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EVALUATION OF MANAGEMENT PROCEDURES FOR PACIFIC HERRING (*CLUPEA PALLASII*) IN HAIDA GWAII, PRINCE RUPERT DISTRICT, AND THE CENTRAL COAST MANAGEMENT AREAS OF BRITISH COLUMBIA

Context

Fisheries and Oceans Canada (DFO) has committed to renewing the current management framework to address a range of challenges facing Pacific Herring stocks and fisheries in British Columbia. Renewal of the management framework includes conducting a Management Strategy Evaluation (MSE) process to evaluate the performance of candidate management procedures (MPs) against a range of hypotheses related to future uncertain stock and fishery dynamics. The purpose of MSE is to identify MPs that provide acceptable outcomes related to conservation and fishery management objectives.

Identification of a preferred management procedure for each Pacific Herring management area is an iterative process conducted through:

(i) collaboration with coastal First Nations, and

(ii) engagement with the fishing industry, government and non-government organizations.

Additionally, DFO and the Heiltsuk Nation maintain their commitments to annual development of a Joint Fisheries Management Plan for Pacific Herring in the Central Coast. Results from the MSE process may inform this on-going commitment.

The DFO Sustainable Fisheries Framework policy suite includes the Fishery Decision-making Framework Incorporating the Precautionary Approach (PA Policy; DFO 2009). The PA Policy requires the identification of limit reference points (LRPs) to serve as thresholds to undesirable stock states. Status-based LRPs were presented and approved for the five major Pacific Herring management areas in February 2017 (DFO 2017, Kronlund et al. 2018). Closed-loop feedback simulation testing of candidate MPs was recommended as a next step to evaluate the consequences of LRP choice for each area. However, the identification of a preferred management procedure requires a fully specified set of measurable objectives that includes reference points (typically categorized as limits and targets) and to the extent possible, specification of objectives related to catch, catch variability, and socio-cultural goals. Therefore, core fisheries management objectives, proposed by DFO at the Integrated Herring Harvest Planning Committee in May 2017, as well as potential stock-specific objectives are included in this first cycle of MSE processes for the Haida Gwaii (HG), Prince Rupert District (PRD), and the Central Coast (CC) management areas. Note that a fully specified set of objectives has not yet been developed for each management area. The DFO will continue to collaborate with coastal First Nations to develop area-specific objectives specific to Food, Social and Ceremonial fisheries and spawn-on-kelp (SOK) fisheries. These and additional objectives may be captured within the Heiltsuk-DFO Joint Fisheries Management Plan for Herring in the Central Coast and through the development of a Rebuilding Plan for Haida Gwaii Herring (under development through a partnership between the Council of Haida Nation, DFO, and Parks Canada).

Finally, DFO will continue to engage with the herring industry, government and non-government organizations to describe broader objectives related to conservation, economics and access.

In July 2018, a formal peer review was conducted on the Pacific Herring operating model (modified from Cox et al. 2019) and management procedure evaluation for the West Coast of Vancouver Island (WCVI) and Strait of Georgia (SOG) management areas (DFO 2019). The review focused on closed-loop simulation testing of MPs under three scenarios describing future trends in natural mortality, which is the dominant factor in Herring stock dynamics. These two management areas were chosen to initiate MSE processes for Pacific Herring for two reasons. First, stocks and fisheries in these two areas span the range of historical patterns in stock dynamics observed across Herring management areas in British Columbia. Therefore, experience gained could be applied to the remaining three major management areas. Second, conservation and fishery objectives were available, having been developed in part via application of the PA Policy as well as workshops with WCVI First Nations and industry participants.

DFO Fisheries Management requested that DFO Science Branch evaluate the performance of candidate management procedures for northern stock areas in order to complete initial cycles of the MSE processes. Harvest strategies in northern stock areas (i.e., HG, PRD, and CC) were to be evaluated utilizing the operating model and experience gained from WCVI and SOG management areas.

Evaluation of results and advice produced from this Canadian Science Advisory Secretariat (CSAS) Science Response Process (SRP) will support renewal of the Pacific Herring management framework and inform development of the 2019/2020 Pacific Herring Integrated Fisheries Management Plan (IFMP), where appropriate. The publication of these results does not constitute consultation with First Nations, but presents DFO’s initial simulations for the northern Pacific Herring management areas. DFO is committed to collaborating with First Nations on the development of objectives and management procedures within the MSE process.

This Science Response results from the Science Response Process of August 15, 2019 on the Evaluation of Management Procedures for Pacific Herring (*Clupea pallasii*) in the Haida Gwaii, Prince Rupert District, and the Central Coast Management Areas of British Columbia.

Background

Pacific Herring (*Clupea pallasii*) in British Columbia (BC) are managed based on five major stock management areas: Haida Gwaii, Prince Rupert District, Central Coast, Strait of Georgia, and West Coast of Vancouver Island, and two minor stock management areas.

Renewal of the management framework for Pacific Herring uses MSE to evaluate the performance of candidate management procedures (MPs) against hypotheses about past and future stock and fishery dynamics.

Core stock and fishery objectives common to all management areas are listed in Table 1. The proposed core objectives reflect DFO policy intent to avoid a biomass limit and achieve a target biomass, and goals regarding the level and variability of catches over time. These objectives do not necessarily reflect the objectives of First Nations or herring stakeholders in each area. This paper reports the relative performance of MPs based on metrics related to each core objective. The performance of MPs is evaluated against current hypotheses about Pacific Herring stock dynamics represented by the operating models (Benson et al. 2018[1]). Analysis of performance relative to the core objectives is the basis of advice provided by this paper.

Area specific objectives are under development to reflect goals proposed by First Nations and the fishing industry via bilateral workshops; a number of these are included in Appendix A (Table A1). Results of simulation tests of MP performance are reported in Appendix B using metrics matched to the area-specific objectives. These results provide a preliminary illustration of the likely trade-offs in management outcomes that arise from area-specific objectives.

The first MSE cycles for the WCVI and SOG management areas were completed in 2018 (DFO 2019). Steps included operating model (OM) development, fitting the OM to Pacific Herring stock and fishery monitoring data, and closed-loop simulations of MP performance for alternative future natural mortality scenarios (DFO 2019). That study specifically evaluated whether candidate harvest control rules within management procedures designed for each area could avoid the LRP with a high probability (75-95%) over three herring generations (15-years).

Lessons from the simulation analyses for the WCVI and SOG management areas can be applied to the northern stock areas. These lessons include:

(i) individual stock areas probably require different MPs because underlying stock dynamics and response to harvest differs among areas;

(ii) long-term management performance and risk of breaching a limit was dominated by the maximum target harvest rate and was less dependent on the particular form of harvest control rule (e.g., hockey stick, constant escapement); and

(iii) a maximum catch cap may be needed to mitigate the effects of positive assessment errors.

The herring assessment model is generally unbiased over many simulation trials. However, annual estimates of spawning biomass can be highly variable, with some years exhibiting large positive or negative assessment errors depending on how the model responds to new data. A very large overestimate of biomass and catch limit may lead to short-term overfishing, which is usually more costly than under-exploitation. The reason is that it can take many years, or even decades in the case of herring, to recover from a low biomass state. Simulations for the WCVI management area showed that risks of positive assessment errors could be mitigated via catch caps that provide an upper limit to the catch independent of the assessment model. For the SOG management area, catch caps investigated in 2018 were too high to take effect very often in the simulations. In order to determine whether MP performance could be improved, supplemental analyses involving lower catch caps are conducted here using the same methods and objectives applied by DFO (2019). A brief summary appears below; full analysis and response is reported in Appendix C.

Analysis and response

This paper uses a closed-loop simulation approach to evaluate the relative performance of candidate MPs for the HG, PRD and CC management areas, using the identical methodology presented in DFO (2019). Within each area, the MPs differ in the form of the harvest control rule (HCR) and choices of catch cap, but use the same stock and fishery monitoring data and assessment model. We retain the term MP for the sake of generality, as future evaluations may

[1] Benson, A.J., J.S. Cleary, S.P. Cox, S. Johnson, M.H. Grinnell. 2018. Performance of management procedures for British Columbia Pacific Herring (*Clupea pallasii*) in the presence of model uncertainty: closing the gap between precautionary fisheries theory and practice. CSAP Working Paper 2015PEL02. *In prep.*

employ alternative assessment methods or data choices as well as differences in HCRs. The following sub-sections provide brief descriptions of each element involved in simulating MP performance. In particular, we focus on aspects of MPs and operating models that are unique to each northern stock area. Additional details of the simulation procedures, diagnostic checks, and performance measure calculations are given in DFO (2019). Supplemental analyses for the SOG management area detailed in Appendix C, with key results presented below.

Management objectives

This paper only evaluates MP performance against the core conservation objective – "avoid LRP of $0.3B_0$ with high probability (75-95%) over three herring generations (DFO 2019)". Any MP failing to achieve this objective must either be modified or discarded from further consideration. Some MPs requested via workshops initially failed to meet the conservation objective. For PRD and CC management areas, we nevertheless report their performance to illustrate the effects of modifications aimed at increasing the likelihood of passing the conservation test.

Performance relative to biomass and yield objectives (Table 1) that are subordinate to the core conservation objective would normally be assessed via ranking against objectives or trade-off analyses. However, the order of priority in applying biomass and yield objectives has not yet been identified for Pacific Herring. The PA Policy (DFO 2009) implies that a broader set of objectives related to social and economic aspects of fisheries can be emphasized when the stock is well above the LRP. Engagement with First Nations and the fishing industry can provide a more complete appreciation of socio-cultural and economic goals for each stock and management area and ideally lead to the establishment of the priority of both core objectives and area-specific objectives.

Management procedures for northern management areas

Historical MP

The historical MP (MP1) for Pacific Herring is comprised of

(i) a statistical catch-at-age stock assessment model (Martell et al., 2012; Cleary et al. 2018) that estimates current spawning stock biomass in year T ($\hat{B}_T$), unfished equilibrium spawning stock biomass ($\hat{B}_0$), and a pre-fishery spawning stock biomass forecast for the upcoming year ($\hat{B}_{T+1}$), and

(ii) a minimum escapement harvest control rule consisting of a 20% maximum target harvest rate when the forecast spawning biomass is above a minimum spawning biomass escapement level (E) or "cutoff" set at an estimate of 0.25B0 (Hall et al. 1988).

To mimic historical application of the HCR, MP1 implements fixed cutoff values from year 1996. The mathematical form of the minimum escapement rule for setting a total allowable catch (C_{T+1}) for the upcoming year is:

Eq 1. $$C_{T+1} = \min\{B_{T+1} - E, 0.2 * B_{T+1}\}$$

Values for the minimum escapement (E) for each stock are given in Figure 1 and as Table 2 MP1. Data requirements for the historical MP are described in Table 1.

Alternative MPs

We examined 10 alternative MPs for the HG, PRD, and CC management areas (Table 2). We include a 0 catch ("NoFish") MP for each stock-scenario combination to demonstrate the probability of meeting the LRP objective in the absence of fishing and to provide a common reference for MP performance. We also include a “slow-up” MP that requires spawning biomass to be above the lower control point on the harvest control rule for at least 3 years before allowing any fishing.

Food, Social, and Ceremonial (FSC) removals of 136 t (150 short tons) is simulated in each projection year for all MPs except MP9, which assumes no fisheries of any kind. The simulations assume that the full catch (C_{T+1}), including FSC, is taken each year even though, in practice, full catches are often not achieved.

Operating models

Herring population dynamics for the three northern management areas are simulated using single-sex, age-structured operating models previously described in Tables 3 and 4 of Benson et al. 2018[1]. The operating models simulate a historical period $T_0 \le t \le T_1 - 1$ corresponding to 1951 - 2018, and a projection period $T_1 \le t \le T_2$ corresponding to 2019 – 2033 (i.e., 3 herring generations, where generation time is calculated following Seber 1997). Uncertainty about stock history is represented by an approximation to the joint posterior probability distribution of operating model parameters. These distributions were obtained by numerically integrating the 2018 Pacific Herring stock assessment model posterior density functions over the parameter space using Markov Chain Monte Carlo (MCMC, Gelman 2013), in which a sample of 5,000 posterior points are selected from 5,000,000 MCMC draws under either a time-varying-*M* or constant-*M* natural mortality hypothesis. Further details are described in Benson et al. (2018)[1].

We used three operating model (OM) scenarios to represent the dynamics of Pacific Herring based on different assumptions about temporal variability in natural mortality (M). Following reviewer recommendations for the analysis of WCVI and SOG management areas (DFO 2018), we define a Reference OM scenario that is most consistent with historical observations of herring stocks and fisheries. A separate set of Robustness OMs represent alternative hypotheses about future herring productivity. Reference and Robustness OMs are described in Table 1. Each OM conditioning fit follows the methods described in Benson et al. (2018)[1] and OM parameter estimates for HG, PRD, and CC are presented in Table 3

Reference Operating Model: Density-dependent $\mathbf{M}$

The density-dependent mortality (DDM) operating model scenario includes the assumption that future natural mortality rates return to the long-term average estimated over the entire historical period (1951-2018; Figure 3, top row). In addition, the DDM scenario adds a low-frequency/ high-natural mortality pulse when biomass drops below 30% of operating model B_0 to simulate conditions where low spawning biomass may lead to serious harm for the stock. In this scenario, operating model B_0 values are fixed at the estimated value from the conditioning stock assessment in the terminal year of the historical period.

Robustness Operating Model: Density-independent $\mathbf{M}$

Robustness OMs are included as plausible alternative hypotheses about the future patterns in natural mortality that could have important implications for management outcomes. The density-independent mortality (DIM) scenario implements the assumption that future natural mortality rates return to the average estimated over the most recent 10 years (Figure 3, middle row). The DIM scenario does not incorporate low frequency natural mortality pulses as implemented for the DDM scenario.

Robustness Operating Model: Constant M

A constant natural mortality (conM) scenario is used as a second Robustness OM to represent an alternative view in which natural mortality remains constant over time (Figure 3, bottom row). This scenario involves a constant natural mortality rate for the historical period and simulates a constant average natural mortality during the projection period. The conM scenario represents a fairly large, but potentially important departure from the Reference OM where, in contrast, natural mortality is highly variable over past and future periods as described in Benson et al. (2018)[1].

Management procedure evaluation results

Haida Gwaii

No MP, including the No_Fish_NoFSC MP (MP9) was able to satisfy the core conservation objective (Table 1) under the reference DDM scenario for the HG management area (Table 4.. The probability of spawning biomass being above the LRP ranged from 21% to 36% over the 11 MPs. Further simulations based on the Robustness OMs were deemed unnecessary given failure of MPs under the Reference OM. The Reference OM (Figure 3) simulates a scenario in which natural mortality over the next three future generations will not decrease to pre-2000 levels when herring biomass and productivity were higher. Simulated MP performance for HG is consistent with the most recent stock assessment, which described the HG stock as persisting in a low biomass, low productivity state in since 2000 (DFO 2019b).

Central Coast

The historical MP for CC Herring (MP1), which uses a maximum target harvest rate of 20%, was not able to meet the LRP objective under the density-dependent mortality assumptions of the Reference OM (Table 5). However, MPs that applied target harvest rates at, or below, 10% did meet the core LRP objective under the Reference OM. This result is consistent with the experience from the SOG and WCVI analyses (see Background section, lessons learned (ii)). Including a catch cap of 5,000 t (MP6) did not substantially improve conservation status possibly because the cap was set too high to affect performance.

The 7 MPs satisfying the conservation objective under the Reference OM were further tested against scenarios defined by the DIM and conM Robustness OMs (Table 6). As expected, performance against the conservation objective was worse for all MPs (including no fishing) for the DIM scenario, because natural mortality rates increase over the projection period for this OM. In contrast, all MPs are able to meet the conservation objective (all probabilities > 98%) under the conM Robustness OM because projected natural mortality rates are lower than in the recent past.

Prince Rupert District

Similar to CC herring, the historical MP (MP1) failed to meet the conservation objective under the Reference OM. All MPs with maximum target harvest rates of 10% or less met the conservation objective with 76-78% probability and two of the MPs with 20% maximum target harvest rates (MP2 and MP13) also met the conservation objective (Table 7). Overall, when evaluated for performance against the conservation objective, the best performing MPs for PRD encompass a range of operational control points, target harvest rates at or below 20%, and catch caps. A catch cap of 2,500 t (MP6) did not substantially increase the probability of exceeding the LRP over 15-years, although it does reduce average catch by 620 t (MP6 vs. MP5).

The 8 MPs satisfying the conservation objective under the Reference OM were tested against scenarios defined by the DIM and conM Robustness OMs (Table 8). Similar to results for the CC management area, performance against the LRP objective is worse for all MPs under the DIM scenario and relatively better under conM, primarily due to the lower average natural mortality.

Slow-up MP

The slow-up MPs were unable to meet the conservation objective for both the CC and PRD management area, mainly because we only included this option with 20% maximum target harvest rates, which generally fared poorly under conditions simulated by the Reference OM.

Strait of Georgia

Harvest recommendations for 2019 SOG Herring fisheries were provided using MP4 with a catch cap of 30,000 t (HS30-60_HR.2_cap30.0, DFO 2019b). Appendix C describes supplemental analyses of six different catch caps for MP4 used to further investigate the role of lower catch caps in mitigating risks of positive assessment errors. For SOG, catch caps between 30,000 t and 5,000 t had no discernable gain in conservation performance under all 3 OM scenarios (Table C2) and median harvest rates never exceed the target maximum harvest rate of 20% (Figure C1, bottom row, first column). As MPs range from the no-cap MP (HS30-60_HR.2) to the most restrictive 5 kt cap (HS30-60_HR.2_cap5.0), the cap is applied more often, and entire harvest rate envelopes move further below the target maximum harvest rate of 20%. MPs with catch caps of 20 kt or less rarely exceed the 20% target maximum harvest rate (Figure C1, bottom row).

Conclusions

Selection of a management procedure for each Pacific Herring fisheries management area is an iterative process conducted with the participation of First Nations, the fishing industry, government, and non-government organizations. This study extends DFO (2019) to the 3 northern Pacific Herring management areas with stock and fishery monitoring data updated to include 2018. Similar to DFO (2019), failure to achieve the core conservation objective (Table 1) is used to eliminate MPs from further consideration.

For the HG management area, no MP, including the historical and no fishing MPs, performed satisfactorily against the conservation objective. For the CC and PRD management areas, several MPs were able to avoid the LRP with at least 75% probability under the Reference DDM scenario and conM scenario, but failed to do so under conditions simulated by the DIM scenario.

Robustness OM scenarios such as DIM and conM are included here as alternative hypotheses about past and future productivity of Pacific Herring stocks. Although there are many possible ways to incorporate MP performance in robustness trials into decision-making, there is currently no accepted "best scientific" way of combining results from multiple operating models (Rossi et al. 2019). For Pacific Herring, a density-independent increase in natural mortality in the future under DIM would lead to probabilities lower than 75% for meeting the conservation objective, even in the absence of fishing. Furthermore, under this scenario, several MPs had only minor impacts on the LRP probabilities. For example, for the CC management area under the DIM scenario, MP5 (HS30-60_HR.1) and MP7 (HS30-60_HR.05) had probabilities of maintaining the stock above the LRP of 52% and 55%, respectively, compared to 60% in the absence of fishing.

This study indicates that a range of MPs can meet the conservation objective set for Pacific Herring under the Reference OM for the CC and PRD management areas; and that the particular set of MPs meeting these objectives differs between the management areas. This result reflects one of the key lessons learned from the SOG and WCVI analyses where MP performance differed among areas because of differing stock and fishery dynamics (see Background section, lessons learned (i), DFO 2019).

For the CC management area, MPs performing best against the conservation objective have a 10% or lower harvest rate and include a range of operational control point choices. The proposed catch cap of 5,000 t had no effect on management performance under the conditions simulated, suggesting that estimated biomass (and potentially assessment errors) and catch rarely increased to the point where application of the target harvest rate produced a catch > 5,000 t.

For the PRD management area, the best performing MPs generally had 10% or lower harvest rates, although one with a 20% harvest rate, MP2, met the conservation objective because it also used a highly conservative $0.5B_0$ lower control point. This choice resulted in more frequent fishery closures as spawning biomass declined below the lower control point.

While several MPs are able to meet core conservation objectives for CC and PRD, they also imply different trade-offs among biomass (e.g., ecosystem) and yield outcomes. For management areas where multiple MPs meet the conservation objective, further ranking of the remaining objectives is needed in order to provide decision-makers with a tractable set of trade-off choices. Mechanisms for ranking objectives can include workshops and explicit identification of existing harvest or access priorities. Ranking of objectives can reveal tradeoffs between MPs in order to identify and eliminate undesirable outcomes.

For the SOG management area, a comparison of catch caps from 30,000 t to 5,000 t (added to MP4) showed no discernable gain in conservation performance under all 3 OM scenarios. Concerns over positive assessment errors leading to overharvesting were investigated by examining simulated harvest rates. Within a simulation framework overharvesting occurs when simulated harvest rates exceed the MP’s target harvest rate.

Results for 15-year projections show that median harvest rates never exceed the target maximum harvest rate of 20% for SOG. For individual projection years, the entire harvest rate envelope moves further below the target maximum harvest rate of 20% as catch caps become more restrictive. MPs with catch caps of 20 kt or less rarely exceed the 20% target maximum harvest rate and could be considered if this is indeed an operational objective.

Tables

Table 1. Components of the Herring management framework common to MSE cycle 1 in all stock areas.

Management framework component		**Description**	**Details**
Core Objectives	Conservation (LRP)	Avoid the Limit Reference Point (LRP) of $0.3B_0$ with high probability over three herring generations, where "high probability" is defined as 75-95%	Objective 1
	Biomass (Target B)	Maintain spawning stock biomass at or above $0.60B_0$ with at least 50% probability over three herring generations	Objective 2
	Catch	Maintain average annual variability in catch of less than 25% over three herring generations	Objective 3
		Maximize average annual catch over three herring generations	Objective 4
Operating model	Density dependent natural mortality (DDM)	Future M_t returns to the long-term average estimated to occur over the entire historical period 1951-2018. Simulates low-frequency/high-mortality events when biomass drops below the LRP of 30% of B_0.	Figure 3, top row
	Density independent natural mortality (DIM)	Future natural mortality rates M_t return to the average rate estimated to occur over the most recent 10 years (i.e., the average of $\hat{M}_{2009:2018}$).	Figure 3, middle row
	Constant natural mortality (conM)	Future natural mortality rates M_t held at historical average.	Figure 3, bottom row

Management framework component		Description	Details
Management procedure	Data	(1) fishery catch data from the reduction (pre-1970), seine-roe, gillnet-roe, food and bait, and special use fisheries; (2) herring spawning biomass index for Survey 1 (surface, 1951-1987) and Survey 2 (dive, 1988-2018); (3) proportions-at-age observations from commercial fisheries and from the test fishery/biological sampling program.	(Cleary et al. 2018)
	Herring stock assessment model	Estimates historical biomass, recruitment, natural mortality, selectivity, and stock-recruitment parameters up to time step *t*, as well as projected biomass for upcoming year and operational control points.	(Cleary et al. 2018)
	Harvest control rule	Focus of MP evaluations in MSE cycle 1 in all stock areas. See Table 2 for candidates	Table 2

Table 2. Management procedures (MPs) tested against the Reference OM (DDM) for each of the three northern management areas. MPs are a combination of the HCR functional form, lower control point (LCP), upper control point (not required for minE functional form; UCP), harvest rate (U_{target}), maximum catch (cap), and number of years above the LCP. For example, for Haida Gwaii Herring, MP1 is minE10.7_HR.2; for PRD Herring, MP 13 is HS50-60_HR.2_cap2.5. MP labels are used to refer to MPs in the text. The historic MP (MP1) is marked with an asterisk and grey shading denotes MPs that appear in DFO 2019. Three additional MPs (MP10, MP11, MP14) appear in Appendix B (Table A2).

MP	Label	U_{target} (HR)	Maximum Catch (t)			HCR Functional Form	Lower control point (LCP)			UCP	Years Above LCP
			HG	CC	PRD		HG	CC	PRD		
MP1*	minE-LCP_HR.2	0.2	-	-	-	minE	10,700 t	17,600 t	12,100 t	-	-
MP2	minE0.5B0_HR.2	0.2	-	-	-	minE	$0.5B_0$	$0.5B_0$	$0.5B_0$	-	-
MP3	minE.5B0_HR.1	0.1	-	-	-	minE	$0.5B_0$	$0.5B_0$	$0.5B_0$	-	-
MP4	HS30-60_HR.2	0.2	-	-	-	HS	$0.3B_0$	$0.3B_0$	$0.3B_0$	$0.6B_0$	-
MP5	HS30-60_HR.1	0.1	-	-	-	HS	$0.3B_0$	$0.3B_0$	$0.3B_0$	$0.6B_0$	-
MP6	HS30-60_HR.1_cap	0.1	3,000	5,000	2,500	HS	$0.3B_0$	$0.3B_0$	$0.3B_0$	$0.6B_0$	-
MP7	HS30-60_HR.05	0.05	-	-		HS	$0.3B_0$	$0.3B_0$	$0.3B_0$	$0.6B_0$	-
MP8	NoFish_FSC	est.	136	136	136	FSC Only	-	-	-	-	-
MP9	NoFish_NoFSC	0	0	0	0	No FSC	-	-	-	-	-
MP12	HS30-60_HR.2_slowUp3	0.2	-	-	-	HS	$0.3B_0$	$0.3B_0$	$0.3B_0$	$0.6B_0$	3
MP13	HS50-60_HR.2_cap	0.2	3,000	5,000	2,500	HS	$0.5B_0$	$0.5B_0$	$0.5B_0$	$0.6B_0$	

Table 3. Herring operating model properties arising from fits to historical data. For each Herring management area and M assumption, the first row shows (left to right) the negative log likelihood followed by key estimated and derived parameter posterior mean values with posterior standard deviations in the following row. Estimated and derived quantities are: observation error standard deviation (t_{obs}), stock-recruitment process error standard deviation (s_R), estimated catchability for the surface survey (q_4), stock-recruitment steepness (h), initial natural mortality rate (M_0), average historical natural mortality rate ($\bar{M}$), unfished spawning biomass (B_0), spawning stock biomass in 2018 (B_{2018}), and spawning stock depletion in 2018 ($D_{2018} = B_{2018} / B_0$). Biomass units are thousands of metric tonnes and natural mortality is yr^{-1}.

Stock	*M* assumption	l	t_{obs}	s_R	$q_{4(surface)}$	h	M_0	$\bar{M}$	B_0	B_{2018}	D_{2018}
HG	Time-varying	-388.156	0.539	0.864	0.412	0.776	0.411	0.577	22.610	4.029	0.127
		-	0.045	0.062	0.047	0.075	0.142	0.031	3.581	1.815	0.084
HG	Constant	-257.164	0.644	1.096	0.120	0.494	0.645	-	71.323	12.320	0.166
		-	0.016	0.020	0.005	0.025	0.005	-	3.932	1.365	0.024
CC	Time-varying	-834.62	0.444	0.782	0.333	0.806	0.471	0.424	52.938	16.480	0.361
		-	0.042	0.054	0.029	0.070	0.156	0.025	8.036	5.928	0.202
CC	Constant	-705.698	0.634	0.884	0.248	0.687	0.456	-	75.295	35.483	0.634
		-	0.048	0.063	0.021	0.075	0.017	-	16.518	5.781	0.168
PRD	Time-varying	-763.7795	0.494	0.767	0.555	0.685	0.450	0.365	59.012	16.524	0.293
		-	0.044	0.057	0.046	0.096	0.160	0.022	15.703	5.730	0.155
PRD	Constant	-656.9275	0.477	0.814	0.426	0.649	0.417	-	61.698	23.776	0.461
		-	0.039	0.058	0.025	0.100	0.015	-	16.675	4.655	0.127

Table 4. Management procedure (MP) performance for the Haida Gwaii stock under the Reference OM (HG_DDM). Performance criteria are calculated over 3 generations (15 years) from the start of the projection period for all objectives (Table 1). MPs are ordered within each scenario by performance achieving the Conservation Objective (Obj1).

			Conservation	Biomass	Yield		
			Obj 1 (LRP)	Objective 2	Objective 3	Objective 4	Catch < 650 t
		Criterion	> 75%	>50%	< 25%	max	min
Scenario	MP	Label	$P(B_t > .3B_0)$	$P(B_t > .6B_0)$	AAV	$\bar{C}_t$	$P(C_t < 650)$
HG_DDM	9	NoFish_NoFSC	0.36	0.1	0	0	1
HG_DDM	8	NoFish_FSC	0.33	0.09	10.6	0.16	1
HG_DDM	7	HS30-60_HR.05	0.32	0.09	31.45	0.25	0.88
HG_DDM	3	minE.5B0_HR.1	0.32	0.08	40.1	0.3	0.87
HG_DDM	5	HS30-60_HR.1	0.31	0.08	42.56	0.34	0.84
HG_DDM	6	HS30-60_HR.1_cap3.0	0.31	0.08	42.5	0.34	0.84
HG_DDM	13	HS50-60_HR.2_cap3.0	0.31	0.07	45.09	0.38	0.87
HG_DDM	2	minE.5B0_HR.2	0.31	0.07	55.47	0.4	0.87
HG_DDM	1	minE10.7_HR.2	0.31	0.07	44.01	0.36	0.89
HG_DDM	12	HS30-60_HR.2_slowUp3	0.30	0.07	53.76	0.41	0.85
HG_DDM	4	HS30-60_HR.2	0.29	0.06	56.77	0.49	0.8

Table 5. Management procedure (MP) performance for the Central Coast management area under the Reference OM (CC_DDM). Performance criteria are calculated over 3 generations (15 years) from the start of the projection period for all objectives (Table 1). MPs are ordered within each scenario by performance achieving the conservation objective (Obj 1), with those that pass the minimum 75% threshold in bold font.

			Conservation	Biomass	Yield		
			Obj 1 (LRP)	Objective 2	Objective 3	Objective 4	Catch < 650
		Criterion	> 75%	>50%	< 25%	max	min
Scenario	**MP**	**Label**	$P(B_t > .3B_0)$	$P(B_t > .6B_0)$	**AAV**	$\bar{C}_t$	$P(C_t < 650)$
CC_DDM	9	**NoFish_NoFSC**	79%	44%	0	0	100%
CC_DDM	8	**NoFish_FSC**	78%	42%	6.74	0.27	100%
CC_DDM	7	**HS30-60_HR.05**	77%	37%	39.92	1.09	45%
CC_DDM	3	**minE.5B0_HR.1**	76%	33%	52.3	1.54	57%
CC_DDM	5	**HS30-60_HR.1**	75%	32%	47.96	1.81	33%
CC_DDM	6	**HS30-60_HR.1_cap5.0**	75%	32%	46.1	1.81	33%
CC_DDM	2	minE.5B0_HR.2	74%	25%	69.8	2.32	60%
CC_DDM	13	HS50-60_HR.2_cap5.0	72%	27%	44.97	2.6	30%
CC_DDM	4	HS30-60_HR.2	71%	21%	60.14	2.96	31%
CC_DDM	12	HS30-60_HR.2_slowUp3	71%	22%	62.17	2.92	36%
CC_DDM	1	minE17.6_HR.2	70%	20%	62.84	3.26	38%

Table 6. Management procedure (MP) performance under the Reference OM (CC_DDM) and Robustness OMs (CC_DIM and CC_conM) for procedures that passed the LRP performance metric criterion under the Reference OM. Performance criteria are calculated over 3 generations (15 years) from the start of the projection period for all objectives (Table 1). MPs are ordered within each scenario by performance achieving the conservation objective (Obj1).

			Conservation	Biomass	Yield		
			Objective 1 (LRP)	Objective 2	Objective 3 (Catch Variability)	Objective 4 (Average Yield)	Catch < 650 t (Prob. Ct < 650 t)
		Criterion	**> 75%**	**>50%**	**< 25%**	**max**	**min**
Scenario	**MP**	**Label**	$P(B_t > .3B_0)$	$P(B_t > .6B_0)$	**AAV**	$\bar{C}_t$	$P(C_t < 650)$
CC_DDM	9	NoFish_NoFSC	79%	44%	0	0	100%
CC_DDM	8	NoFish_FSC	78%	42%	6.74	0.27	100%
CC_DDM	7	HS30-60_HR.05	77%	37%	39.92	1.09	45%
CC_DDM	3	minE.5B0_HR.1	76%	33%	52.3	1.54	57%
CC_DDM	5	HS30-60_HR.1	75%	32%	47.96	1.81	33%
CC_DDM	6	HS30-60_HR.1_cap5.0	75%	32%	46.1	1.81	33%
CC_DIM	9	NoFish_NoFSC	60%	22%	0	0	100%
CC_DIM	8	NoFish_FSC	58%	21%	9.33	0.27	100%
CC_DIM	7	HS30-60_HR.05	55%	17%	40.94	0.66	64%
CC_DIM	3	minE.5B0_HR.1	55%	15%	44.3	0.78	74%
CC_DIM	5	HS30-60_HR.1	52%	14%	54.68	1	52%
CC_DIM	6	HS30-60_HR.1_cap5.0	52%	14%	53.32	1	52%
CC_conM	9	NoFish_NoFSC	100%	85%	0	0	100%
CC_conM	8	NoFish_FSC	100%	84%	6.67	0.27	100%
CC_conM	7	HS30-60_HR.05	99%	75%	39.69	2.68	15%
CC_conM	6	HS30-60_HR.1_cap5.0	99%	69%	26.62	3.93	11%
CC_conM	5	HS30-60_HR.1	98%	67%	41.6	4.69	11%
CC_conM	3	minE.5B0_HR.1	98%	67%	45.77	4.62	24%

Table 7. Management procedure (MP) performance for the Prince Rupert District management area under the Reference OM (PRD_DDM). Performance criteria are calculated over 3 generations (15 years) from the start of the projection period for all objectives (Table 1). MPs are ordered within each scenario by performance achieving the conservation objective (Obj 1), with those that pass the minimum 75% threshold in bold font.

			Conservation	**Biomass**	**Yield**		
			Obj 1 (LRP)	**Objective 2**	**Objective**	**Objective 4**	**Catch < 650 t**
		Criterion	**> 75%**	**>50%**	**< 25%**	**max**	**min**
Scenario	**MP**	**Label**	$P(B_t > .3B_0)$	$P(B_t > .6B_0)$	AAV	$\bar{C}_t$	$P(C_t < 650)$
PRD_DDM	8	**NoFish_FSC**	79%	44%	3.82	0.27	100%
PRD_DDM	9	**NoFish_NoFSC**	79%	45%	0	0	100%
PRD_DDM	7	**HS30-60_HR.05**	78%	40%	36.5	1.28	44%
PRD_DDM	13	**HS50-60_HR.2_cap2.5**	78%	40%	39.43	1.43	57%
PRD_DDM	3	**minE.5B0_HR.1**	78%	37%	51.86	1.85	57%
PRD_DDM	6	**HS30-60_HR.1_cap2.5**	77%	38%	33.35	1.64	39%
PRD_DDM	5	**HS30-60_HR.1**	76%	35%	48.97	2.26	40%
PRD_DDM	2	**minE.5B0_HR.2**	76%	28%	67.14	2.71	58%
PRD_DDM	4	HS30-60_HR.2	73%	24%	53.19	3.62	35%
PRD_DDM	12	HS30-60_HR.2_slowUp3	73%	23%	53.45	3.6	37%
PRD_DDM	1	minE12.1_HR.2	61%	18%	41.8	4.74	18%

Table 8. Management procedure (MP) performance under the Reference OM (PRD_DDM) and Robustness OMs (PRD_DIM and PRD_conM) for MPs that passed the LRP performance criterion under the Reference OM. Performance criteria are calculated over 3 generations (15 years) from the start of the projection period for all objectives (Table 1). Management procedures are ordered within each scenario by performance achieving the conservation objective (Obj1).

			Conservation	**Biomass**	**Yield**		
			Obj 1 (LRP)	**Objective 2**	**Objective 3**	**Objective 4**	**Catch < 650**
		Criterion	**> 75%**	**>50%**	**< 25%**	**max**	**min**
Scenario	**MP**	**Label**	$P(B_t > .3B_0)$	$P(B_t > .6B_0)$	AAV	$\bar{C}_t$	$P(C_t < 650)$
PRD_DDM	8	NoFish_FSC	79%	44%	3.82	0.27	100%
PRD_DDM	9	NoFish_NoFSC	79%	45%	0	0	100%
PRD_DDM	7	HS30-60_HR.05	78%	40%	36.5	1.28	44%
PRD_DDM	13	HS50-60_HR.2_cap2.5	78%	40%	39.43	1.43	57%
PRD_DDM	3	minE.5B0_HR.1	78%	37%	51.86	1.85	57%
PRD_DDM	6	HS30-60_HR.1_cap2.5	77%	38%	33.35	1.64	39%
PRD_DDM	5	HS30-60_HR.1	76%	35%	48.97	2.26	40%
PRD_DDM	2	minE.5B0_HR.2	76%	28%	67.14	2.71	58%
PRD_DIM	9	NoFish_NoFSC	69%	33%	0	0	100%
PRD_DIM	8	NoFish_FSC	68%	32%	3.98	0.27	100%
PRD_DIM	7	HS30-60_HR.05	66%	27%	41.91	0.97	53%
PRD_DIM	13	HS50-60_HR.2_cap2.5	66%	27%	41.89	0.94	67%
PRD_DIM	3	minE.5B0_HR.1	66%	24%	57	1.2	67%
PRD_DIM	6	HS30-60_HR.1_cap2.5	65%	26%	41.46	1.43	48%
PRD_DIM	5	HS30-60_HR.1	64%	23%	53.65	1.59	49%
PRD_DIM	2	minE.5B0_HR.2	63%	18%	75.94	1.56	70%
PRD_conM	9	NoFish_NoFSC	100%	75%	0	0	100%
PRD_conM	8	NoFish_FSC	100%	73%	3.61	0.27	100%
PRD_conM	7	HS30-60_HR.05	100%	65%	37	2.02	22%
PRD_conM	13	HS50-60_HR.2_cap2.5	100%	66%	40.1	1.76	38%
PRD_conM	6	HS30-60_HR.1_cap2.5	99%	63%	24.63	2.12	19%
PRD_conM	5	HS30-60_HR.1	98%	56%	49.98	3.21	24%
PRD_conM	3	minE.5B0_HR.1	98%	58%	52.45	3.11	37%
PRD_conM	2	minE.5B0_HR.2	96%	43%	62.26	5.17	37%

Figures

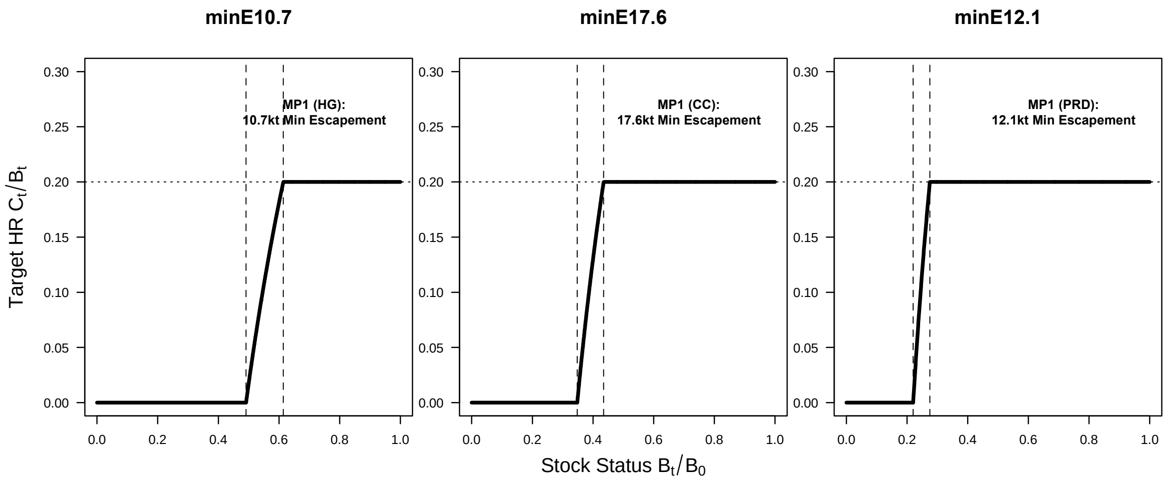

Figure 1. Harvest control rules showing the functional relationship between harvest rate and stock status for MP1 in the three stock areas. Each rule differs in the effective stock status implied by the fixed biomass cutoff used in this minimum escapement rule: HG= 10,700t, CC= 17,600t, and PRD= 12,100t.

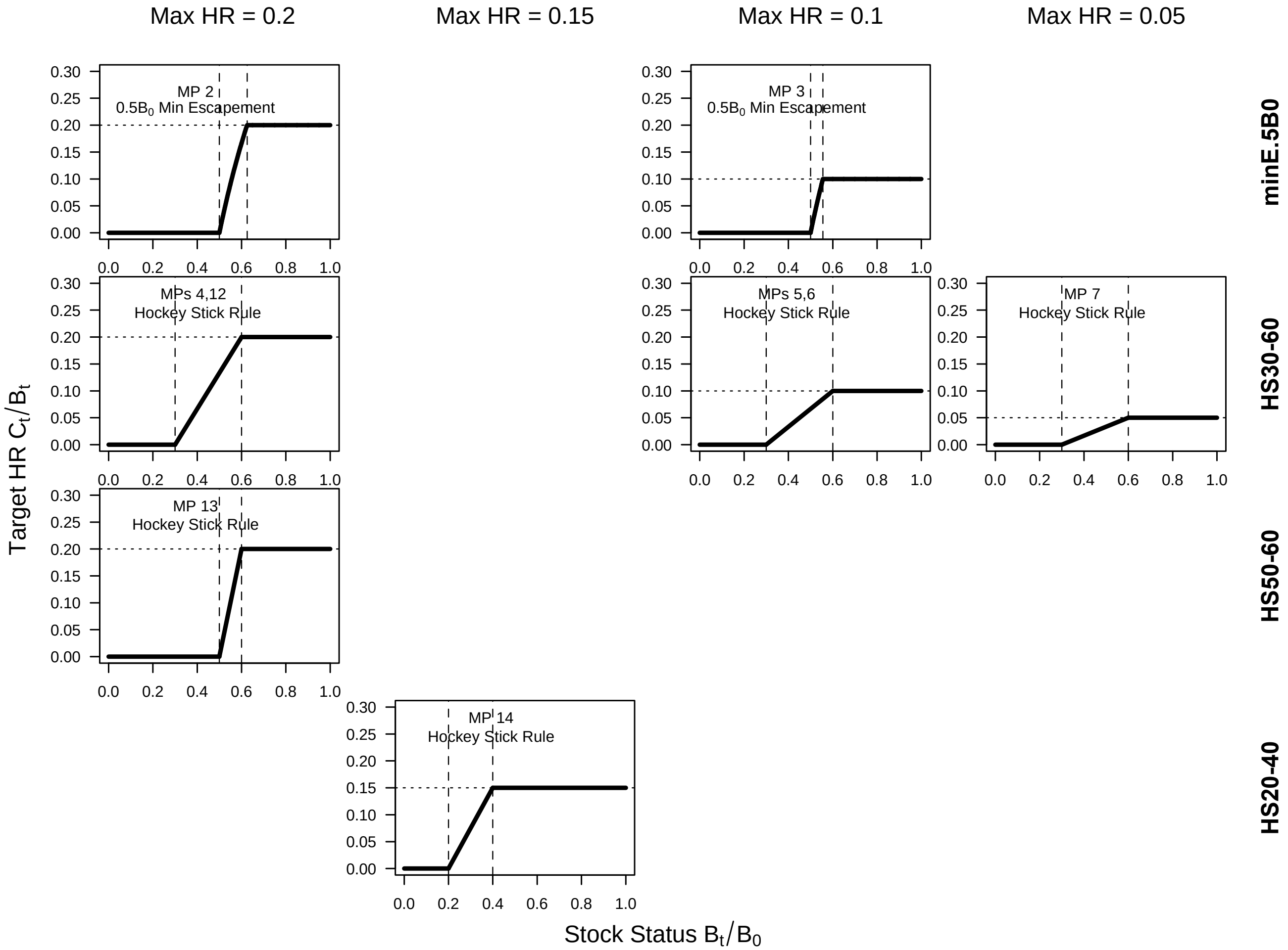

Figure 2. Harvest control rules showing the functional relationship between harvest rate and stock status for each MP. Top row shows the minimum escapement (minE) functional form, while the other rows show the hockey-stick (HS) functional form. Each row within a functional form represents a set of control points. MPs that include extra precautionary controls such as catch caps or slow-up are not graphically representable.

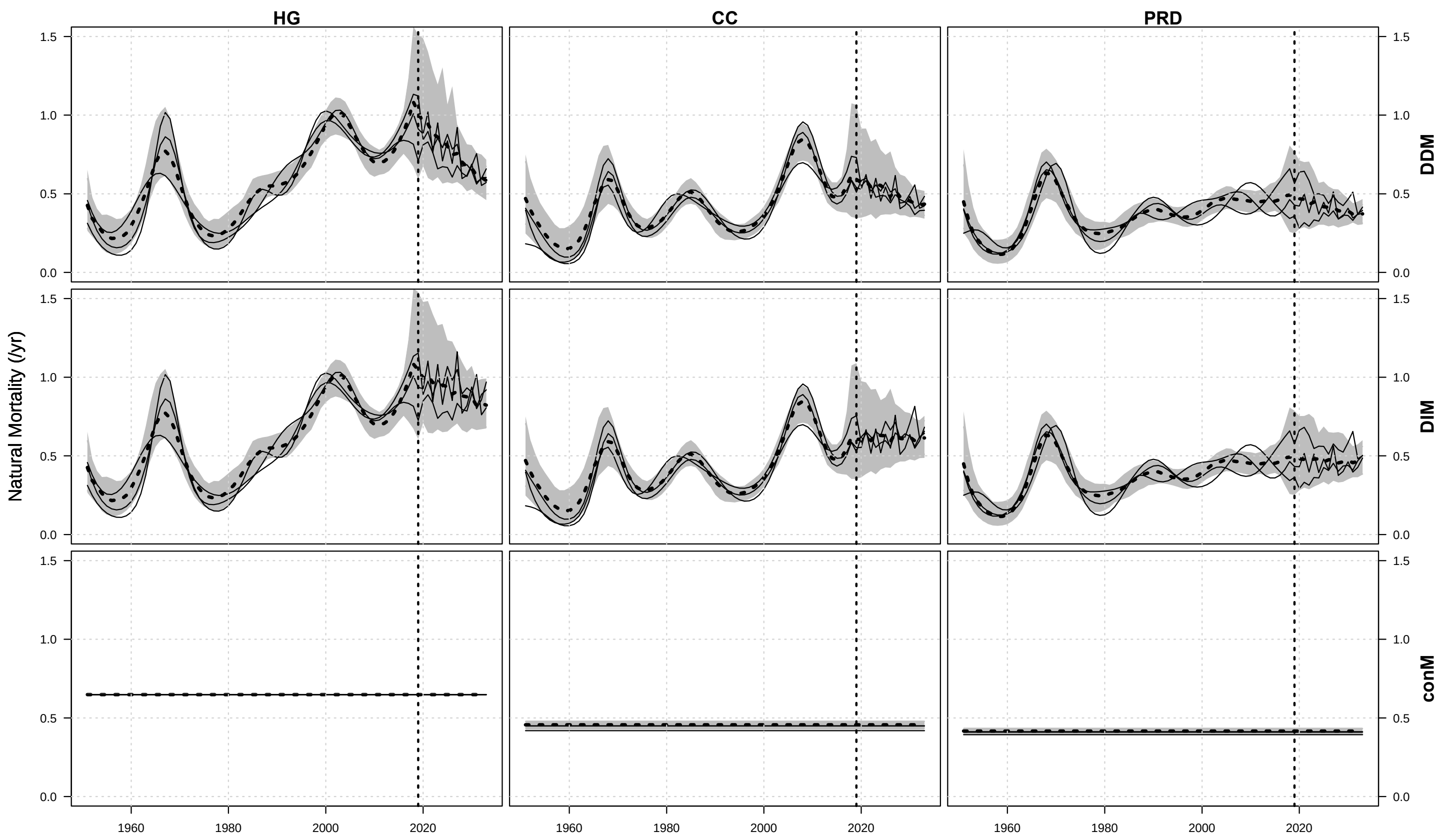

Figure 3. Simulation envelopes for time varying natural mortality in the density-dependent scenario (top row), density-independent scenario (middle row), and constant M scenario (bottom row) for Northern Herring management areas. The envelopes were derived from 5,000 draws from an MCMC approximation to the marginal Bayes posterior distribution of natural mortality. The historical time period is shown from 1951-2018. The vertical dotted line at 2019 denotes the start of the projection period. The grey region denotes the central 95% of the simulated mortality rates, the black dashed line denotes the median of the envelope, and the thin black lines denote mortality rates for three randomly selected replicates.

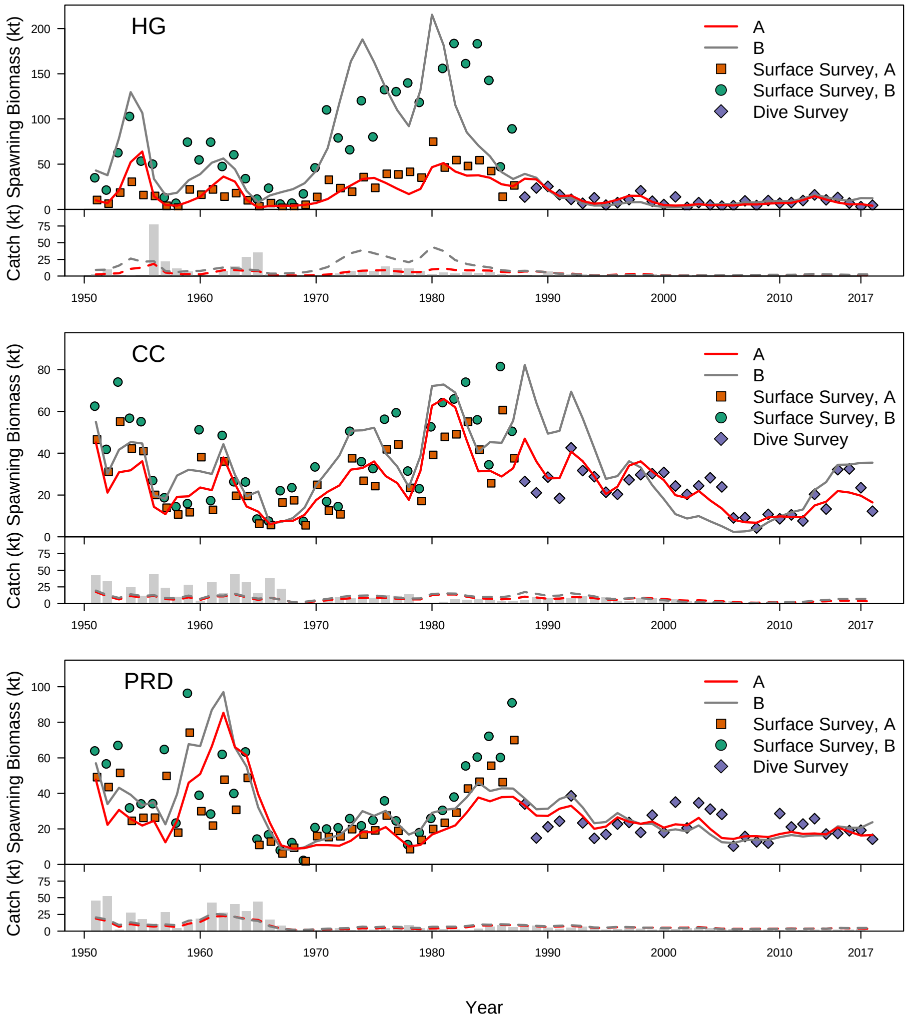

Figure 4. Assessment model estimates of spawning biomass under time-varying M (A) and constant M (B) assumptions for Central Coast Herring (top), Haida Gwaii Herring (middle), and Prince Rupert District Herring (bottom) since 1951. Shaded regions show the central 95% of the posterior biomass distributions, and the solid lines show the median. Points in the spawning biomass plots show the spawn-index observations from the dive survey (diamonds), the surface survey indices scaled by the time-varying M estimate of catchability (squares), and surface survey indices scaled by the constant M estimate of catchability (circles). Grey vertical bars show the historic catch in each year, and the dashed horizontal lines show the catch associated with a 20% harvest rate, using the median biomass under the time-varying M assessment (red) or the constant M assessment (grey).

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Appendix A – Objectives and management procedures proposed for HG, PRD, and CC management areas, articulated through bilateral workshops with First Nations and the herring industry

In 2018 and 2019, DFO initiated a series of bilateral workshops with First Nations in HG (through the Haida Technical Working Group), CC (with representatives from the Heiltsuk Nation and the Central Coast Indigenous Resource Alliance) and PRD (with representatives for the Lax Kw'alaams Band and the Metlakatla First Nation), and with the Herring Industry Advisory Board (HIAB), to inform the first MSE cycle for the northern Pacific Herring management areas. A number of biomass and yield objectives were articulated through these workshops, as well operational objectives linked to underlying goals related to the spatial scale of management, resource access and/or allocation, as well as biological considerations and yield. Some of the objectives proposed through these workshops are summarized by management area in Table A1. Objectives specific to management of Herring in the CC are captured directly in the DFO-Heiltsuk Joint Management Plan (and are not included here).

Discussions with First Nations in the CC and PRD have been preliminary and have not progressed to the development of measurable objectives. Follow-up will continue through 2019/ 2020 when objectives may be modified or new objectives identified. Additionally, HIAB requested simulation-evaluation of three new candidate MPs: two constant catch procedures (MP10 and MP11) where a constant amount of catch is removed every year regardless of stock status (i.e., no biomass-related feedback control of catch) and a hockey-stick shaped HCR with a 15% harvest rate and operational control points set at $0.2B_0$ and $0.4B_0$ (MP14), where for PRD, $0.2B_0$ approximates the lowest estimated biomass from which the stock recovered above long-term (1951-2018) median spawning biomass. The estimated spawning biomass most closely meeting the HIAB-proposed criterion occurred in 1978 (Cleary et al. 2018). These MPs are summarized in Table A2.

A rebuilding plan is required for Herring in Haida Gwaii due to spawning biomass being below the biological limit reference point. To meet these requirements, the Council of Haida Nation, DFO, and Parks Canada initiated the formation of a technical working group to develop a rebuilding plan for Haida Gwaii Herring by December 2020, including advancement of the MSE process. This commitment is also aligned with the *Gwaii Haanas Gina 'Waadluxan KilGulGa Land-Sea-People Management Plan 2018* which includes a herring rebuilding strategy and implementation plan as one of its targets. The Haida Technical Working Group proposed the target biomass objective in Table A1.

Table A1. First Nation and industry-proposed management objectives for the northern Pacific Herring management areas.

Management area	Management framework component	Description	Details
Haida Gwaii	Target biomass objective	Maintain spawning stock biomass at, or above, a target biomass equivalent to average spawning biomass from 1976-1985 with high probability over three herring generations, where "high probability" is defined as 75-95%	This objective was submitted by the Haida Technical Working Group, intended to prioritize rebuilding of herring biomass until stocks are resilient enough to sustain a sac roe fishery while maintaining spawning stock biomass at or above a target biomass equivalent to average spawning biomass from 1976-

Management area	Management framework component	Description	Details
			1985, selected based on high stable biomass and successful fisheries. Additional biomass and SOK fishery objectives will be provided for future MSE cycles and for inclusion in the Haida Gwaii Herring Rebuilding Plan.
Prince Rupert District	Conservation objective	Avoid a biomass limit equivalent to the median spawning biomass in 1978 with high probability over three herring generations, where "high probability" is defined as 75-95%	This biomass limit objective was provided by HIAB based on a rationale that PRD does not show evidence of a low productivity-low biomass state used to define evidence of serious harm for HG, CC, and WCVI (Kronlund et al. 2018). This limit reflects the lowest biomass from which the PRD stock has recovered above the long-term median spawning biomass (which occurred in 1978).
	Target biomass objective	Maintain spawning stock biomass at or above a target biomass level equivalent to the average biomass from 1951-2019, with at least 50% probability over three herring generations	This objective was submitted by HIAB as target biomass objective.
All management areas	Operational objective	Maintain access to as many management areas as possible in each year in order to reduce the risk of fishery failure and to improve financial returns by spreading the harvest out over time to better utilize limited catching, packing and processing capacity.	This objective was submitted by HIAB

Table A2. Industry-proposed management procedures for the northern Pacific Herring management areas. See description Table 2.

MP	Label	U_{target} (HR)	Maximum Catch (t)			HCR Functional Form	Lower control point (LCP)			UCP
			HG	CC	PRD		HG	CC	PRD	
MP10	consTAC0.5	est.	500	500	500	Constant C	-	-	-	-
MP11	consTAC1.0	est.	1000	1000	1000	Constant C	-	-	-	-
MP14	HS20-40_HR.15	0.15	-	-	-	HS	-	-	$0.2B_0$	$0.4B_0$

Appendix B – Supplementary management procedure evaluations for HG, CC, and PRD management areas

DFO is committed to including and evaluating objectives and management procedures provided by First Nations and the herring industry, as well as those proposed by Fisheries Management. However, DFO has not established a process for integrating new objectives and management procedures into Pacific Herring MSE. Furthermore, decision-making may benefit from specification of an approach for ranking MP performance relative to biological and catch objectives, subject to the conservation priority. As is discussed in the "Roadmap to more sustainable Pacific Herring fisheries in Canada: a step-by-step guide to the management strategy evaluation approach" (Landmark Fisheries Research Ltd., unpublished report), when multiple objectives are aligned it is relatively straightforward to rank MP performance and choose the best one. However, in multi-objective contexts such as Pacific Herring, some objectives may conflict to the point where ranking or weighting of objectives is needed.

Tables A3 and A4 present simulation modelling results responding to objectives and MP discussions with First Nations and with the herring industry advisory board.

Analysis and response

For Haida Gwaii, the Haida Technical Working Group proposed a target biomass objective centred on rebuilding spawning biomass to the average levels from 1976-1985 (Table A1, first row). The simulation-evaluations presented in Table 4. show that no MP can meet the conservation objective with high probability, including the 0 catch (no fishing) MPs. In the Herring MSE, target biomass objectives are considered after spawning biomass has rebuilt above the LRP, thus, we did not include MP evaluations against this objective at this time.

Three additional MPs were proposed by the Herring Industry Advisory Board (Table A2). We present results of the constant catch MPs for HG, CC and PRD and of an additional hockey-stick rule with lower control points for PRD (Table B1). For both CC and PRD management areas, under the Reference OM (DDM scenario), the 500 t constant catch rule (MP10) was able to meet the core conservation objective (Obj 1, Table 1) with a 76% probability. Performance of the 500 t constant catch rule (MP10) for CC and PRD shows a 2-3% reduction in the probability of spawning biomass meeting the conservation objective when compared to the 0 catch (no fishing) MPs. For the PRD management area, 6 MPs achieve the same (76%) or higher conservation performance and have higher average catch levels than the 500 t constant catch MP (Table 7 vs. Table B1). MP10 (conTAC0.5) however has better performance against biomass objective 2. Observations are similar but less pronounced for the CC management area (Table 5 vs. Table B1).

The conservation objective was not met for CC or PRD at constant catch levels of 1,000 t (MP11). The hockey-stick rule with lower control points (MP14) could not achieve the conservation objective (Table B1, final row).

For the PRD management area, HIAB proposed a spawning biomass limit reference point based on stock recovery from the estimated biomass in 1978 (Table A1). The median estimated spawning biomass depletion in 1978 is 0.17 (17%) under time-varying *M* scenarios (DDM, DIM) and 0.27 (27%) under constant *M* (conM), thus lower than the established LRP of $0.3B_0$ (Kronlund et al. 2018) for scenarios with time-varying *M*. MP evaluations show all tested MPs are able to meet this HIAB-proposed objective with at least a 90% probability (Table B2). Consideration of alternates to the core management objectives requires analyses of both the rationale for the choice and evaluation of the consequences of changing objectives in terms of stock preservation and other outcomes. Such analyses should include an examination of stock depletion and spawning biomass levels (average, minimum, maximum) over the projections to determine, for example, whether spawning biomass persists at a lower spawning biomass by the end of the projection period (e.g., overall biomass may be lower on average even though the conservation objective is met).

Lastly, the HIAB-proposed target biomass objective based on long-term average biomass (Table A1, fourth row) was shown to be achievable under a variety of MP functional forms (Table B2).

Table B1. Management procedure performance for the three Northern management areas under the Reference OM (HG_DDM, CC_DDM, PRD_DDM) for the NoFish and constant catch management procedures proposed by the Herring Industry Advisory Board (HIAB, grey fill). MPs are ordered within each scenario by performance achieving the core conservation objective (Obj 1), with those that pass the minimum 75% in bold font.

			Conservation	**Biomass**	**Yield**		
			Obj 1 (LRP)	**Objective 2**	**Objective 3**	**Objective 4**	**Catch < 650 t**
		Criterion	**> 75%**	**>50%**	**< 25%**	**max**	**min**
Scenario	**MP**	**Label**	$P(B_t > .3B_0)$	$P(B_t > .6B_0)$	AAV	$\bar{C}_t$	$P(C_t < 650)$
HG_DDM	9	NoFish_NoFSC	36%	1%	0	0	100%
HG_DDM	8	NoFish_FSC	33%	9%	10.6	0.16	100%
HG_DDM	10	consTAC0.5	25%	7%	7.94	0.64	69%
HG_DDM	11	consTAC1.0	21%	5%	7.84	1.11	17%
CC_DDM	9	**NoFish_NoFSC**	79%	44%	0	0	100%
CC_DDM	8	**NoFish_FSC**	78%	42%	6.74	0.27	100%
CC_DDM	10	**consTAC0.5**	76%	40%	6.77	0.76	3%
CC_DDM	11	consTAC1.0	72%	37%	6.77	1.26	0%
PRD_DDM	9	**NoFish_NoFSC**	79%	45%	0	0	100%
PRD_DDM	8	**NoFish_FSC**	79%	44%	3.82	0.27	100%
PRD_DDM	10	**consTAC0.5**	76%	42%	3.25	0.77	0%
PRD_DDM	11	consTAC1.0	74%	39%	4.62	1.27	0%
PRD_DDM	14	HS20-40_HR.15	68%	24%	38.98	3.73	16%

Table B2. Management procedure performance for the Prince Rupert District management area under the Reference OM (PRD_DDM) comparing the objectives and management procedures proposed by the Herring Industry Advisory Board (HIAB, grey fill) with core objectives and MPs appearing in Table 7. MPs are ordered within each scenario by performance achieving the core conservation objective (Obj 1), with those that pass the minimum 75% in bold font.

			Conservation	Biomass	Yield			HIAB proposed	
			Obj 1 (LRP)	Obj 2	Obj 3	Obj 4	Catch < 650 t	Conservation	Biomass
		Criterion	> 75%	>50%	< 25%	max	min	> 75%	> 50%
Scenario	**MP**	**Label**	$P(B_t > .3B_0)$	$P(B_t > .6B_0)$	AAV	$\bar{C}_t$	$P(C_t < 650)$	$P(B_t > B_{1978} / B_0)$	$P(B_t > \bar{B}_t)$
PRD_DDM	9	**NoFish_NoFSC**	79%	44%	3.82	0.27	100%	94%	63%
PRD_DDM	8	**NoFish_FSC**	79%	45%	0	0	100%	95%	64%
PRD_DDM	7	**HS30-60_HR.05**	78%	40%	36.5	1.28	44%	94%	59%
PRD_DDM	13	**HS50-60_HR.2_cap2.5**	78%	40%	39.43	1.43	57%	94%	60%
PRD_DDM	6	**HS30-60_HR.1_cap2.5**	78%	37%	51.86	1.85	57%	94%	59%
PRD_DDM	3	**minE.5B0_HR.1**	77%	38%	33.35	1.64	39%	94%	58%
PRD_DDM	10	**consTAC0.5**	76%	42%	3.25	0.77	0%	92%	59%
PRD_DDM	5	**HS30-60_HR.1**	76%	35%	48.97	2.26	40%	94%	56%
PRD_DDM	2	**minE.5B0_HR.2**	76%	28%	67.14	2.71	58%	94%	54%
PRD_DDM	11	consTAC1.0	74%	39%	4.62	1.27	0%	90%	56%
PRD_DDM	4	HS30-60_HR.2	73%	24%	53.19	3.62	35%	94%	48%
PRD_DDM	12	HS30-60_HR.2_slowUp3	73%	23%	53.45	3.6	37%	94%	48%
PRD_DDM	14	HS20-40_HR.15	68%	24%	38.98	3.73	16%	93%	45%
PRD_DDM	1	minE12.1_HR.2	61%	18%	41.8	4.74	18%	91%	36%

Appendix C – Supplementary management procedure evaluations for the SOG management area

Background

The 2018 simulation study revealed all 10 MPs tested could meet the core conservation objective (Table 1) for the Strait of Georgia (SOG) management area with greater than 90% probability under all operating model scenarios (DFO 2019). The 2019 harvest recommendations for the SOG fishery reflected application of a management procedure that utilizes a stock assessment forecast of 2019 spawning biomass and operational control points at (0.3, 0.6) of B_0 with a 20% target harvest rate and a catch cap of 30,000 t (DFO 2019b). DFO Fisheries Management requested evaluation of alternative catch caps for the current (most recently implemented) SOG MP, denoted HS30-60_HR.2_ cap30.0, to better understand interactions between catch caps and realized harvest rates, given that the assessment model estimates could be positively biased in some years.

We evaluated six variations of the current MP that differed in the choice of catch caps under scenarios defined by the Reference (SOG_DDM) and Robustness (SOG_DIM and SOG_conM) OMs. Catch caps of 5, 10, 15, 20, 25, and 30 kt were tested. MPs are ranked within each scenario by performance against the conservation objective (Obj 1). Operating models are conditioned using SOG historical data from 1951-2017, as per DFO 2019, and do not include data updates from the 2018/19 herring season. As with the northern stocks, operating model equations appear in Tables 3 and 4 of Benson et al. (2018)[1]. Estimated OM properties arising from fits to the historical data are reported in Table C1. Figures showing simulation envelopes for natural mortality, and assessment model estimates of spawning biomass under the time varying and constant *M* scenarios, appear in DFO 2019 as Figures 2 and 3, respectively, and are thus not reproduced here.

Analysis and response

Reducing the catch cap from 30,000 t to 5,000 t had no discernable improvement in conservation performance (Obj 1) under all 3 OM scenarios (Table C2). Gains in MP performance for the biomass objective (Obj 2) are most noticeable under the SOG_conM scenario. For example, there is a change in the probability of being above $0.6B_0$ from 55% to 78% when comparing the no-cap MP (HS30-60_HR.2) to the 5 kt cap MP (HS30-60_HR.2_cap5.0). Conversely, reductions in MP performance for Obj 4 (maximizing catch) are most noticeable under the two time-varying *M* scenarios, with median average catch dropping from 35.6 kt without a cap for DDM (37.5 kt for DIM), to 5 kt under the 5 kt cap. This is because projected biomass is decreasing from the highest levels on record under these scenarios, leading to larger catches when the cap is not applied.

Simulation envelopes comparing no cap MP (HS30-60_HR.2) with catch caps of 25,000 t (cap25.0) and 30,000 t (cap30.0) show similar performance across the 3 OM scenarios (Reference OM shown in Figure C1). In the short term, harvest rates are reduced below the maximum target of 20%, due to high biomass in time-varying *M* scenarios, and due to a persistent negatively biased assessment error in the constant *M* scenario around 2020-2021 (not shown). Over time, the simulation envelopes for harvest rate approach the target maximum rate of 20%, with median harvest rates never exceeding this limit (Figure C1, bottom row, first column). As MPs range from the uncapped MP (HS30-60_HR.2) to the most restrictive 5 kt cap (HS30-60_HR.2_cap5.0), the cap is applied more often, and entire harvest rate envelopes move further below the target maximum harvest rate of 20%, which is rarely exceeded under catch caps of 20 kt or less.

Table C1. Herring operating model properties arising from fits to historical data for SOG. See Table 3 for description.

M assumption	l	τ_{obs}	σ_R	$q_{4(surface)}$	h	M_0	$\bar{M}$	B_0	B_{2017}	D_{2017}
Time-varying	-1300.825	0.428	0.683	1.034	0.743	0.466	0.552	138.203	113.978	0.804
	-	0.040	0.053	0.103	0.084	0.177	0.029	30.346	32.340	0.259
Constant	-1187.015	0.455	0.710	0.804	0.663	0.618	0.618	140.221	59.211	0.416
	-	0.038	0.052	0.046	0.085	0.012	0.012	26.249	11.267	0.099

Table C2. Performance of variations on the current MP (HS30-60_HR.2_cap30.0) when catch caps are varied for SOG Herring under the Reference OM (SOG_DDM) and Robustness OMs (SOG_DIM and SOG_conM). Performance criteria are calculated over 3 generations (15 years) from the start of the projection period (2018-2032) for all objectives. MPs are ordered within each scenario by performance against the conservation objective (Obj 1).

			Conservation	Biomass	Yield		
			Obj 1 (LRP)	Obj 2	Obj 5	Obj 6	Closures
		Criterion	> 75%	>50%	< 25%	max	min
Scenario	MP	Label	$P(B_t > .3B_0)$	$P(B_t > .6B_0)$	AAV	$\bar{C}_t$	$P(C_t < 650)$
SOG_DDM	2	HS30-60_HR.2_cap5.0	100%	96%	25.93	5.12	1%
SOG_DDM	3	HS30-60_HR.2_cap10.0	100%	93%	10.09	10.11	1%
SOG_DDM	4	HS30-60_HR.2_cap15.0	100%	91%	4.66	15.09	1%
SOG_DDM	5	HS30-60_HR.2_cap20.0	100%	90%	2.63	19.93	1%
SOG_DDM	6	HS30-60_HR.2_cap25.0	100%	88%	4.37	24.09	1%
SOG_DDM	7	HS30-60_HR.2_cap30.0	100%	87%	8.3	27.85	1%
SOG_DDM	1	HS30-60_HR.2	100%	86%	25.35	35.6	1%
SOG_DIM	2	HS30-60_HR.2_cap5.0	100%	96%	25.93	5.12	1%
SOG_DIM	3	HS30-60_HR.2_cap10.0	100%	94%	9.97	10.11	1%
SOG_DIM	4	HS30-60_HR.2_cap15.0	100%	92%	4.57	15.09	1%
SOG_DIM	5	HS30-60_HR.2_cap20.0	100%	91%	2.04	20.06	1%
SOG_DIM	6	HS30-60_HR.2_cap25.0	100%	89%	2.93	24.54	1%
SOG_DIM	7	HS30-60_HR.2_cap30.0	100%	89%	6.86	28.38	1%
SOG_DIM	1	HS30-60_HR.2	100%	88%	24.82	37.55	1%
SOG_conM	2	HS30-60_HR.2_cap5.0	100%	78%	35.83	4.86	3%
SOG_conM	3	HS30-60_HR.2_cap10.0	100%	70%	27.03	8.95	4%
SOG_conM	4	HS30-60_HR.2_cap15.0	100%	64%	25.26	12.22	5%
SOG_conM	5	HS30-60_HR.2_cap20.0	99%	59%	30.59	14.62	5%

SOG_conM	6	HS30-60_HR.2_cap25.0	99%	56%	33.98	16.09	5%
SOG_conM	7	HS30-60_HR.2_cap30.0	99%	55%	37.78	16.73	5%
SOG_conM	1	HS30-60_HR.2	99%	55%	40.27	16.75	5%

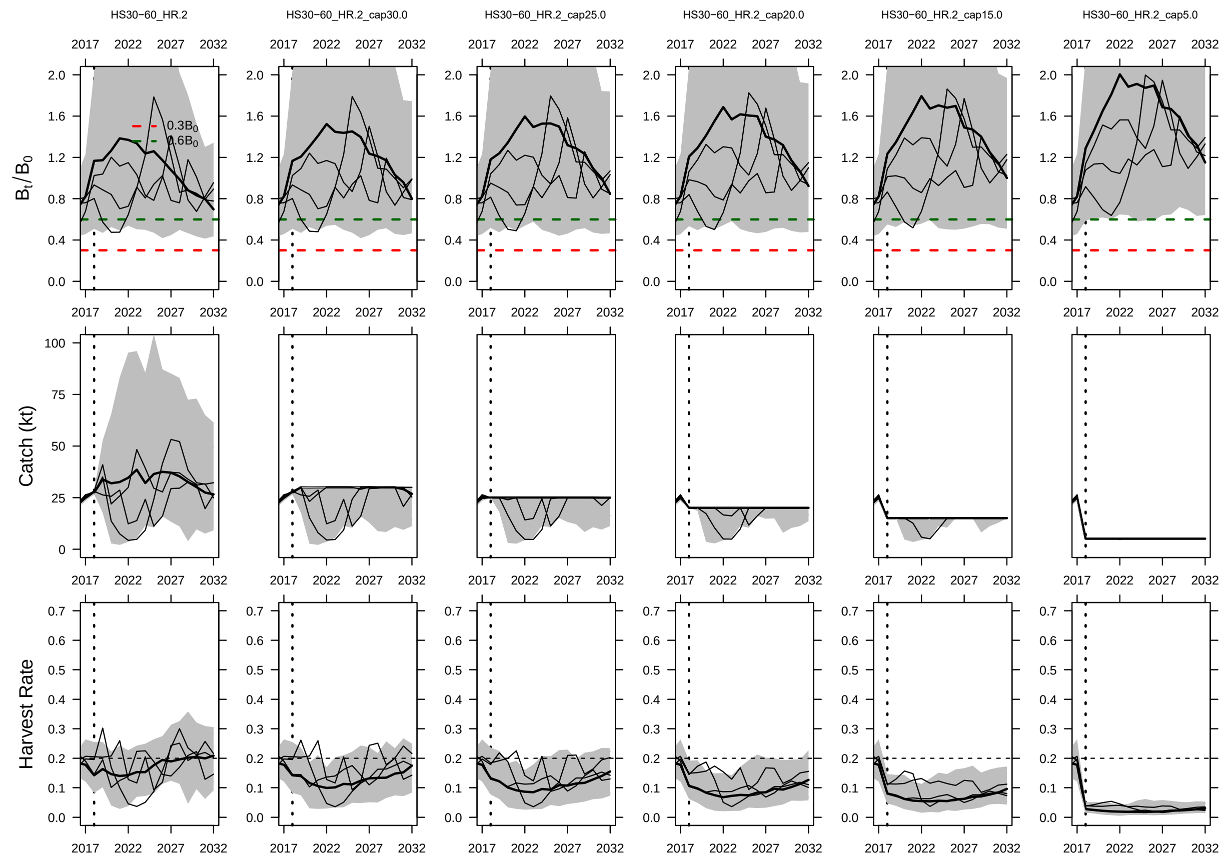

Figure C1. Simulation envelopes for depletion (top row), catch (middle), and realized harvest rate (bottom row) for SOG Herring under the Reference OM when managed using a range of caps on the current MP (HS30-60_HR.2, with caps decreasing from left to right). Grey areas show the central 95% of simulated trajectories, the heavy black line shows the median of all 100 replicates, and the thin black lines show randomly chosen trajectories for 3 individual replicates. The vertical dotted line at 2018 denotes the beginning of the projection period, and the horizontal dashed lines in the top row show 0.3B0 (red) and .6B0 (green), while in the bottom row the horizontal dashed line shows the maximum target harvest rate.

Appendix D – Supplementary model outputs for CC and PRD management areas

Table D1. Distributions of biomass depletion relative to unfished for 5 year increments under the MPs that passed the conservation objective criterion for Central Coast herring, starting in 2018. The first number in each year shows the median relative biomass, with the limits of the central 90% of the distribution shown in parentheses. All values correspond to Figure D1.

		Biomass Depletion			
Scenario	MP	2018	2023	2028	2033
CC_DDM	NoFish_NoFSC	0.31 (0.156, 0.519)	0.448 (0.096, 1.318)	0.538 (0.147, 1.311)	0.806 (0.433, 1.343)
CC_DDM	NoFish_FSC	0.31 (0.156, 0.519)	0.435 (0.093, 1.305)	0.525 (0.137, 1.303)	0.791 (0.414, 1.327)
CC_DDM	HS30-60_HR.05	0.31 (0.156, 0.519)	0.425 (0.092, 1.205)	0.483 (0.137, 1.143)	0.713 (0.389, 1.229)
CC_DDM	minE.5B0_HR.1	0.31 (0.156, 0.519)	0.431 (0.093, 1.126)	0.464 (0.137, 0.995)	0.659 (0.367, 1.15)
CC_DDM	HS30-60_HR.1	0.31 (0.156, 0.519)	0.418 (0.092, 1.11)	0.443 (0.137, 0.993)	0.644 (0.354, 1.135)
CC_DDM	HS30-60_HR.1_cap5.0	0.31 (0.156, 0.519)	0.418 (0.092, 1.11)	0.443 (0.137, 1.083)	0.653 (0.354, 1.177)

Table D2. Distributions of biomass depletion relative to unfished for 5 year increments under the MPs that passed the conservation objective criterion for Prince Rupert District herring, starting in 2018. The first number in each year shows the median relative biomass, with the limits of the central 90% of the distribution shown in parentheses. All values correspond to Figure D2.

		Biomass Depletion			
Scenario	MP	2018	2023	2028	2033
PRD_DDM	NoFish_FSC	0.298 (0.153, 0.429)	0.454 (0.091, 1.275)	0.595 (0.135, 1.595)	0.816 (0.327, 1.476)
PRD_DDM	NoFish_NoFSC	0.298 (0.153, 0.429)	0.464 (0.096, 1.286)	0.612 (0.148, 1.611)	0.832 (0.35, 1.493)
PRD_DDM	HS30-60_HR.05	0.298 (0.153, 0.429)	0.43 (0.091, 1.206)	0.546 (0.135, 1.411)	0.691 (0.313, 1.314)
PRD_DDM	HS50-60_HR.2_cap2.5	0.298 (0.153, 0.429)	0.43 (0.091, 1.207)	0.543 (0.135, 1.508)	0.701 (0.309, 1.394)
PRD_DDM	minE.5B0_HR.1	0.298 (0.153, 0.429)	0.431 (0.091, 1.143)	0.53 (0.135, 1.199)	0.622 (0.311, 1.166)
PRD_DDM	HS30-60_HR.1_cap2.5	0.298 (0.153, 0.429)	0.41 (0.091, 1.229)	0.524 (0.135, 1.478)	0.69 (0.298, 1.334)
PRD_DDM	HS30-60_HR.1	0.298 (0.153, 0.429)	0.41 (0.091, 1.18)	0.514 (0.135, 1.349)	0.623 (0.299, 1.161)
PRD_DDM	minE.5B0_HR.2	0.298 (0.153, 0.429)	0.413 (0.091, 1.061)	0.465 (0.131, 0.949)	0.543 (0.293, 1.007)

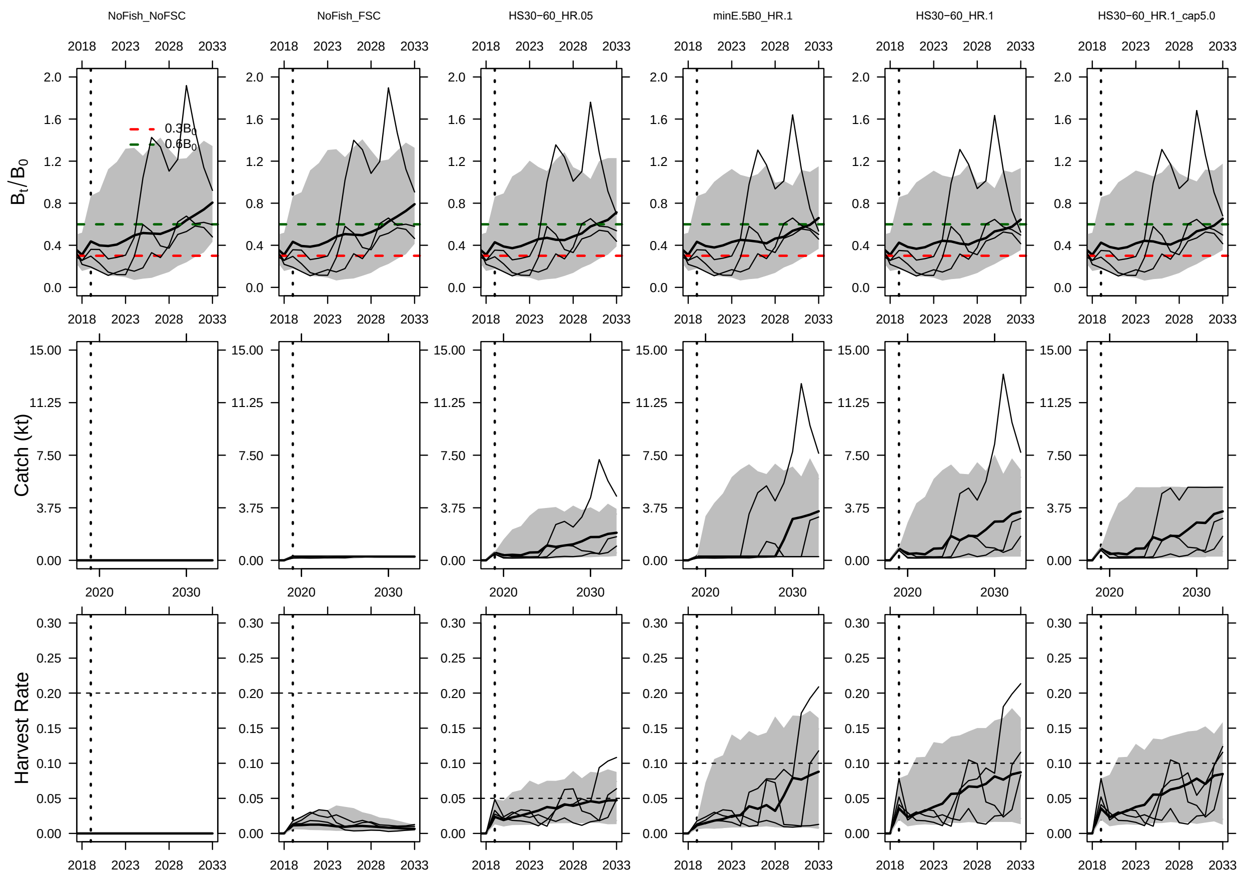

Figure D1. Simulation envelopes for depletion (top row), catch (middle), and realized harvest rate (bottom row) for CC Herring under the Reference OM when managed using MPs that passed the conservation objective. Grey areas show the central 95% of simulated trajectories, the heavy black line shows the median of all 100 replicates, and the thin black lines show randomly chosen trajectories for 3 individual replicates. The vertical dotted line at 2018 denotes the beginning of the projection period, and the horizontal dashed lines in the top row show .3B0 (red) and .6B0 (green), while in the bottom row the horizontal dashed line shows the maximum target harvest rate.

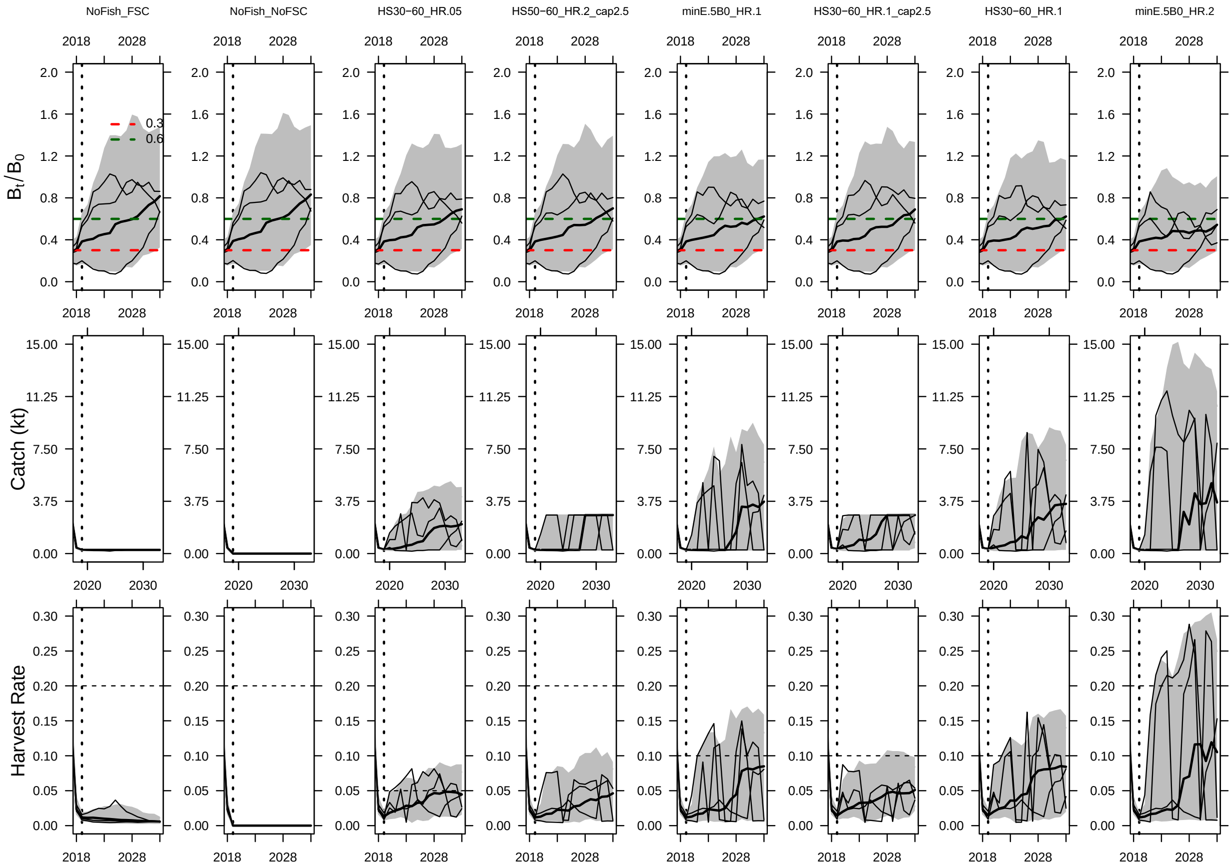

Figure D2. Simulation envelopes for depletion (top row), catch (middle), and realized harvest rate (bottom row) for PRD Herring under the Reference OM when managed using MPs that passed the conservation objective. Grey areas show the central 95% of simulated trajectories, the heavy black line shows the median of all 100 replicates, and the thin black lines show randomly chosen trajectories for 3 individual replicates. The vertical dotted line at 2019 denotes the beginning of the projection period, and the horizontal dashed lines in the top row show .3B0 (red) and .6B0 (green), while in the bottom row the horizontal dashed line shows the maximum target harvest rate.

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