UPDATED EVALUATION OF MANAGEMENT PROCEDURES FOR PACIFIC HERRING (*CLUPEA PALLASII*) IN THE STRAIT OF GEORGIA AND THE WEST COAST OF VANCOUVER ISLAND MANAGEMENT AREAS OF BRITISH COLUMBIA

Context

Fisheries and Oceans Canada (DFO) has committed to renewing the current Pacific Herring management framework to address a range of challenges facing Pacific Herring stocks and fisheries in British Columbia. Renewal of the Pacific Herring 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 uncertainty in stock and fishery dynamics. The purpose of MSE is to identify MPs that provide acceptable management risks and outcomes through model simulation, relative to defined conservation and fishery management objectives.

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

1. collaboration with coastal First Nations, and
2. engagement with the fishing industry, government and non-government organizations.

In July 2018, a formal peer review was conducted on the Pacific Herring MSE operating models (based on 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 (*M*), which is the dominant factor evaluated in Pacific Herring stock dynamics.

In the spring of 2019, the first cycle of the MSE process was initiated using the method presented in DFO (2019) for the three remaining Pacific Herring stock management areas. The process included performance evaluation of MPs for Haida Gwaii (HG), Prince Rupert District (PRD), and Central Coast (CC; DFO 2020).

In 2020, DFO Fisheries Management requested that DFO Science Branch update the simulations to include stock and fishery data up to 2019 (WCVI) and 2020 (SoG) and to evaluate the performance of additional candidate management procedures for the WCVI and SoG management areas; now considered the second MSE cycle for these stocks.

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 2020/2021 Pacific Herring Integrated Fisheries Management Plan (IFMP).

This Science Response results from the Science Response Process of September 30, 2020 on the Management Strategy Evaluation Update: Evaluation of Management Procedures for Pacific

Herring (*Clupea pallasii*) in the Strait of Georgia and West Coast of Vancouver Island 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.

The first MSE cycle for the WCVI and SoG management areas was completed in 2018 (DFO 2019). Steps in those analyses included developing Operating Models (OMs) to represent future natural mortality (*M*) scenarios, fitting the OMs to historic Pacific Herring stock and fishery monitoring data from 1951-2017, constructing candidate MPs, identifying objectives and closed-loop simulations of MP performance for each of the alternative OMs over three herring generations (15-years; DFO 2019). The same approach was applied to the HG, PRD, and CC stock management areas in 2019 (DFO 2020).

The only component of the MPs evaluated to date is the harvest control rules (HCRs) identified for each area; alternative data streams and stock assessment models have not been considered. The objectives applied to all MSEs to date (DFO 2019, DFO 2020) reflect policy goals for avoiding the biological limit reference point (LRP) for all major Pacific Herring stock management areas ($0.3SB_{0;}$ Kronlund et al. 2017), as well as achieving a proposed target biomass, and options for the level and variability of catch over time. The first objective, avoiding the LRP, establishes a conservation priority and acts as a constraint for the other biomass target and catch objectives. Additionally, area- and group-specific objectives are under development to reflect the goals of First Nations and the fishing industry. When available, these objectives are included in the evaluation of MPs. The MSE objectives used in this cycle 2 evaluation are described in Table 1. All the MSE results provided so far are a preliminary illustration of the likely trade-offs between these objectives that arise from the application of various management procedures.

Several lessons have been learned from past MSE analyses which have helped to inform this evaluation and to identify areas of future investigation:

1. The annual catch-at-age stock assessment model can produce large positive assessment errors. Such assessment errors cause over-estimation of spawning biomass and result in recommended catch limits that exceed the intended target harvest rate specified by a HCR (e.g., over-harvest). The assessment model is generally unbiased over many simulation trials which supports the use of simulation evaluation over several generations to investigate the outcomes of proposed management procedures.
2. Reducing harvest rates (in this case from 20% to 10%) is the most effective means of mitigating stock assessment errors. The use of a catch cap, implemented as a maximum annual catch level, was an effective model-free way to further mitigate assessment errors in simulated years when biomass levels are high. Simulation analyses additionally showed that outcomes are insensitive to the choice of operational control points (OCPs) that define a HCR when a low harvest rate (HR) and catch cap are applied. This occurs because low biomass levels (associated with the lower OCP) are avoided for these MPs. The MSE simulations continue to apply the same assessment model and therefore these findings are considered for stock areas and all new MPs proposed for analysis.
3. Differences in Pacific Herring MPs, including the HCR components, are expected among stock management areas. The reasons relate to differences in objectives deemed important

by resource users, differences in historical and current stock and fishery dynamics, and differences in the magnitude and direction of assessment model errors in each stock management areas. In contrast, conservation objectives such as those based on avoiding a threshold to serious harm (i.e., a limit reference point) in alignment with the DFO Precautionary Approach (PA) Policy Framework (DFO 2009), are held constant among stock management areas based on the analyses of Kronlund et al. (2018). All stock management areas continue to be evaluated independently in the MSE cycles with the conservation objective being common to all areas.

4. There are many possible ways to incorporate MP performance from multiple operating models into decision-making (i.e. averaging performance of an MP across operating models) but there is currently no scientific best practice for combining results from multiple operating models. Ultimately, a scientific review of potential approaches for weighting alternative hypotheses is required.
5. In situations where multiple MPs meet the minimum criteria for the conservation objective (using the same operating model), further decision criteria are needed. For example, ranking a secondary objective (e.g., biomass target or yield) would provide decision-makers with a tractable set of trade-off choices.

An extension to this list appears in the Conclusion of this report to include lessons learned from this analysis.

Analysis and Response

A closed-loop simulation approach was used to evaluate the relative performance of candidate MPs for the WCVI and SoG management areas, using the method presented in DFO (2019), with updated historical stock and fishery monitoring data from 1951-2019 (WCVI) and 1951-2020 (SoG). Time series differences are explained below. Within each area, the MPs differ in the functional form of the HCR and choice of catch cap, but use the same biological and fishery monitoring data structure and assessment model to extend stock status inferences. While not all components of the MP varied, we retain the term MP for the sake of generality, as future evaluations may 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 model parameters that are unique to each management area. Additional details of the simulation procedures, diagnostic checks, and performance measure calculations are given in DFO (2019).

Management objectives

This paper focuses on evaluating MP performance against the conservation objective – “avoid LRP of $0.3SB_0$ with high probability (≥75%) over three herring generations (DFO 2019)”. Any MP failing to achieve this objective is either modified or discarded from further consideration. Performance relative to biomass and yield objectives Table 1) that are subordinate to the core conservation objective (i.e. the LRP) 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 DFO 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 and conservation concerns are low. Continued engagement with Pacific Herring users (e.g., First Nations, industry) can provide a more complete understanding of socio-economic and cultural goals for each management area that will ideally lead to the prioritization of objectives in future MSE work.

Management procedures for WCVI and SoG management areas

The MP evaluation explores three alternative functional forms of HCRs: hockey stick, constant escapement, and constant catch procedures. Specific MPs are described in Table 2 with graphical representations in Figure 1.

Science advice in 2018 recommended discontinuing use of the historical fixed cut-off HCR and adopting a HCR with two OCPs for two reasons (DFO 2019):

1. the fixed cut-off values were calculated outside of the current assessment model, last updated in 1996, and therefore ignore 22 years of stock and fishery monitoring data, as well as substantial changes to the structural form of the assessment model; and
2. use of separate lower and upper OCPs allows for altering the slope of the HCR to better meet stock and fishery objectives by avoiding fishery closures and encouraging stock growth.

The historical fixed cut-off HCR has therefore been removed from the list of MP options. Additional MPs have been added to the list for this cycle 2 evaluation upon request from Fisheries Management, and informed by meetings with First Nations, the commercial fishing industry, sport fishers, and environmental non-governmental organizations (ENGOs).

As was the case in cycle 1, Food, Social, and Ceremonial (FSC) removals of 136 t (150 short tons) were simulated in each projection year for all MPs. 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 taken.

Operating models

Herring population dynamics for WCVI and SoG management areas are simulated using single-sex, age-structured operating models previously described in Tables 3 and 4 of Benson et al. (2018)[1]. For WCVI, the operating models simulate a historical period $T_0 \leq t \leq T_1 - 1$ corresponding to 1951 - 2019, and a 15-year projection period $T_1 \leq t \leq T_2$ corresponding to 2020 – 2034 (i.e., three herring generations, where generation time is calculated following Seber 1997). Although historical data for 2020 became available during the analysis an abrupt change in survey index was not observed for WCVI and hence an additional update to 2020 was not undertaken. For SoG, the spawn data in the historical period, $T_0 \leq t \leq T_1 - 1$, extends to 2020 (due to the abrupt increase in the 2020 spawn index relative to 2019, which has an influence on stock status) with the projection period $T_1 \leq t \leq T_2$ corresponding to 2021 – 2035. Uncertainty in stock dynamics was incorporated by either a time-varying or constant natural mortality hypothesis (Figure 2). Models corresponding to each hypothesis were fit to the same set of historical data, creating two historical patterns of population dynamics and fishing mortality (Figure 3), with two different interpretations of current stock status and productivity. Within each operating model, parameter uncertainty was represented by the joint posterior

[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*.

probability distribution of the parameters. Based on the methods used in the current Pacific Herring stock assessment model (Cleary et. al. 2018), approximations of the joint posterior distributions were obtained using 5,000,000 Markov Chain Monte Carlo (MCMC, Gelman 2013) draws from which a sample of 5,000 posterior points were selected via thinning. For the MSE simulations, a different MCMC draw was used to condition each simulation replicate within each operating model hypothesis, with draws sampled using a stratified random design. Further details are described in Benson et al. (2018)[1].

We used three operating models (OM) to represent the dynamics of Pacific Herring based on different assumptions about temporal variability in natural mortality: density-dependent mortality (DDM, Figure 2a) , density-independent mortality (DIM, Figure 2b) and constant mortality (conM, Figure 2c). A brief description of these OMs is included in Table 1 and further details can be found in Benson et al. (2018)[1], DFO (2019), and DFO (2020). In MSE cycle 1 for the northern stock management areas (DFO 2020), the DDM OM scenario was defined as the Reference OM scenario because it appears to be most consistent with historical observations of Pacific Herring stocks and fisheries. The alternative OM hypotheses (DIM and conM) were termed the Robustness OM scenarios. This naming approach was adopted here for WCVI and SoG. There is, however, still no scientifically reviewed method for choosing one OM for predicting Pacific Herring natural mortality over another, therefore results of the MP evaluation are presented for all three of the operating model scenarios described above. Updated OM posterior mean parameter estimates for WCVI and SoG in this MSE cycle 2 analysis are presented in Table 3.

Management procedure evaluation results

West Coast of Vancouver Island

Seven MPs were simulation tested for the WCVI. With the additional years of historical data, all of the candidate MPs met the conservation objective (Table 1) under all OM scenarios with probabilities between 90-92% for DDM, 80-85% for DIM and 89-94% for conM (Table 4). The addition of 2018 and 2019 historical data shows an improvement in performance relative to MSE cycle 1 (DFO 2019) where comparable MPs met the conservation objective with 84-88% probability under the Reference OM (DDM) scenario, 68-78% for DIM and 86-94% for conM. The modest improved performance appears to be the result of the increase in estimated spawning stock biomass in 2018 and 2019 relative to 2016, which increases current stock status relative to the long-term average estimated unfished spawning biomass (SB_o).

Depletion levels for the projection period suggests that WCVI herring biomass can rebuild towards SB_o within the 15-year projection period under two of the OM scenarios (DDM and conM), using a no fishing (i.e., FSC only) MP (Figure 5). The MP with the lowest performance relative to the conservation objective (HS50-60_HR.15) also showed growth potential for the stock under two of the OM scenarios (DDM and conM, Figures 8 & 9). This magnitude of stock growth is not achieved under the DIM OM scenario due to higher projected natural mortality rates. All MPs meet the Herring Industry Advisory Board (HIAB)-proposed target biomass objective ($0.4SB_0$) at the 50% probability level across all three OM scenarios. All MPs meet the DFO-proposed candidate biomass target objective ($0.6SB_0$) under the DDM scenario, however most MPs (all except NoFish_FSC MP) failed to meet the 50% probability criteria under the Robustness OM scenarios (Table 4). Biomass objectives proposed by the Nuu-chah-nulth Nations could not be achieved with a 75% probability, however there are several MPs that do meet the 0.65 and $0.75SB_0$ biomass objectives at the 50% level.

Strait of Georgia

Seven MPs were simulation tested for the SoG. With the exception of the MP with a harvest rate of 30% (HS30-40_HR.30, Table 2), all MPs evaluated met the conservation objective with probabilities ranging from 77-87% for DDM, 75-85% for DIM and 98-100% for conM (Table 5). These results showed a small decrease in conservation performance compared to MSE cycle 1, where all MPs met the conservation objective with 97-100% under the DDM OM scenario. Decreased performance is related to the updated historical data used in the OMs, where the additional years of the most recent data revealed sensitivity of the performance metrics to recent changes in the spawn index. Specifically, spawning biomass estimates for 2017-2019 are lower relative to 2014-2016 and 2020 (Figure 3), while natural mortality estimates under OM hypotheses have increased since MSE cycle 1 was conducted (Figure 2). Overall these results show that the MPs perform well when the population varies according to known dynamics of small pelagic species and potentially, observation error.

Examination of simulated depletion levels showed potential for growth of SoG Herring under the no fishing (FSC only) MP (Figure 5) and low growth under the MP with the lowest performance relative to the conservation objective (minE_LRP_HR.2, Figures 6 & 7). All MPs meet the HIAB-proposed target biomass objective ($0.4SB_0$) at the 50% probability level across all three scenarios, and no MPs with simulated commercial harvest (i.e., harvest rate > 0%) meet the DFO-proposed candidate target biomass objective ($0.6SB_0$) under the DDM and DIM OM scenarios (Table 5).

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 MSE cycle analysis updates the cycle 1 (DFO 2019) analysis of the WCVI and SoG Pacific Herring management areas by including stock and fishery monitoring data up to 2019 for WCVI and 2020 for SoG. Similar to DFO (2019), failure to achieve the core conservation objective (Table 1) was used to eliminate MPs from further consideration.

To date, there remains no consensus on a quantitative method for combining results from multiple operating model scenarios (Rossi et al. 2019) therefore it is recommended that the Robustness OM scenarios, such as DIM and conM, continue to be included as alternative hypotheses about past and future natural mortality of Pacific Herring stocks. The operating model scenarios presented in the study can be used in a decision-making context when considering the performance of candidate MPs and the associated trade-offs under alternative OM hypotheses. However, development of a consistent process to specify how the results from multiple operating models will be integrated to inform decisions is still needed.

For the WCVI management area, the simulation results showed that all candidate MPs met the conservation objectives (i.e., were able to avoid the LRP with at least 75% probability), under all updated OM scenarios. Performance increased slightly relative to the MSE cycle 1 analysis of comparable MPs due to the slight increase in stock status in 2018 and 2019 (DFO 2019). This is an example of a management area where multiple MPs have met the conservation objective and further ranking of the remaining objectives is needed in order to provide decision-makers with a tractable set of trade-off choices. In this case mechanisms for ranking objectives could include collaborative workshops and explicit identification of existing harvest or access priorities.

For the SoG management area, all MPs, except the MP with a target harvest rate of 30% (HS30-40_HR.30, Table 2), were able to avoid the LRP with at least 75% probability under all

OM scenarios. Performance decreased relative to the comparable MPs in MSE cycle 1 (DFO 2019). However, given that the MPs still met the conservation objective within the performance criterion (min 75%), we suggest that the MPs simulated in these analyses perform well when the population varies according to known population dynamics of small pelagic species and potentially, observation errors. The outcomes of MP evaluations appear to be heavily influenced by the last 3-5 years of stock status and natural mortality trends used to condition the OM and future work is recommended to examine this issue further. It is important to investigate the sensitivity of MP performance to hypothesized trends in population dynamics and natural mortality under short-, medium-, and long-term projections as the influences of stock status and natural mortality trends may be most appropriate to inform stock response to management actions in the short-term (e.g., in the next 15 years). If simulations were run over a longer duration (e.g., 50 years) performance might be expected to approach equilibrium, unaffected by most recent trends in OM conditioning data.

The following lessons learned, identified in this MSE cycle 2 analysis, are to be added to the list presented in the Background section:

1. Performance of MPs appears to be influenced by the last 3-5 years of stock status and natural mortality trends used to condition the OMs. If the historical estimates in the most recent years are relatively constant, then the performance will also be relatively constant with the addition of new data. However, if there are large changes in stock status and natural mortality estimates in the most recent years of the historical portion of the OM, then the performance of MPs will change. More work is needed to examine the sensitivity of MP performance to hypothesized trends in natural mortality under short-, medium-, and long-term projections.
2. Decision making under MSE requires a pre-specified process that identifies how simulation results will be applied to fisheries management decision making. For example, a pre-specified process would outline how results from multiple OMs would be combined or weighted to inform decision making (addressing lesson #4 in the Background section) and include a decision criteria about ranking objectives (addressing lesson #5). Details about spatial scales of application, the utility of including best/worst case scenario OMs, weighting OMs based on expert knowledge or model fits to historical data, and/or management actions under exceptional circumstances are appropriately defined prior to reviewing results and decision making. An exceptional circumstance would occur, for example, when a new data observation falls outside the range simulated by the OM and management may need to consider deviation from the chosen MP. Future work is needed to develop this process within the framework of the Pacific Herring MSE.

Tables

Table 1. Components of the Pacific Herring management framework for management strategy evaluation (MSE). Cycle 2.

Component		**Description**	**Details**
Objectives	Conservation (LRP)	Avoid the Limit Reference Point (LRP) of $0.3SB_0$ with high probability over three herring generations (15 years), where "high probability" is defined as 75-95%.	Obj 1
	Spawning Biomass Target	Maintain spawning stock biomass at or above $0.6SB_0$ with at least 50% probability over three herring generations.	Obj 2
	Nuu-chah-nulth Nations (NCN) WCVI Spawning Biomass Target	Maintain spawning stock biomass at or above $0.65SB_0$ with at least 50% or 75% probability over three herring generations.	NCN
		Maintain spawning stock biomass at or above $0.75SB_0$ with at least 50% or 75% probability over three herring generations.	NCN
		Maintain spawning stock biomass at or above a target biomass level equivalent to the average biomass from 1990-1999, with at least 75% probability over two herring generations.	NCN
	Herring Industry Advisory Board (HIAB) Spawning Biomass Target	Maintain spawning stock biomass at or above $0.4SB_0$ with at least 50% probability over three herring generations.	HIAB
	Yield	Maintain average annual variability (AAV) in catch of less than 25% over three herring generations.	Obj 3
		Maximize average annual catch ($\bar{C}_t$) over three herring generations.	Obj 4
		Minimize annual fishery closures ($C_t < 650t$) over three herring generations.	
Operating model	Density dependent natural mortality (DDM)	Future M_t returns to the long-term average estimated to occur over the entire historical period corresponding to 1951-2019 (WCVI) and 1951-2020 (SoG). Simulates low-frequency/high-mortality events when biomass drops below the LRP of $0.3SB_0$.	Reference OM 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 of the historical period.	Robustness OM Figure 3, middle row

Component		Description	Details
	Constant natural mortality (conM)	Future natural mortality rates M_t held at historical average.	Robustness OM Figure 3, bottom row
Management procedure	Data	(1) fishery catch data from 1951-2020 for reduction (pre-1970), seine-roe, gillnet-roe, food and bait, and special use fisheries; (2) herring spawning biomass index for Surface Survey (1951-1987) and Dive Survey(1988-2019 for WCVI; 1988-2020 for SoG); (3) proportion-at-age observations from commercial fisheries and from the test fishery/biological sampling program (1951-2019).	(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 management procedures (MP) evaluations in MSE cycle 2. See Table 2 for list of MPs.	Table 2

Table 2. Management procedures (MPs) tested for the West Coast of Vancouver Island (WCVI) and Strait of Georgia (SoG) management areas. MPs are a combination of the harvest control rule (HCR) functional form, lower control point (LCP), upper control point (not required for minE functional form; UCP), harvest rate (U_{target}), and maximum catch (cap). MP labels are used to refer to MPs in the text. The grey shading denotes MPs that appear in the first management strategy evaluation (MSE) cycle (DFO 2019). Limit reference point (LRP) is $0.3SB_0$.

WCVI Management Area

MP	MP Label	U_{target} (HR)	Maximum Catch (t)	HCR Functional Form	Lower control point (LCP)	Upper control point (UCP)
1	NoFish_FSC	est.	136	FSC Only	-	-
2	HS30-60_HR.10_cap	0.10	2,000	HS	$0.3SB_0$	$0.6SB_0$
3	HS30-60_HR.15_cap	0.15	2,000	HS	$0.3SB_0$	$0.6SB_0$
4	HS50-60_HR.10	0.10	-	HS	$0.5SB_0$	$0.6SB_0$
5	HS50-60_HR.15	0.15	-	HS	$0.5SB_0$	$0.6SB_0$
6	minE-LRP_HR.05	0.05	-	minE	$0.3SB_0$	-
7	consTAC1.0	est.	1,000	Constant C	-	-

SoG Management Area

MP	MP Label	U_{target} (HR)	Maximum Catch (t)	HCR Functional Form	Lower control point (LCP)	Upper control point (UCP)
1	NoFish_FSC	est.	136	FSC Only	-	-
2	HS30-60_HR.10	0.10	-	HS	$0.3SB_0$	$0.6SB_0$
3	HS30-60_HR.15	0.15	-	HS	$0.3SB_0$	$0.6SB_0$
4	HS30-60_HR.20	0.20	-	HS	$0.3SB_0$	$0.6SB_0$
5	HS30-40_HR.30	0.30	-	HS	$0.3SB_0$	$0.6SB_0$
6	minE-LRP_HR.10	0.10	-	minE	$0.3SB_0$	-
7	minE-LRP_HR.20	0.20	-	minE	$0.3SB_0$	-

Table 3. Operating model parameter estimates arising from fits to historical data. For each Pacific 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 (τ_{obs}), stock-recruitment process error standard deviation (σ_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 (SB_0), spawning stock biomass in 2019 for WCVI and 2020 for SoG (SB_t), and spawning stock depletion in 2019 for WCVI and 2020 for SoG ($D_t = SB_t / SB_0$). Biomass units are thousands of metric tonnes and natural mortality is yr^{-1}.

Stock	M assumption	l	τ_{obs}	σ_R	$q_{4(surface)}$	h	M_0	$\bar{M}$	SB_0	SB_t	D_t
WCVI	Time-varying	-673.32	0.490	0.724	0.850	0.729	0.610	0.583	46.161	20.778	0.444
		-	0.041	0.054	0.091	0.076	0.194	0.029	7.082	7.681	0.168
WCVI	Constant	-525.635	0.612	0.882	0.447	0.536	0.636	-	97.981	32.696	0.333
		-	0.047	0.064	0.050	0.072	0.019	-	32.235	6.379	0.116
SoG	Time-varying	-1380.68	0.435	0.693	1.024	0.737	0.472	0.569	135.641	95.350	0.705
		-	0.039	0.053	0.098	0.087	0.162	0.028	29.115	36.287	0.279
SoG	Constant	-1266.83	0.447	0.711	0.802	0.663	0.618	-	142.356	94.318	0.658
		-	0.037	0.052	0.043	0.084	0.011	-	26.565	18.972	0.160

Table 4. Management procedure (MP) performance for the West Coast of Vancouver Island (WCVI) management area under the three operating model (OM) scenarios: density-dependent natural mortality (DDM), density-independent natural mortality (DIM), and constant natural mortality (conM). Performance criteria are calculated over three Pacific Herring generations (gens, i.e., 15 years) from the start of the projection period for all objectives (Obj). MPs are ordered within each scenario by performance of achieving Objective 1. Legend: limit reference point (LRP); Probability (P); maximum (max); Spawning biomass in year t (SB_t); Estimated unfished spawning biomass (SB_0); average annual variability (AAV); Average catch ($\bar{C}_t$); and Average spawning biomass from 1990 to 1999, calculated over two Pacific Herring generations (SB_{AVE}). MPs are defined in Table 2. Performance criteria $SB_t \geq 0.4SB_0$ is proposed by the Herring Industry Advisory Board (HIAB) as a biomass target at $P \geq 50\%$ level. Performance criteria $SB_t \geq 0.65SB_0$, $SB_t \geq 0.75SB_0$, and $SB_t \geq SB_{AVE}$ are proposed by the Nuu-chah-nulth Nations (NCN) as biomass targets at $P \geq 50\%$ and $P \geq 75\%$ levels.

			Conservation	Biomass					Yield		
			Obj 1 (LRP)	HIAB	Obj 2	NCN (see caption)			Obj 3	Obj 4	Catch < 650 t
		Criterion	≥ 75%	≥ 50%	≥ 50%	≥ 50% (or ≥ 75%)	≥ 50% (or ≥ 75%)	≥ 75% *(2 gens)*	< 25%	max	min
Scenario	**MP**	**Label**	$P(SB_t > .3SB_0)$	$P(SB_t \geq .4SB_0)$	$P(SB_t \geq .6SB_0)$	$P(SB_t \geq .65SB_0)$	$P(SB_t \geq .75SB_0)$	$P(SB_t \geq SB_{AVE})$	AAV	$\bar{C}_t$	$P(C_t < 650)$
WCVI_DDM	1	NoFish_FSC	0.92	0.86	0.67	0.63	0.52	0.64	0	0.14	1
WCVI_DDM	6	minE-LRP_HR.05	0.92	0.82	0.61	0.56	0.45	0.56	43.83	1.59	0.25
WCVI_DDM	4	HS50-60_HR.1	0.92	0.83	0.58	0.52	0.40	0.48	55.74	2.47	0.41
WCVI_DDM	2	HS30-60_HR.1_cap	0.91	0.83	0.62	0.55	0.45	0.55	34.71	1.6	0.23
WCVI_DDM	3	HS30-60_HR.15_cap	0.91	0.83	0.61	0.55	0.45	0.55	26.38	1.74	0.22
WCVI_DDM	5	HS50-60_HR.15	0.91	0.81	0.53	0.47	0.34	0.42	60.80	3.38	0.41
WCVI_DDM	7	consTAC1.0	0.90	0.83	0.63	0.57	0.47	0.58	6.77	1.26	0
WCVI_DIM	1	NoFish_FSC	0.85	0.74	0.52	0.47	0.36	0.35	0	0.14	1
WCVI_DIM	6	minE-LRP_HR.05	0.83	0.71	0.47	0.41	0.32	0.29	48.76	1.39	0.31
WCVI_DIM	2	HS30-60_HR.1_cap	0.83	0.70	0.46	0.41	0.31	0.29	46.91	1.46	0.31
WCVI_DIM	4	HS50-60_HR.1	0.83	0.70	0.45	0.39	0.28	0.26	64.52	1.83	0.54
WCVI_DIM	3	HS30-60_HR.15_cap	0.82	0.70	0.47	0.41	0.32	0.29	44.24	1.4	0.37
WCVI_DIM	5	HS50-60_HR.15	0.82	0.69	0.40	0.35	0.23	0.21	67.62	2.54	0.52

		Criterion	Conservation	Biomass					Yield		
			Obj 1 (LRP)	HIAB	Obj 2	NCN (see caption)			Obj 3	Obj 4	Catch < 650 t
			≥ 75%	≥ 50%	≥ 50%	≥ 50% (or ≥ 75%)	≥ 50% (or ≥ 75%)	≥ 75% *(2 gens)*	< 25%	max	min
Scenario	**MP**	**Label**	$P(SB_t > .3SB_0)$	$P(SB_t \geq .4SB_0)$	$P(SB_t \geq .6SB_0)$	$P(SB_t \geq .65SB_0)$	$P(SB_t \geq .75SB_0)$	$P(SB_t \geq SB_{AVE})$	AAV	$\bar{C}_t$	$P(C_t < 650)$
WCVI_DIM	7	consTAC1.0	0.81	0.70	0.48	0.42	0.32	0.31	6.98	1.25	0
WCVI_con	1	NoFish_FSC	0.94	0.84	0.58	0.52	0.41	0.98	0	0.14	1
WCVI_con	7	consTAC1.0	0.93	0.81	0.56	0.49	0.39	0.96	6.67	1.26	1
WCVI_con	2	HS30-60_HR.1_cap	0.93	0.81	0.54	0.48	0.38	0.95	24.51	1.85	0.16
WCVI_con	3	HS30-60_HR.15_cap	0.93	0.80	0.54	0.48	0.38	0.95	21.03	1.92	0.77
WCVI_con	6	minE-LRP_HR.05	0.93	0.80	0.53	0.46	0.37	0.95	45.12	2.76	0.14
WCVI_con	4	HS50-60_HR.1	0.91	0.77	0.47	0.40	0.31	0.92	49.69	5.01	0.23
WCVI_con	5	HS50-60_HR.15	0.89	0.74	0.41	0.36	0.26	0.89	51.66	7.29	0.23

Table 5. Management procedure (MP) performance for the Strait of Georgia (SoG) management area under the three operating model (OM) scenarios: density-dependent natural mortality (DDM), density-independent natural mortality (DIM), and constant natural mortality (conM). Performance criteria are calculated over three Pacific Herring generations (i.e., 15 years) from the start of the projection period for all objectives (Obj). MPs are ordered within each scenario by performance of achieving Objective 1. Legend: limit reference point (LRP); Probability (P); maximum (max); Spawning biomass in year t (SB_t); Estimated unfished spawning biomass (SB_0); average annual variability (AAV); and Average catch ($\bar{C}_t$). MPs are defined in Table 2 above. Performance criteria $SB_t \geq 0.4SB_0$ is proposed by the Herring Industry Advisory Board (HIAB) as a biomass target at $P \geq 50\%$ level.

			Conservation	Biomass		Yield		
			Obj 1 (LRP)	HIAB	Obj 2	Obj 3	Obj 4	Catch < 650 t
		Criterion	≥ 75%	≥ 50%	≥ 50%	< 25%	max	min
Scenario	**MP**	**Label**	$P(SB_t > .3SB_0)$	$P(SB_t \geq .4SB_0)$	$P(SB_t \geq .6SB_0)$	**AAV**	$\bar{C}_t$	$P(C_t < 650)$
SOG_DDM	1	NoFish_FSC	0.88	0.78	0.53	0	0.14	1
SOG_DDM	2	HS30-60_HR.1	0.85	0.71	0.45	50.73	6.16	0.20
SOG_DDM	6	minE-LRP_HR.1	0.83	0.69	0.43	38.21	7.24	0.18
SOG_DDM	3	HS30-60_HR.15	0.83	0.68	0.39	48.59	8.51	0.20
SOG_DDM	4	HS30-60_HR.2	0.82	0.64	0.33	49.67	10.62	0.20
SOG_DDM	7	minE-LRP_HR.2	0.77	0.60	0.30	43.51	12.60	0.20
SOG_DDM	5	HS30-40_HR.3	0.69	0.50	0.21	52.70	16.36	0.22
SOG_DIM	1	NoFish_FSC	0.85	0.74	0.55	0	0.14	1
SOG DIM	2	HS30-60 HR.1	0.82	0.70	0.46	50.16	6.14	0.22
SOG_DIM	6	minE-LRP_HR.1	0.81	0.69	0.45	39.53	7.06	0.20
SOG_DIM	3	HS30-60_HR.15	0.80	0.67	0.40	48.34	8.54	0.22
SOG DIM	4	HS30-60 HR.2	0.78	0.64	0.35	50.93	10.65	0.22
SOG DIM	7	minE-LRP HR.2	0.75	0.61	0.33	42.84	12.38	0.22
SOG_DIM	5	HS30-40_HR.3	0.69	0.51	0.24	54.59	15.79	0.24
SOG_conM	1	NoFish_FSC	1	1	0.93	0	0.14	1
SOG_conM	2	HS30-60_HR.1	1	0.99	0.82	36.74	10.76	0.04

			Conservation	Biomass		Yield		
			Obj 1 (LRP)	HIAB	Obj 2	Obj 3	Obj 4	Catch < 650 t
		Criterion	≥ 75%	≥ 50%	≥ 50%	< 25%	max	min
Scenario	**MP**	**Label**	*P(SB$_t$ > .3SB$_0$)*	*P(SB$_t$ ≥ .4SB$_0$)*	*P(SB$_t$ ≥ .6SB$_0$)*	**AAV**	$\bar{C}_t$	*P(C$_t$ < 650)*
SOG_conM	6	minE-LRP_HR.1	1	0.98	0.81	30.37	11.25	0.04
SOG_conM	3	HS30-60_HR.15	1	0.97	0.75	37.62	15.3	0.05
SOG_conM	4	HS30-60_HR.2	0.99	0.94	0.66	38.95	19.42	0.05
SOG_conM	7	minE-LRP_HR.2	0.98	0.93	0.63	32.79	20.31	0.05
SOG_conM	5	HS30-40_HR.3	0.94	0.82	0.45	38.27	27.62	0.06

Figures

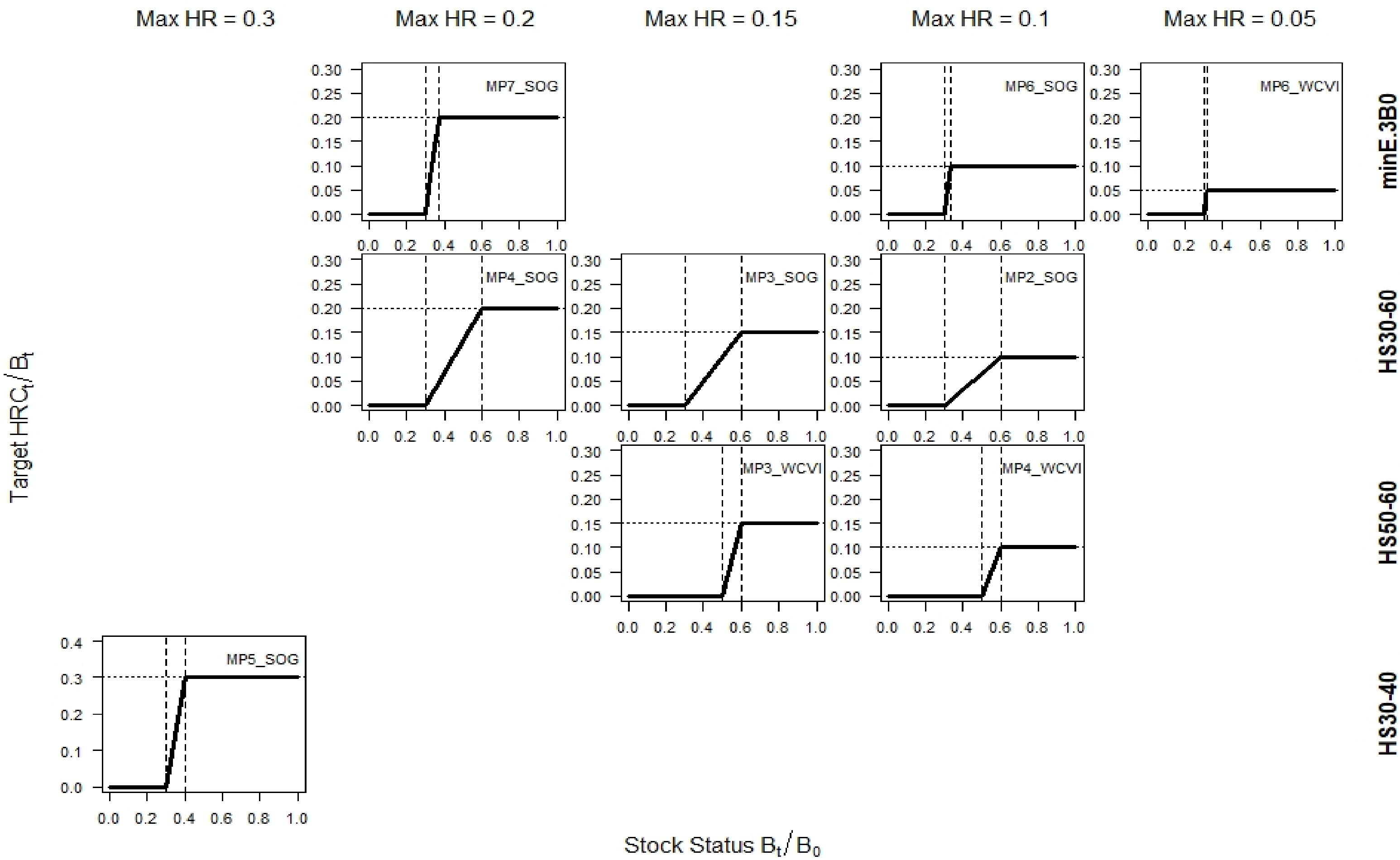

Figure 1. Harvest control rules showing the functional relationship between maximum harvest rate (maxHR) and stock status for each management procedure (MP, refer to Tables 2, 4, and 5 for further description of MPs). Top row shows the minimum escapement (minE) functional form, while the other rows show 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 constant catch are not graphically representable.

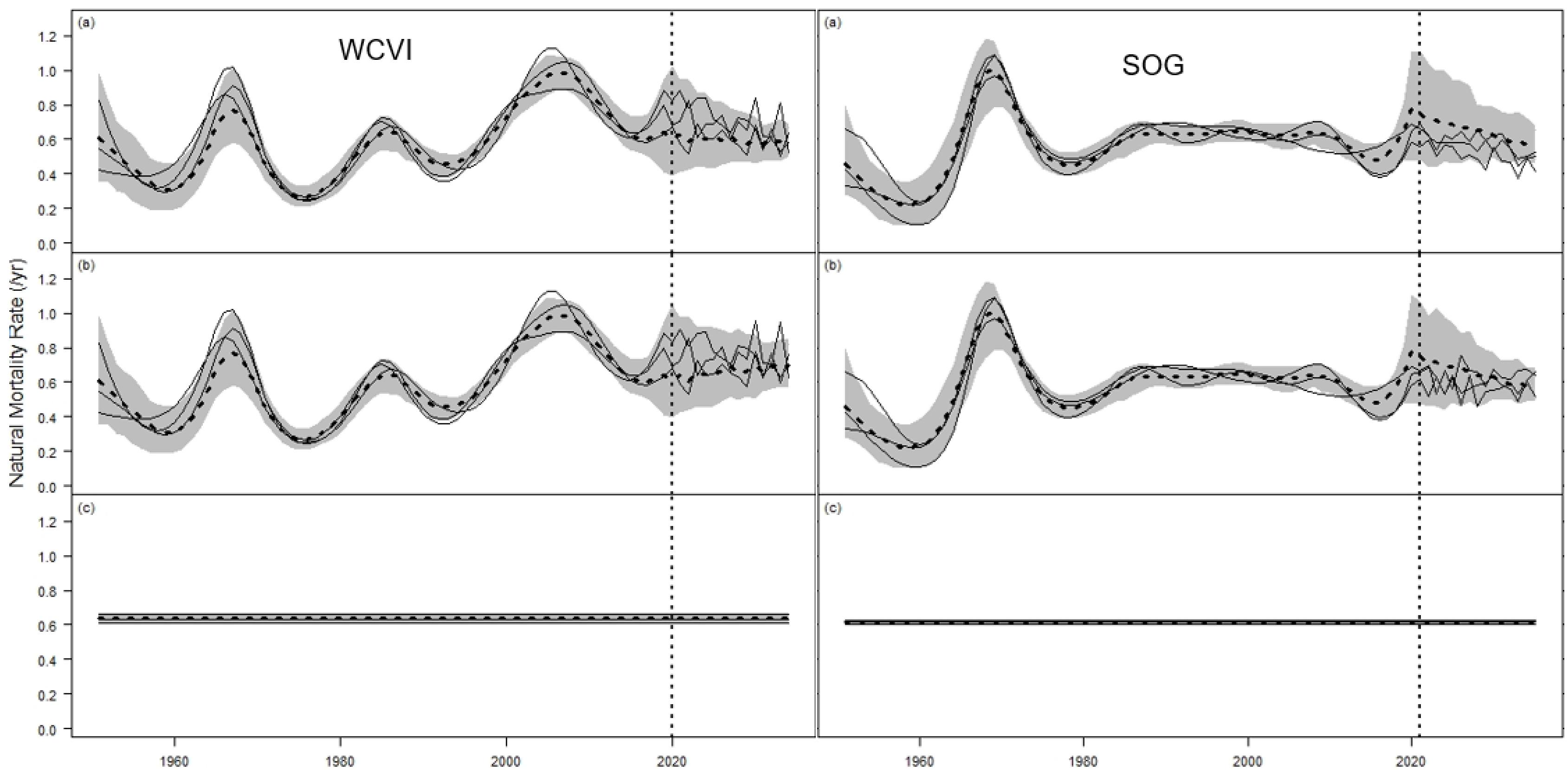

Figure 2. Simulation envelopes for time varying natural mortality (M) in the density-dependent scenario (a), density-independent scenario (b), and constant M scenario (c) for West Coast of Vancouver Island and Strait of Georgia management areas. The envelopes were derived from 5,000 draws from an MCMC approximation to the marginal Bayes posterior distribution of natural mortality. The historical time period is shown from 1951-2019 (WCVI) and 1951-2020 (SOG). The vertical dotted line at 2020 for WCVI and 2021 for SOG denotes the start of the projection period. Grey regions denote the central 95% of the simulated mortality rates, black dashed lines are medians of the envelope, and thin black lines are mortality rates for three randomly selected replicates.

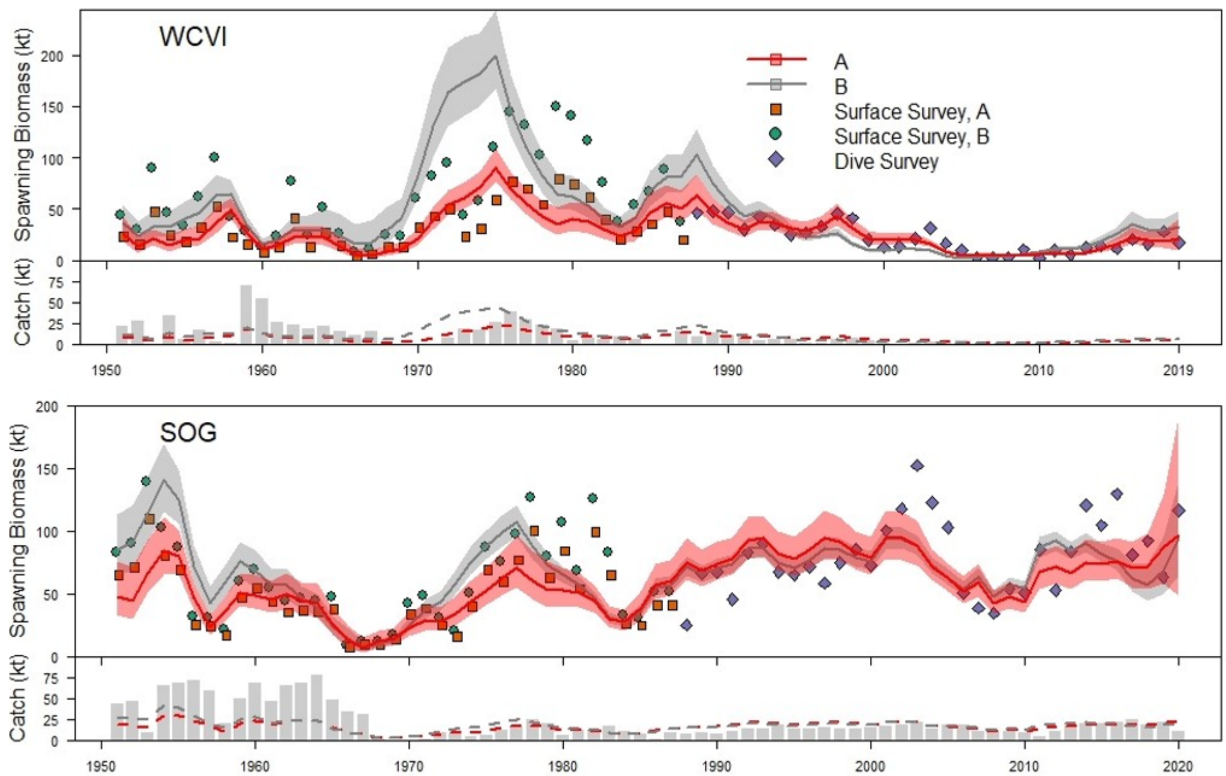

Figure 3. Assessment model estimates of spawning biomass under time-varying natural mortality (A, red) and constant mortality (B, grey) assumptions for West Coast of Vancouver Island Herring (top), and Strait of Georgia Herring (bottom) since 1951. Shaded regions show the central 95% of the posterior 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).

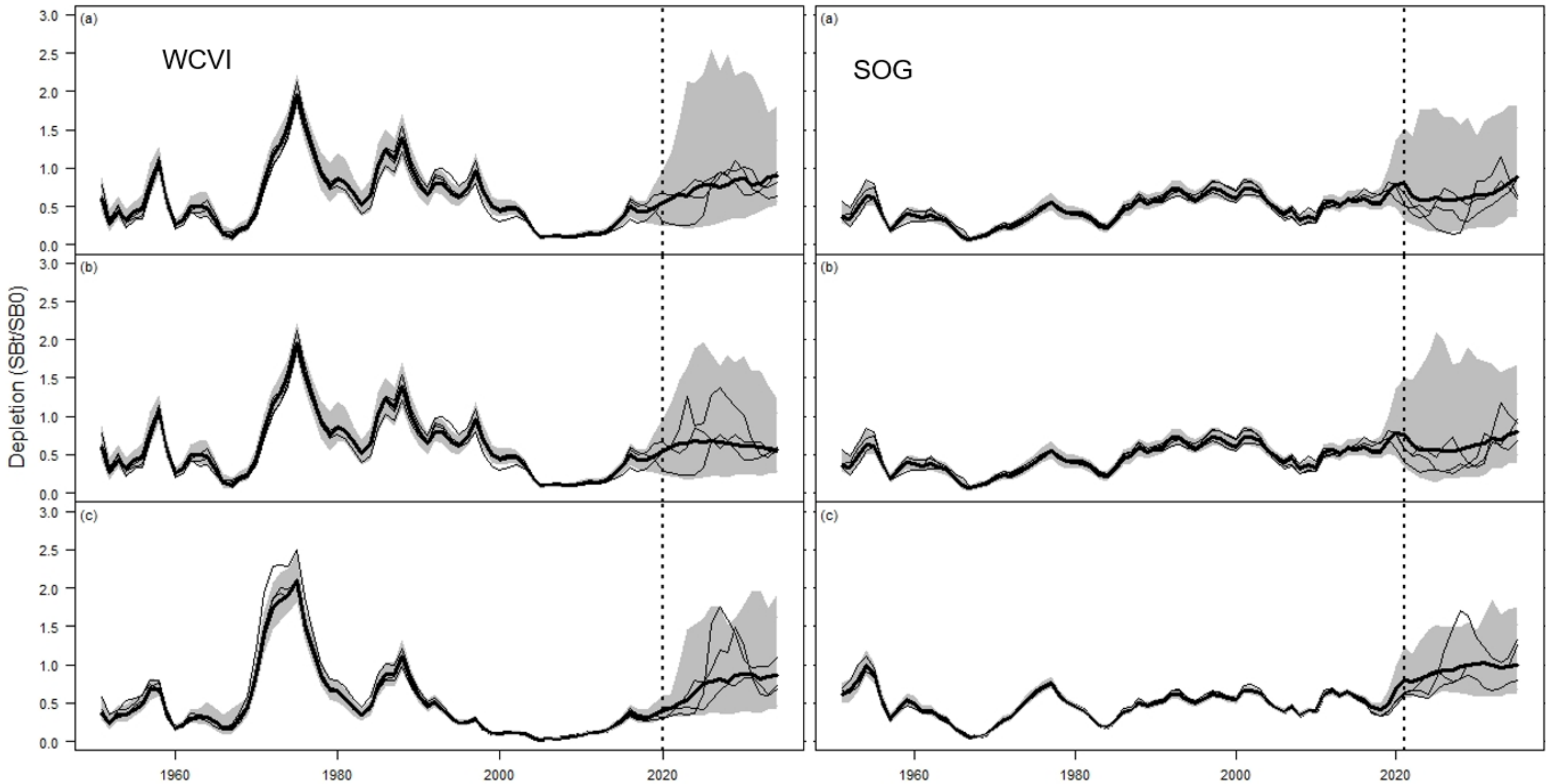

*Figure 4. Depletion simulation envelopes for WCVI and SOG herring for the **NoFish_FSC** management procedure (MP), under the density dependent scenario (a), density independent scenario (b), and constant M scenario (c) for WCVI and SOG herring stocks constant natural mortality (conM) operating model scenario over a 3-generation (15 year) projection period. 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 2020 for WCVI and 2021 for SoG denotes the beginning of the projection period.*

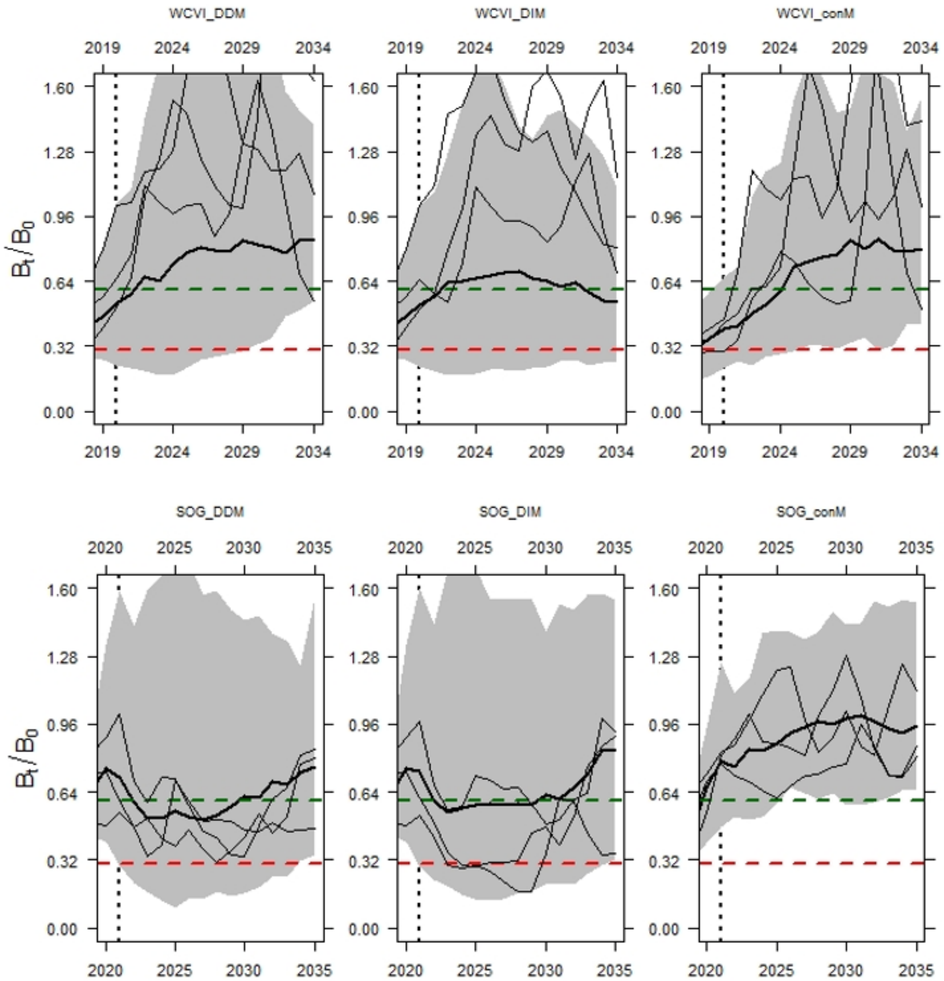

*Figure 5. Depletion simulation envelopes for **WCVI** and **SOG** herring stocks for the **NoFish_FSC** MP, under the density dependent scenario (left), density independent scenario (middle), and constant M scenario (right) operating model scenario over a 3-generation (15 year) projection period. Grey 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 three individual replicates. The vertical dotted line at 2020 for WCVI and 2021 for SOG denotes the beginning of the projection period, and the horizontal dashed lines show 0.3SB0 (red) and 0.6SB0 (green).*

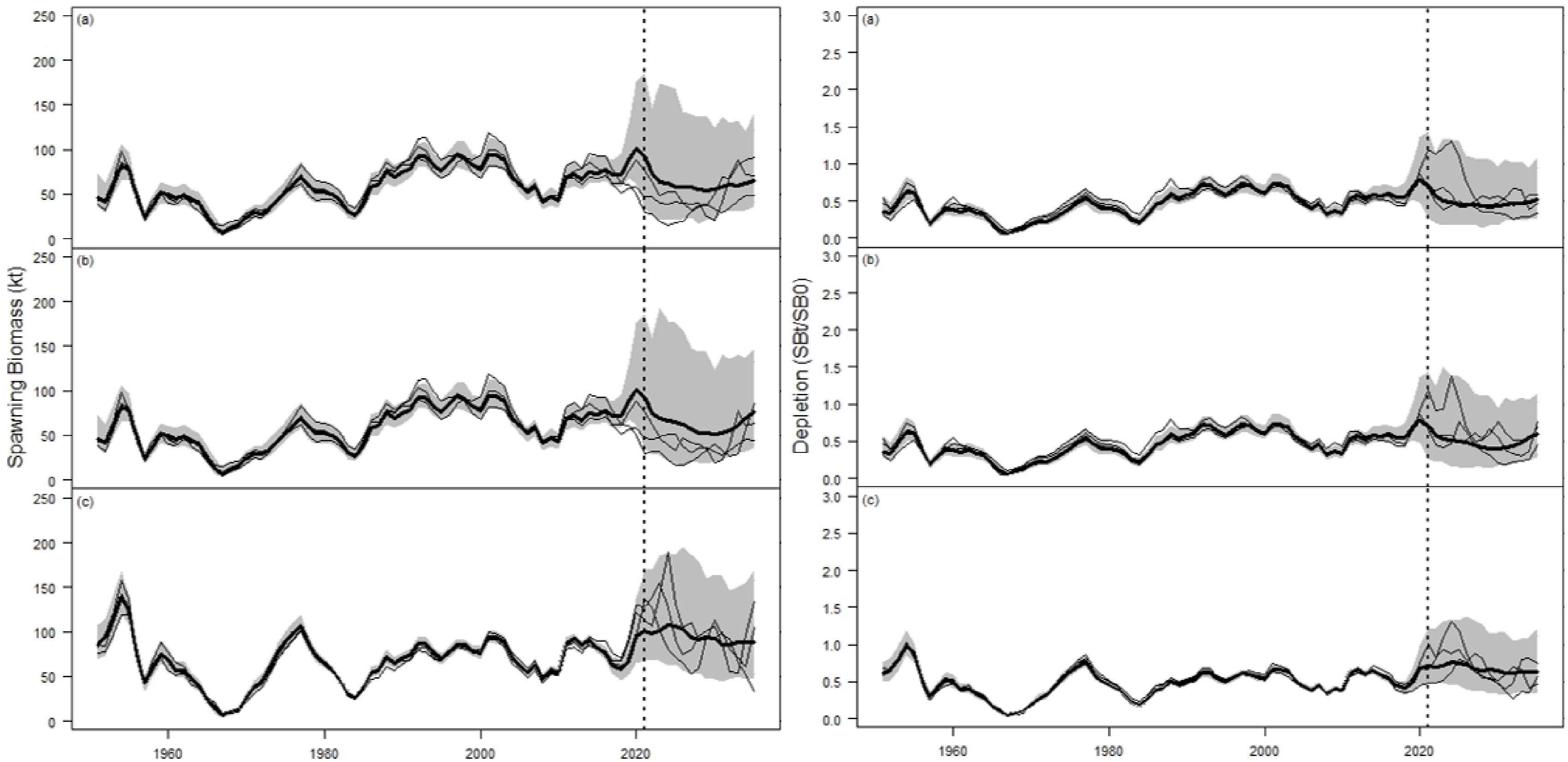

*Figure 6. Spawning biomass and depletion simulation envelopes for **SOG** herring under the **minE_LRP_HR.2** MP, under the three operating model scenarios: density dependent scenario (a), density independent scenario (b), and constant M scenario (c) over a 3-generation (15 year) projection period. 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 selected trajectories for three individual replicates. The vertical dotted line at 2021 denotes the beginning of the projection period.*

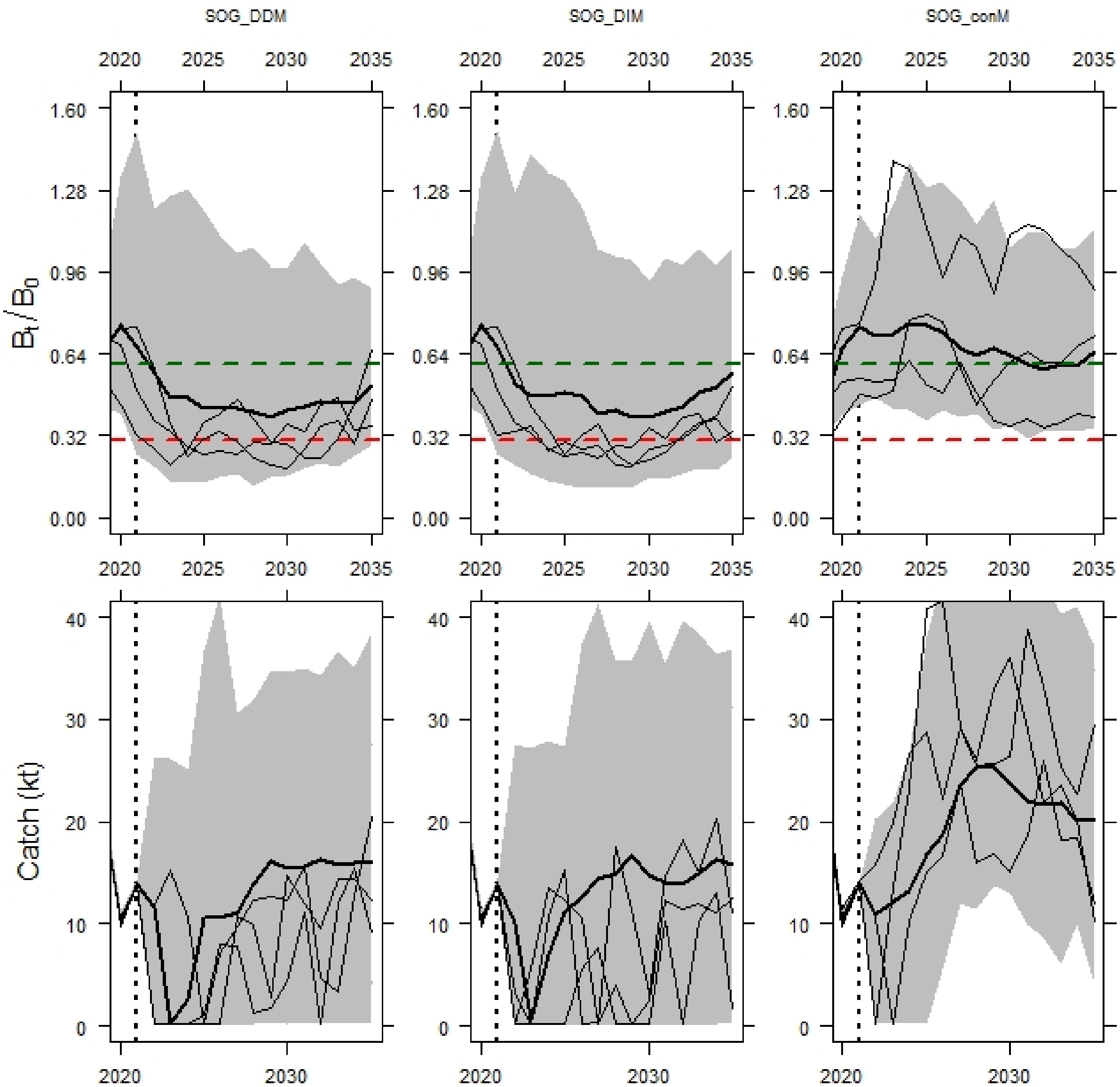

*Figure 7. Depletion simulation envelopes for **SOG** herring stocks under the **minE_LRP_HR.2** MP, constant natural mortality (conM) operating model scenario over a 3-generation (15 year) projection period. Grey areas show the central 95% of simulated trajectories, the heavy black line shows the median of all 100 replicates, and the thin black lines show randomly chosen trajectories for three individual replicates. The vertical dotted line at 2021 denotes the beginning of the projection period, and the horizontal dashed lines show .3SB_0 (red) and .6SB_0 (green).*

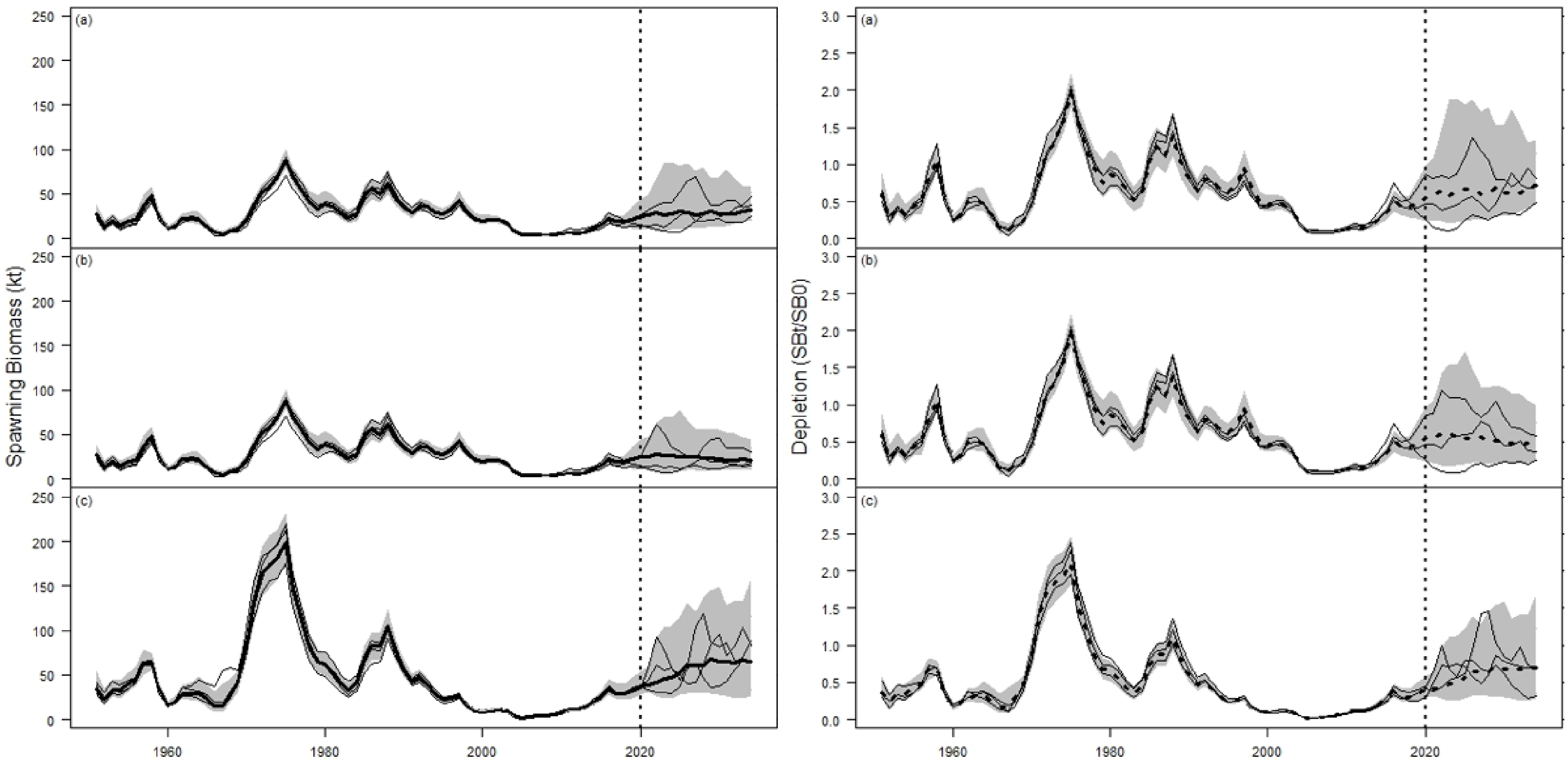

*Figure 8. Spawning biomass and depletion simulation envelopes for **WCVI** herring under the **HS50-60_HR.15** MP, under the three operating model scenarios: density dependent scenario (a), density independent scenario (b), and constant M scenario (c) over a 3-generation (15 year) projection period. 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 selected trajectories for three individual replicates. The vertical dotted line at 2020 denotes the beginning of the projection period.*

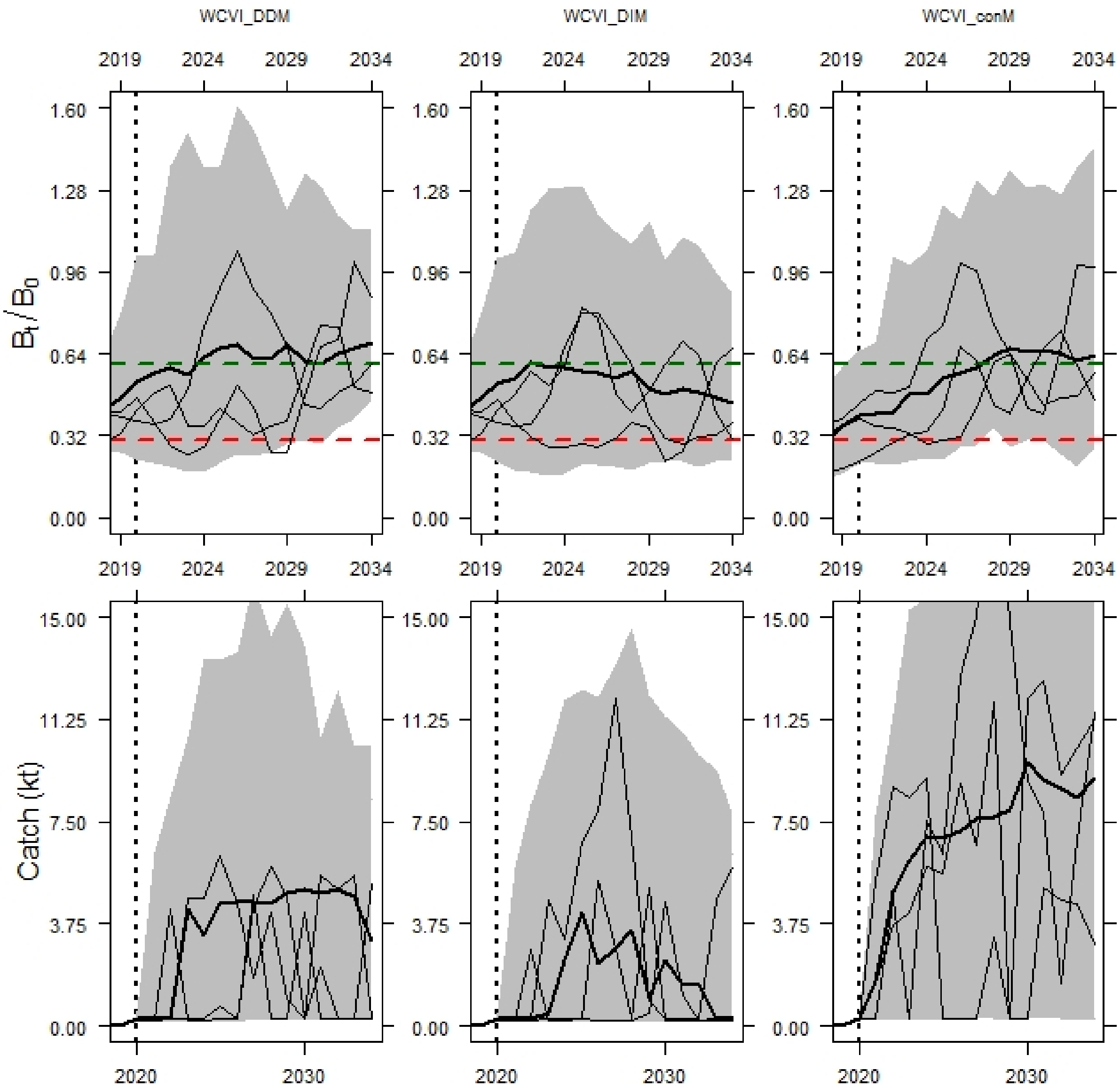

*Figure 9. Depletion simulation envelopes for **WCVI** herring stocks under the **HS50-60_HR.15** MP, constant natural mortality (conM) operating model scenario over a 3-generation (15 year) projection period. Grey areas show the central 95% of simulated trajectories, the heavy black line shows the median of all 100 replicates, and the thin black lines show randomly chosen trajectories for three individual replicates. The vertical dotted line at 2020 denotes the beginning of the projection period, and the horizontal dashed lines show .3SB0 (red) and .6SB0 (green).*

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