In general, some of these key predators may increase further in the future as the continue to recover from historical over-exploitation.

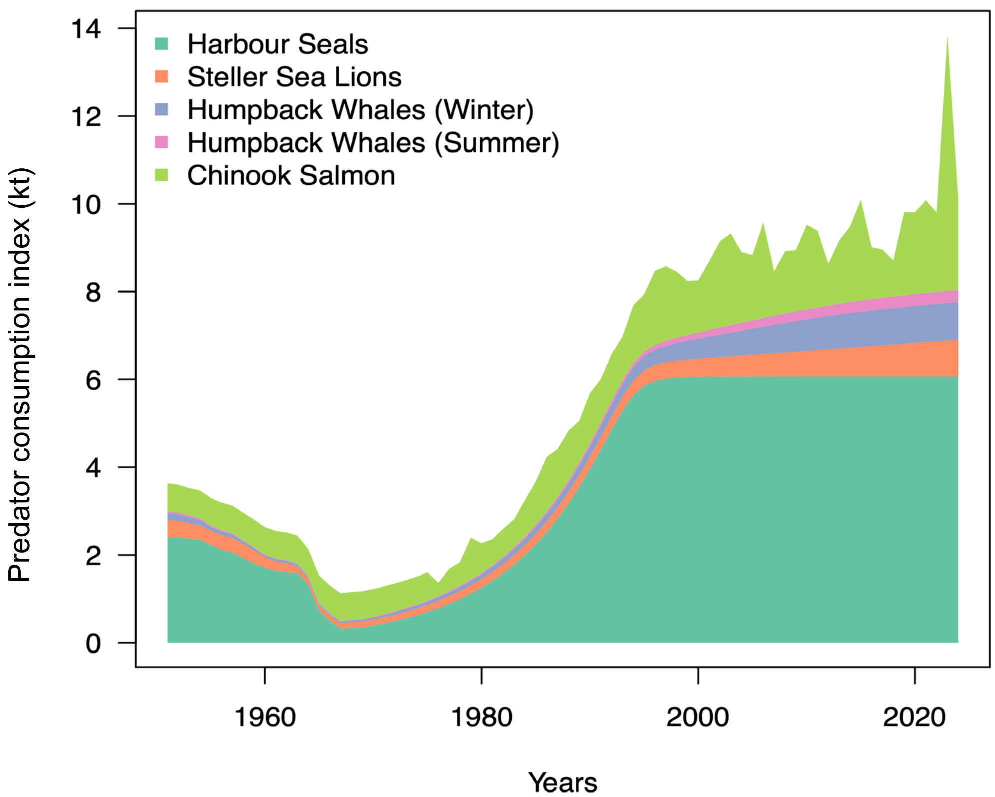

Figure 8. Estimated predator consumption of SoG Herring from 1951 – 2024. Predators consume herring of all ages to varying degrees, depending on their size preference. Consumption index is estimated in thousands of tonnes for each species, with Humpback Whales broken into feeding groups, which differ in size preference and spatio-temporal overlap with SoG Herring.

[2] Johnson, S.D.N., Doherty, B., Wang, S., Benson, A.J.B., Cox, S.P., and Cleary, J.S. In prep. Marine Mammal and Fish Predation Effects on Pacific Herring Natural Mortality in the Strait of Georgia and Prince Rupert District. Department of Fisheries and Oceans, Technical Report.

Spatial dynamics and spawn distribution

While there is no current spatial approach for SoG herring stock assessment and management, there are some spatial dynamics worth noting. The historical distribution of SoG Herring spawn abundance shows that spawning has historically been concentrated in StatAreas 14 and 17 (Figures 1,9). The most herring spawn is observed in Sections 142 and 143 within StatArea 14, which extends from Parksville to Kyle Bay, and includes Denman Island and Hornby Island. Sections 172 and 173, extend from Galiano Island to Nanoose Bay, have consistent spawning activity with more annual variability in the amounts of spawn and relatively less spawn on average than Sections 142 and 143. Spawning has been lower and more sporadic within sections in the Eastern SoG (ESoG), Lazo, and southern Gulf Islands, especially since the late 1980s.

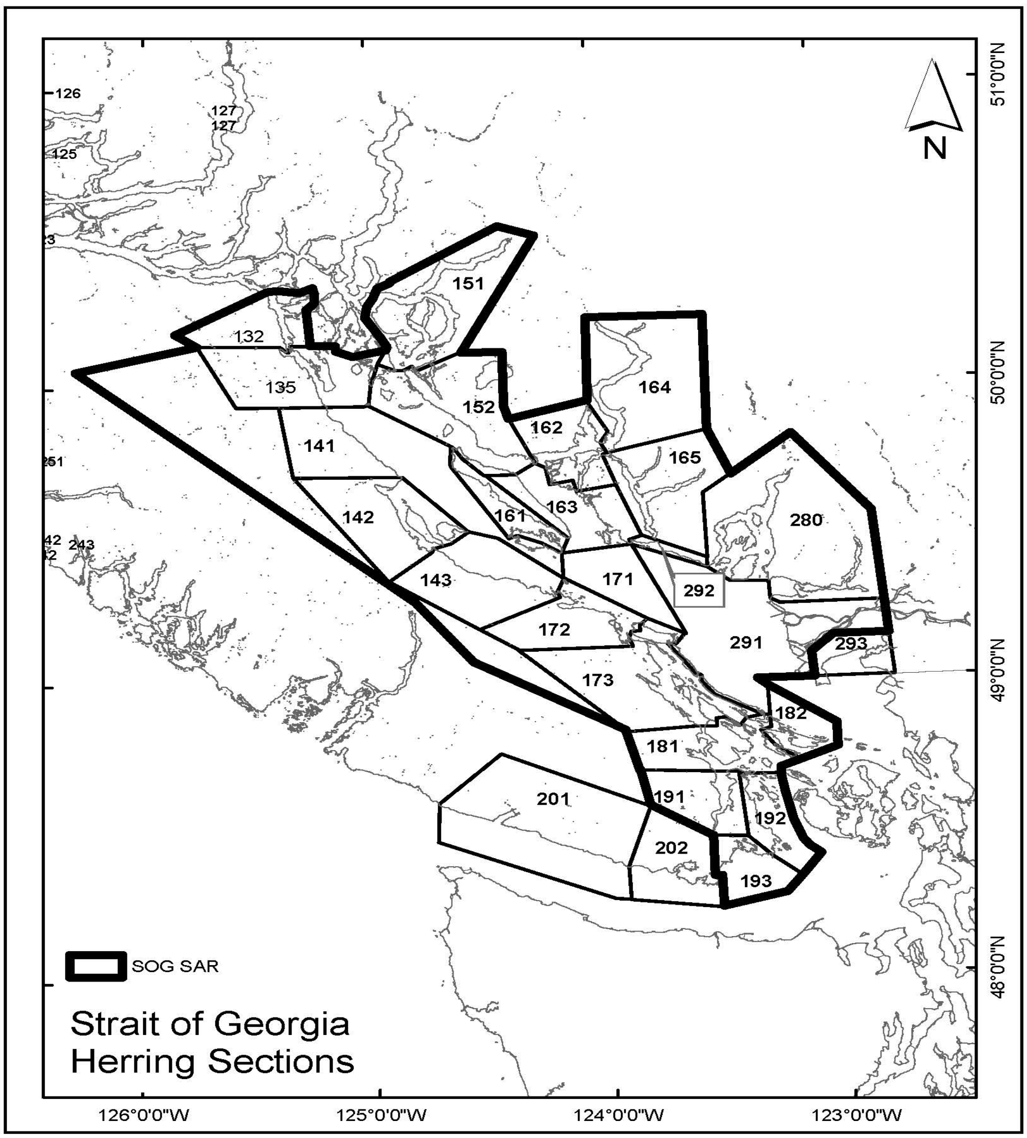

Figure 9. Map of Strait of Georgia Herring Sections.

Implications for science advice

Changing ecosystems and climate are implicitly represented in historical science advice for Pacific Herring; however, their impact on future Herring productivity is of most importance for management. Changes in natural mortality and recruitment are neither random nor independent of Pacific Herring or predator abundance (Doherty et al. 2024). This finding should be integrated into the MSE process.

Historical and future changes to Pacific Herring ecosystems imply a need to modify expectations for future biomass and fisheries, and to account for this in the choice of management objectives. For example, biomass targets (or upper stock reference points) recently proposed for BC Pacific Herring were based on a productive period in the recent history (DFO 2023b). In the SoG region, the proposed objective is to maintain spawning stock biomass at or above a target biomass level equivalent to 80% of the average biomass from 1988-2007, with at least 50% probability over three herring generations. Such target objectives based on periods with different ecosystem conditions may not be achievable under current or future predator regimes. The MP presented herein for SoG Herring does not meet this proposed objective (p = 0.35; Table 2). Future MSE analyses should include scenarios with forecasted future predation that may inhibit the stock's ability to return to historical periods of peak biomass, which occurred during periods with fewer marine mammals.

History of Management

A maximum target harvest rate of 20% was defined for SoG Herring in 1983. The realized harvest rate has mostly hovered below this target since then with reduced harvest rates applied for the past few years (Figure 5, panel D). Since 2015 the selection of annual harvest rates has been informed by MP simulation testing.

Projections

Interim Year Update for 2025

For 2025, the estimation model estimates spawning biomass, $\hat{B}_{2025}$, = 92.06 kt (maximum likelihood estimate), with stock status ($\hat{B}_{2025}/\hat{B}_0$) = 0.9. Time series of maximum likelihood estimates from the estimation model are presented in Figure 15.

Application of MP for 2026

We simulation tested three MPs, each with hockey-stick shaped harvest control rules (Figure 4). The MP 30-60B0_HR0.14 with lower and upper control points at 30% and 60% of unfished spawning biomass B_0, respectively, and a maximum target HR 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 2026 is estimated to be $\hat{B}_{2026} = 93.25$ kt (maximum likelihood estimate), with stock status ($\hat{B}_{2026}/\hat{B}_0$) = 0.91. 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 13.05 kt.

This is shown graphically in Figure 10.

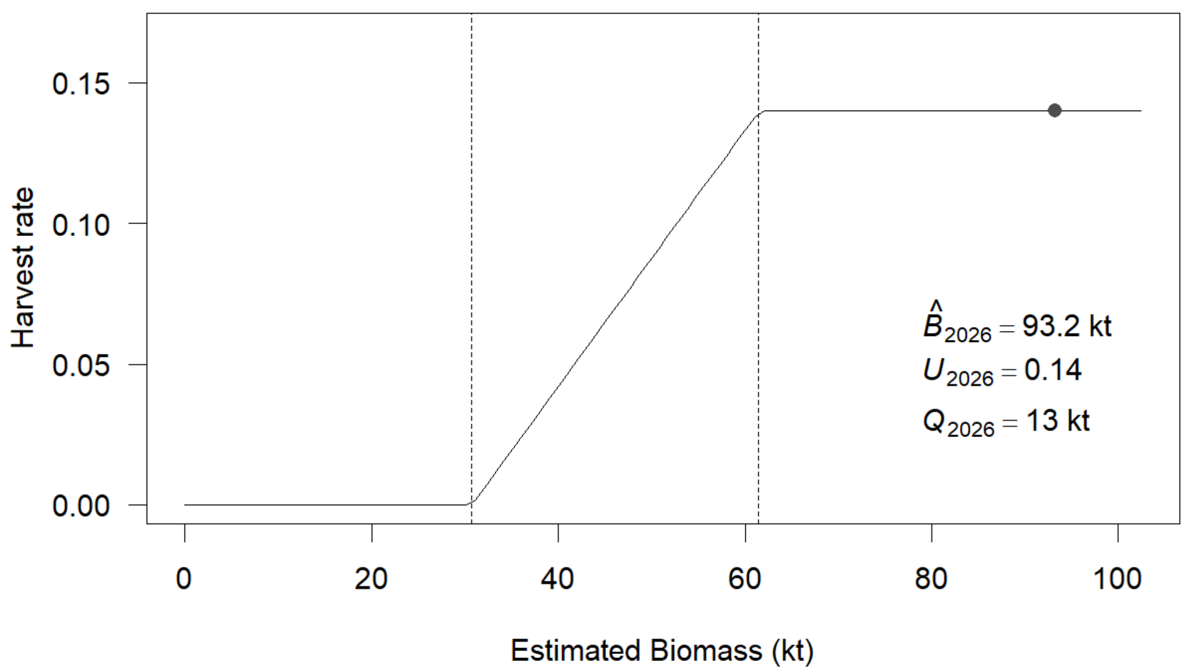

Figure 10. Strait of Georgia (SoG) Pacific Herring management procedure harvest control rule (HCR; line), showing forecast spawning biomass (kt) in 2026 ($\hat{B}_{2026}$, point), and associated harvest rate U_{2026} and total allowable catch (TAC (kt); Q_{2026}) for the 2025/2026 fishing season.

Performance Evaluation for Interim Years and Exceptional Circumstances

There is no indication of operating model misspecification (Figure 11), which is evaluated visually by comparing catch and spawn index values within the central 95% of the simulations.

All routine forms of Herring fishery monitoring data were collected in 2025 and show the population is behaving within ensemble operating model expectations. The most recent spawn index falls within the range of uncertainty that was simulated in the MSE projections starting in 2023 (Figure 11). In the first projection year 2024, the observed catch was lower than the MSE projections, but the second catch data point was within the range of simulated uncertainty from the ensemble operating model.

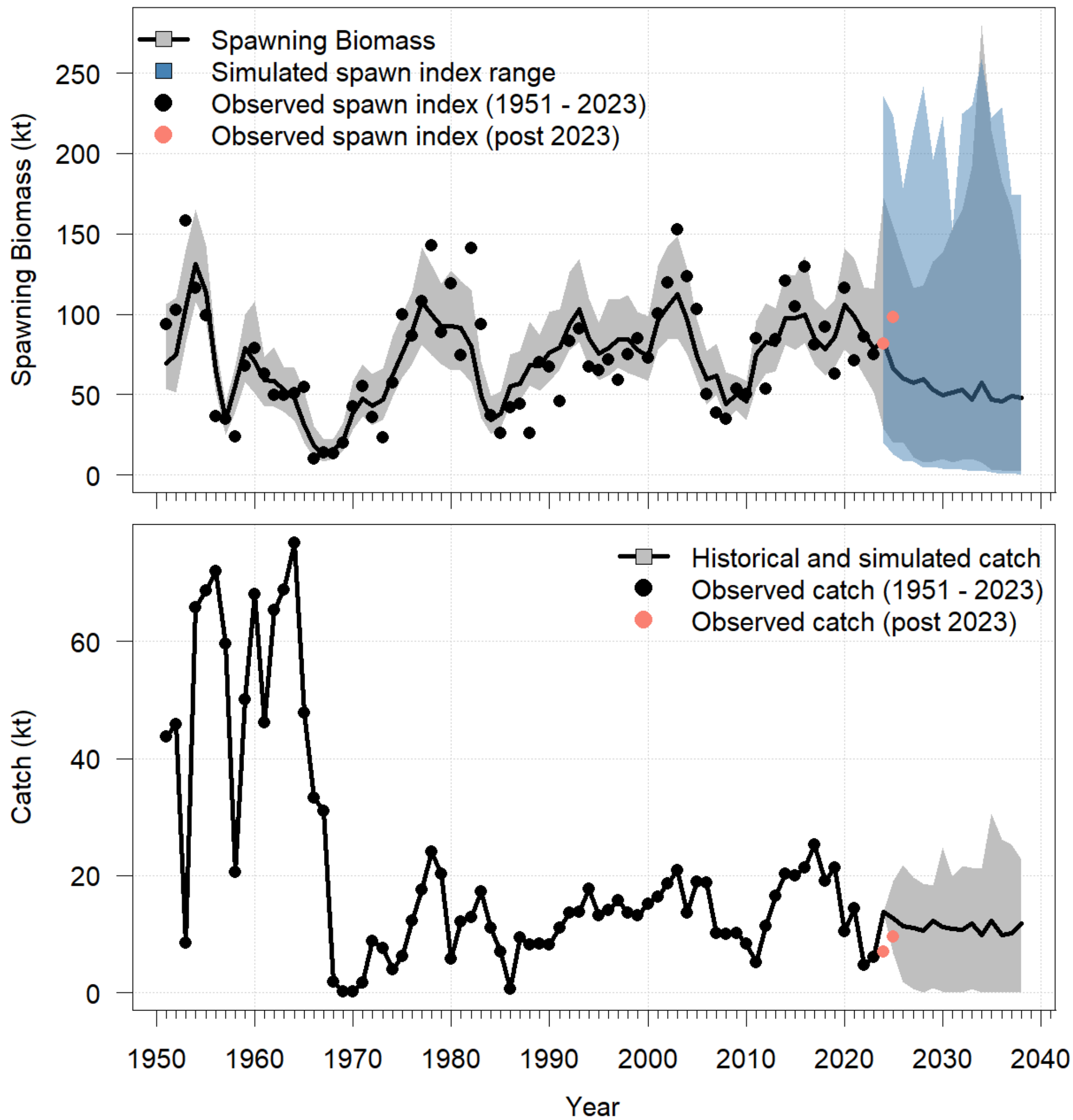

Figure 11. Evaluation of exceptional circumstances and operating model misspecification: graphical comparison of simulation envelopes from the operating model (1951-2023) and catch and spawn index data from interim year (2025). Panels show the central 95% of projected simulated data, including spawn index data (top) and catch (bottom) from the 2023 SoG operating model. Forward projections in time (15-years) represent the 30-60B0_HR0.14 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 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 that meets management 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 the spatially integrated statistical catch at age Herring (SISCAH) model with density independent M (DIM SISCAH). This EM was selected because its performance was similar to the DDM formulation and it is less computationally intensive for interim updates.

Exceptional circumstances criteria will be examining each interim year and if no exceptional circumstances are identified then the 2023 status relative to reference points and objectives would carry forward indicating that the MP was working as intended.

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. See also Appendix A.

Research Recommendations

Future research could look into developing better priors for the depensatory density dependent M (DDM) model. Currently, there is a large amount of uncertainty in the depensation rate m_1 parameter, and the model breaks down when exploring the range of the M_b (asymptotic lower limit on M) parameter. There are several reasons why there is high uncertainty in both of these parameters, including the fact that the effects of the parameters are not directly observable, and that the data used to estimate the parameter is not very informative. Identifiability is also an issue, as several combinations of m_1 and M_b can produce similar results, especially with annual mortality process errors adding flexibility to the historical period for model fitting.

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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 prep[1]).

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 12). 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 12). 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). The five operating models are summarised in 1. Note that productivity at low stock size is also influenced by the rate of depensation in mortality at low stock size m_1 parameter, which has an estimated posterior distribution that varies in all operating models (see Figure 13 for the example from OM 1).

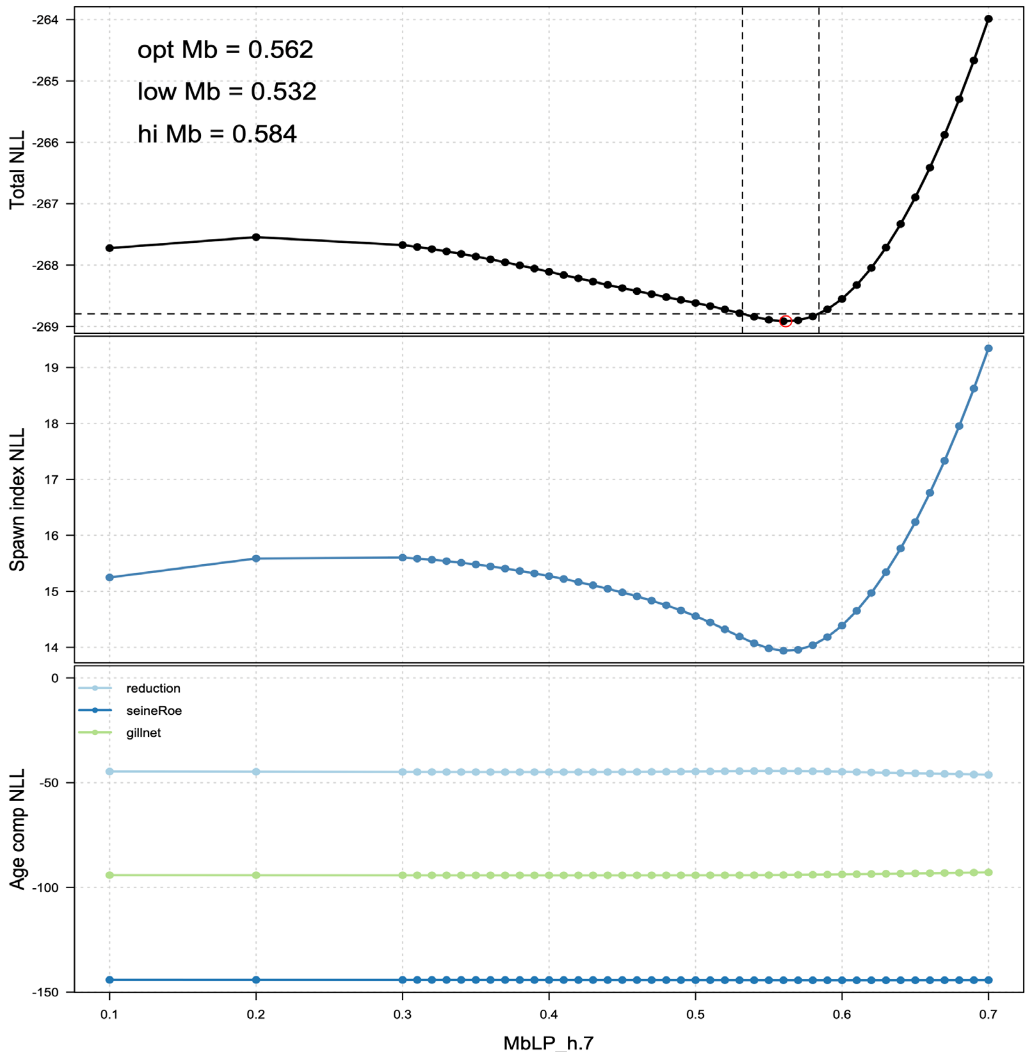

Figure 12. Fishery monitoring data likelihood function profiles relative to a range of natural mortality asymptotic lower limit (M_b) parameter values. The red point shows the most likely value, while the two vertical dashed lines show two values with equal likelihood chosen to bound the central OM1. All SISCAH model fits here have a steepness value of $h = 0.7$

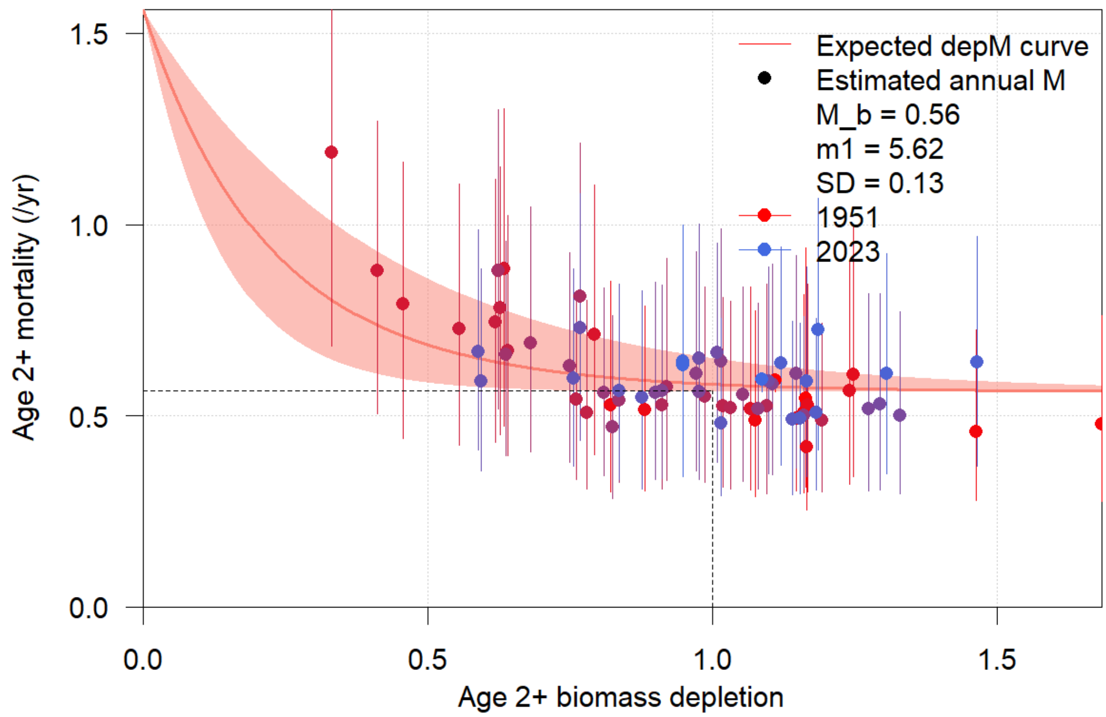

Figure 13. SoG SISCAH model OM1 posterior estimate of the density dependent relationship between age-2+ biomass and age-2+ natural mortality. The median relationship is shown by the red curve, with the posterior 95% credibility range shown by the shaded region. Individual annual M_t estimates with process error are shown as points (posterior median) and vertical line segments (central 95% credibility interval), with the year indicated by point/segement colour. The parameters shown are: M_b = asymptotic lower limit of density dependent mortality; m_1 = depensation rate; and SD = the effective standard deviation of the annual natural mortality process deviations.

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 quantites 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 (B_0, kt), unfished recruitment (R_0, 1e6), unfished mortality (M_0, /yr), mortality depensation rate (m_1), time-averaged mortality ($\bar{M}$, /yr), surface survey design catchability (q_s), spawning biomass in 2023 (B_{2023}/B_0), stock status ($P(B_{2023} > 0.3 B_0)$), spawning biomass at maximum sustainable yield (B_{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).

Parameter	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
$\bar{M}$	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)	1
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

Parameter	OM 1	OM 2	OM 3	OM 4	OM 5	Ensemble
$P(B_{2023} > 0.3\ B_0)$	0.99	0.99	0.99	0.99	0.99	0.99
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
M_{SY}	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 (HR). 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} (Figure 4, Table 2).

Finally, after the three year cycle (e.g., in 2027, Table 3) 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 14). 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 4 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 14). 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 14, 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'. $\bar{B}$ 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 $\bar{C}_t$ and final biomass B_{2038} are in biomass units (kt), and final year B_{2038}/B_0 and average projection year $\bar{B}_t/B_0$ 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, $0.8B_{1998:2007}$.

Management Procedure	**0.3 B_0**	**B_{MSY}**	**0.4 B_0**	**0.5 B_0**	**0.6 B_0**	**$\bar{\bar{B}}_{prod}$**	**$\bar{\bar{B}}$**	**U_{MSY}**	**$\bar{C}_t$**	**AAV**	**$\bar{\bar{B}}_t/B_0$**	**B_{2038}/B_0**	**B_{2038}**
30-60B0_HR0.14	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
30-60B0_HR0.20	N	-	-	-	-	-	-	-	-	-	-	-	-
40-80Bmsy_HRUmsy	N	-	-	-	-	-	-	-	-	-	-	-	-

Table 3. Implementation of the SISCAH operating model framework for Pacific Herring major stocks: MSE update schedule for 2023-2029 (subject to evaluation of exceptional circumstances criteria and available resources).

SAR	2023	2024	2025	2026	2027	2028	2029
SOG	CSAS review of SISCAH OM framework	SISCAH transition and MP evaluations	Interim update	Interim update	OM review and full MSE update	Interim update	Interim update
PRD	CSAS review of SISCAH OM framework	-	SISCAH transition and MP evaluations	Interim update	Interim update	OM review and full MSE update	Interim update
HG	CSAS review of SISCAH OM framework	-	-	SISCAH transition and MP evaluations	Interim update	Interim update	Interim update
CC	CSAS review of SISCAH OM framework	-	-	SISCAH transition and MP evaluations	Interim update	Interim update	Interim update
WCVI	CSAS review of SISCAH OM framework	-	-	SISCAH transition and MP evaluations	Interim update	Interim update	Interim update

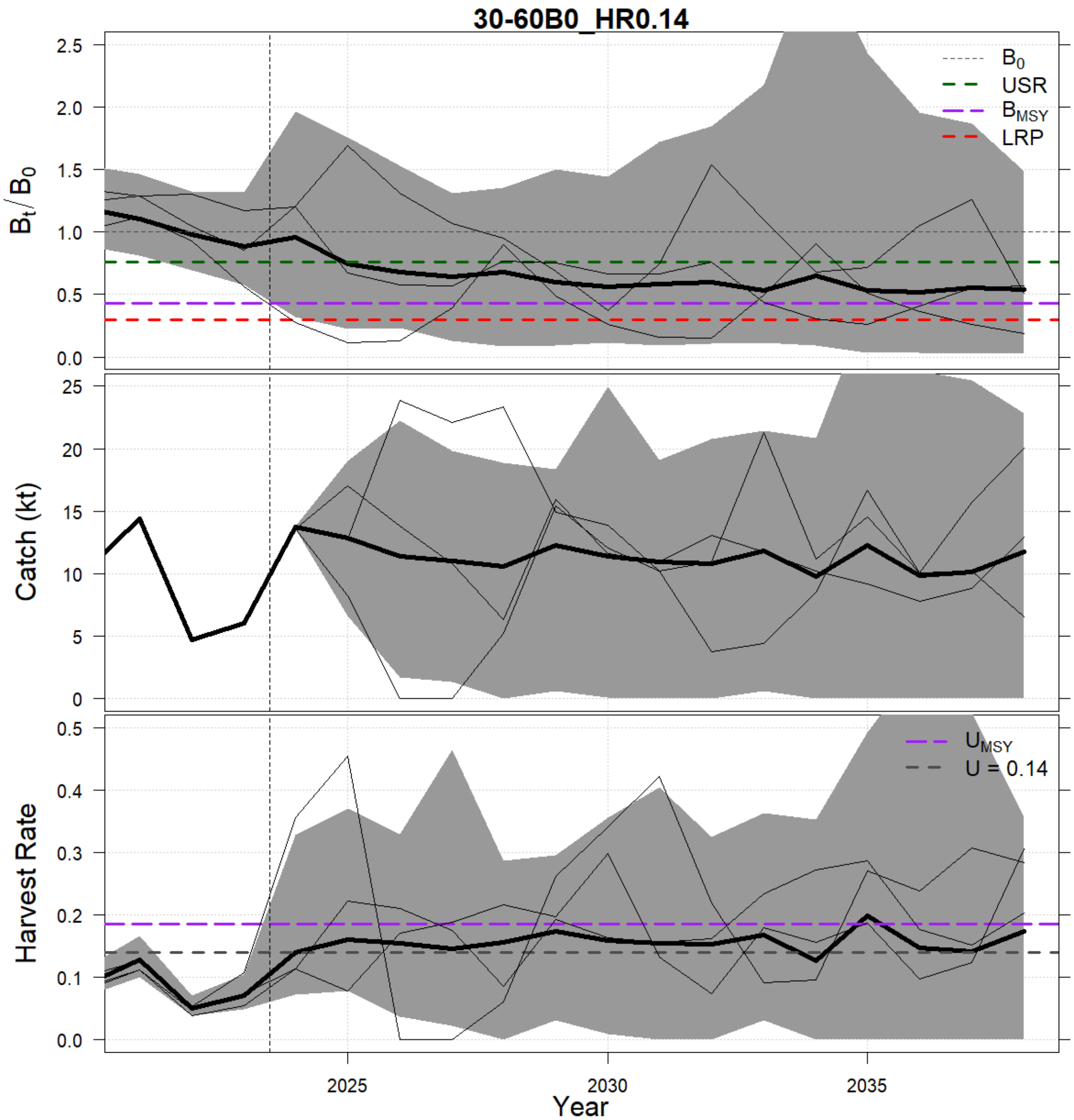

Figure 14. Simulated time series of projected spawning biomass (top), catch (middle), and harvest rate (bottom) for the MP tuned to the conservation objective (HS30-60_HR 0.14). Median values are shown by the thick black lines, the grey shaded region shows the central 95% of each simulation envelope, 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.

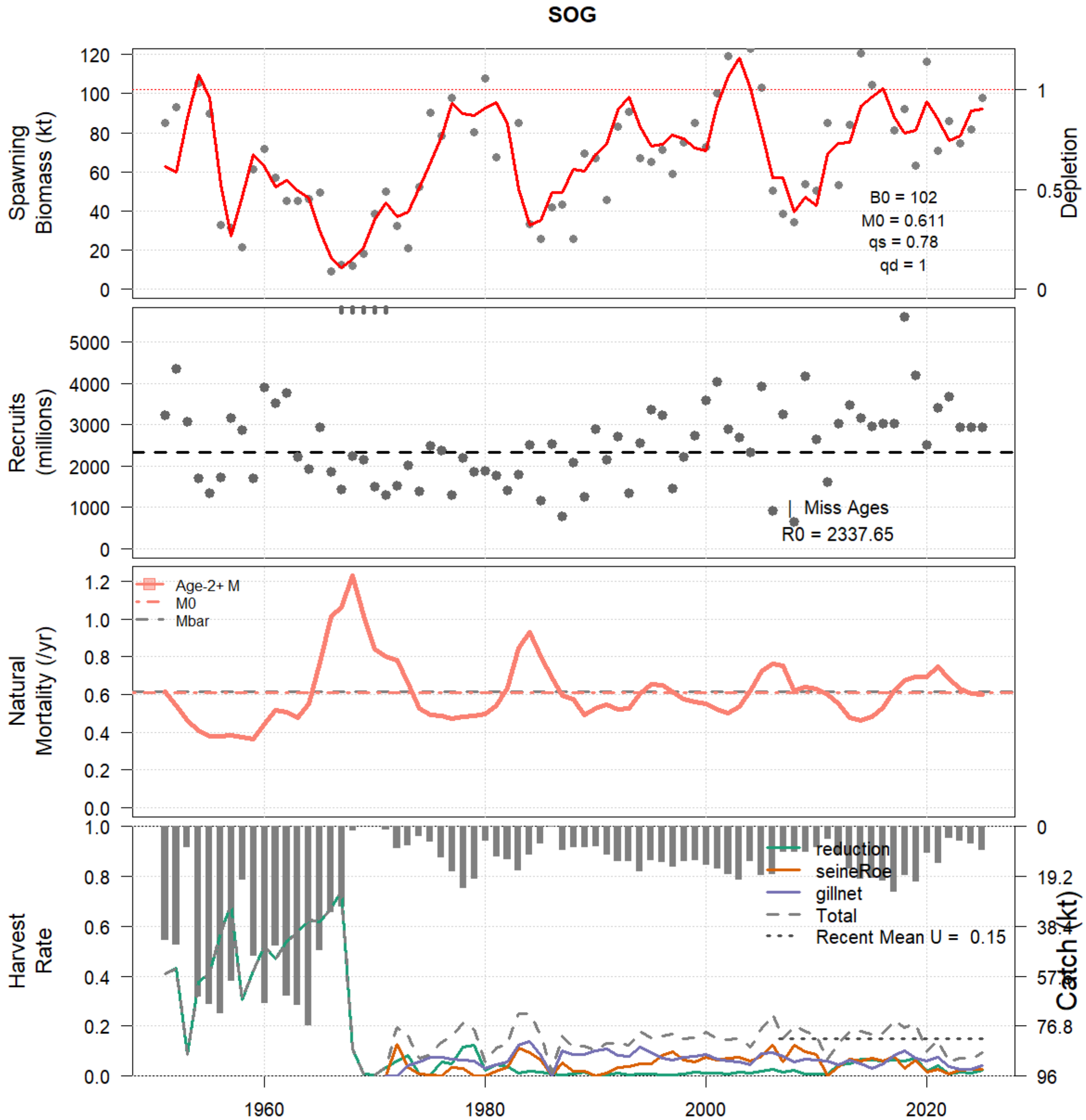

Figure 15. Time series (1951-2025) of maximum likelihood estimates from the estimation model (top to bottom): blended spawn index (circles, kt) and spawning biomass (kt) and depletion (red trend), recruitment in millions of fish (Miss Ages denotes years with no age composition data), estimated natural mortality (density independent formulation), and harvest rate (trend lines), and catch (kt, vertical bars).

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