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

Canadian Science Advisory Secretariat (CSAS)

Research Document 2022/048

Pacific Region

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

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February 2023

Canada

Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
csas-sccs@dfo-mpo.gc.ca

ISSN 1919-5044
ISBN 978-0-660-44862-6 Cat. No. Fs70-5/2022-048E-PDF

Correct citation for this publication:

Benson, A.J., Cleary, J.S., Cox, S.P., Johnson, S., and Grinnell, M.H. 2023. 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. DFO Can. Sci. Advis. Sec. Res. Doc. 2022/048. viii + 70 p.

Aussi disponible en français :

*Benson, A.J., Cleary, J.S., Cox, S.P., Johnson, S., and Grinnell, M.H. 2023. Rendement des procédures de gestion pour le hareng du Pacifique (*Clupea pallasii*) de la Colombie-Britannique en présence d'incertitudes du modèle : combler l'écart entre la théorie et la pratique de la pêche selon l'approche de précaution. Secr. can. des avis. sci. du MPO. Doc. de rech. 2022/048. ix + 77 p.*

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ABSTRACT

The method of setting catch limits for Pacific Herring (*Clupea pallasii*) fisheries in British Columbia (BC) is similar to precautionary harvest policies found elsewhere in the world; however, 3 out of 5 herring fisheries have been closed in most years since 2006 due to persistent low spawning abundances and low productivity. Although the mechanisms underlying declines of these herring stocks remain unknown, temporal variation in natural mortality and stock assessment over-estimation of abundance are potential factors involved in these outcomes. We used closed-loop simulations to evaluate management procedure (MP) performance for West Coast Vancouver Island (WCVI) and Strait of Georgia (SOG) herring fisheries given uncertainties about past and future herring natural mortality and stock assessment estimation errors. This work represents the first phase of management strategy evaluation under Pacific Herring Renewal, where emphasis is on evaluating current MPs and modifications to these MPs, and not on identifying or selecting the most acceptable MP. We develop three operating models representing hypotheses for how stock-specific natural mortality changes over time. The first model (constant-*M*) assumes that natural mortality has remained constant over the 1951-2017 period, while the alternative model (time-varying-*M*) allows natural mortality to vary over that time. The time-varying-*M* operating model is further divided into two models for projecting future patterns in natural mortality. A density-independent-*M* model assumes that future natural mortality rates will fluctuate randomly around the recent 10-year average, while a density-dependent-*M* model allows random pulses of high natural mortality when spawning biomass is low. Increasing natural mortality rates are of concern and are relevant given increasing predator biomass. We simulated performance of nine feedback harvest control rules (HCRs) given by combinations of maximum harvest rate (20% vs 10%), HCR form (i.e., hockey-stick vs. minimum escapement), operational control points defining biomass cutoffs (25%, 30%, and 50% of B_0) and thresholds below which harvest rates are reduced (none vs. 60% of B_0), and absolute catch caps (0 vs 2,000 t for WCVI and 0 vs. 30,000 t for SOG). For WCVI, results show that the current MP would fail to meet spawning biomass objectives under most operating models. Reducing the maximum harvest rate from 20% to 10% and capping fishery quotas at a maximum 2,000 t would reduce the effective harvest rate and protect against over-estimates of abundance when they occur, thus providing acceptable performance against biomass objectives for two of three operating models. For SOG herring, the current MP was robust across almost all scenarios and objectives we examined (thus a more restrictive cap was not explored). For both WCVI and SOG herring, the maximum target harvest rate was the most important harvest control rule element controlling management performance compared to the shape and/or operational control points in harvest control rules.

1. INTRODUCTION

1.1. BACKGROUND

Like almost all fisheries around the world, managers of British Columbia's Pacific Herring (*Clupea pallasii*) fisheries need to recommend annual catch limits despite considerable uncertainty about past stock abundance and dynamics, current stock abundance, and future stock responses to fishing. Over the past two decades or so, scientists and managers dealt with this uncertainty by first fitting stock assessment models to survey and catch data and then using the forecasted stock abundance estimates (i.e., spawning biomass relative to an unfished standard level) in a harvest control rule to compute a catch limit for the next fishing year (Haist 1990; Hall et al. 1988). This approach appeared to work reasonably well through the 1990s and early 2000s, presumably because the harvest control rule had a precautionary feature of reducing fishing when spawning abundance was near or below a fixed cutoff level, and because the actual removals were often lower than prescribed by the harvest control rule. Although this method of setting catch limits is similar to precautionary harvest policies found elsewhere, 3 out of 5 herring fisheries in BC have been closed in most years since 2006 due to persistent low spawning abundances and low productivity (Haida Gwaii, Central Coast, West Coast of Vancouver Island, see Kronlund et al. 2018).

Although the mechanisms underlying the declines and subsequent low productivity of these B.C. herring stocks remain unknown, we can draw a few important lessons about stock assessment models, uncertainty, and precautionary harvest control rules from these outcomes.

First, stock assessment models, in general, provide a false sense of predictability to stock dynamics. A good model fit to historical data makes it appear as though historical dynamics have been "explained", when in fact nothing has been learned about the true cause-effect relationships driving population dynamics. A single, highly parameterized stock assessment model uses random effects in recruitment, fishery selectivity, catchability, natural mortality, etc. to fit almost any data set well. Improvements in fit come at a cost because random effects, by definition, contain no structural information about cause-effect relationships. Thus, future stock dynamics and responses to fishing are much more uncertain than the models predict.

Second, although a stock assessment model might provide unbiased estimates of abundance **on average** *(*e.g., as determined via simulation experiments), we cannot know whether a model is biased, or by how much it is biased, at any particular moment when it is used. In other words, the outcome of an assessment or forecast is like flipping a coin: we know heads will come up in 50% of a large sample of flips, but whether the **next flip** will be a head is completely unknown until it actually occurs. For stock assessment models, such outcome uncertainty creates multiple problems: (i) a very large overestimate (over-estimates are typically larger than underestimates) of abundance and catch limits may lead to short-term over-exploitation; (ii) there is an asymmetric cost of assessment errors in which over-exploitation is much more costly than under-exploitation - the reason being that it takes many years, or even decades in the case of herring, for a stock to rebuild from an over-fished state, while the stock grows in the presence of under-fishing; (iii) it may take several years to recognize and correct the extent of bias and over-exploitation since the only way to understand the bias is via the biased assessment model.

Third, judging the usefulness of a stock assessment model based only on statistical criteria of model fit is dangerous and could exacerbate the outcome uncertainty mentioned above. Stock assessment models are highly non-linear and often very sensitive to new data points, observation errors, and patterns in historical fishing. For example, Figure 1 shows two stock assessment models fitted to the 1988-2017 herring spawn index for the Strait of Georgia stock. Note how both models fit the historical data almost the same, while Model A (a random effects model in natural mortality, *M*) fits the most recent data much better than the simpler Model B (constant *M*). Further, Model A suggests that the stock is increasing rapidly, while Model B suggests that it is decreasing rapidly. The difference in 2018 spawning biomass forecasts between these models might be on the order of 60-70,000 t. So, which model is better? Although Model A appears to fit better, mainly because it has greater scope for fitting data, it might just be "chasing" the recent high survey points. Note that, when the full time series is available, Model A does not chase the similarly high data points that occurred in the 2000-2005 period. As the time-series grows longer, Model A becomes practically indistinguishable from Model B over that period. So, while Model A fits more recent data better, it could just be more sensitive to recent data and thus promoting dangerous levels of fishing. The problem is that we may not know for several years which model is actually more useful for determining sustainable catch limits.

Fourth, harvest control rules that seem precautionary **in theory** may not be precautionary **in practice**. Harvest control rules are only as precautionary as their input components. For instance, when assessment estimates of biomass are biased, the harvest control rule will provide a biased catch limit unless there are further controls, such as catch caps that limit the absolute level of harvesting and mitigate the effects of assessment model over-estimates. Even with caps in place, there is no assurance that they are set appropriately if the stock assessment bias is uncertain. Thus, a harvest control rule may do little for precautionary management when developed in isolation from the assessment models and data used to populate it.

Fifth, our understanding of fish stock dynamics will always be uncertain: there are multiple explanations or hypotheses for any changes in abundance and productivity even when one hypothesis seems much more plausible than another at any particular time, as demonstrated above with Model A and Model B. Not only do we not understand these mechanisms for any particular stock, we also don't know how the dynamics differ among sub-populations, locations, or over time. So, choosing a single assessment model based only on statistical fit seems to only partially deal with uncertainty in harvest management.

Finally, the above points imply that (i) any herring stock and fishery could go through low abundance and low productivity situations experienced in Haida Gwaii, West Coast Vancouver Island, and Central Coast, despite looking highly productive and sustainable over the recent past and (ii) any scientific/precautionary management system is probably masking at least some over-fishing risk. As the saying goes: "absence of evidence is not sufficient evidence of absence"; that is, although Strait of Georgia and Prince Rupert District stocks appear healthy now, it does not follow that they always will be.

A fishery management system can be made more precautionary against the uncertainties listed above by following structured scientific principles. The main idea is to recognize the uncertainties listed above and think in terms of multiple hypotheses and experimental testing rather than in trying to find the single best explanation for past system behaviour. Multiple scientific hypotheses can be used as experimental conditions under which we can test precautionary management procedures. This is a fairly straightforward test: simulate management procedure (MP) performance against each hypothesis and eliminate the MPs that perform poorly. This process of elimination is a practical means of finding management procedures that could potentially work in reality. Any procedure that fails to be precautionary in simulation testing is more likely to fail in the real world, since the real world is more complex and uncertain than most models. Testing MPs against a broad suite of plausible hypotheses should at least reduce the gap between precautionary theory and practice.

In this paper, we use closed-loop simulations to evaluate performance of alternative herring management procedures (including the current procedure) given uncertainties about past and future herring stock dynamics and stock assessment model errors. This work represents the first phase of management strategy evaluation (MSE) under Pacific Herring Renewal. We focus specifically on the West Coast Vancouver Island (WCVI) and Strait of Georgia (SOG) for this first MSE cycle because they exhibit contrasting stock and fishery states that encompass the range of stock conditions observed elsewhere in British Columbia (BC).

Our specific objectives are to:

1. Simulate and rank performance of the current MPs used for WCVI and SOG herring fisheries against alternative operating models for herring dynamics;
2. Simulate and rank performance of alternative MPs that vary target harvest rates, control points, and catch caps used in herring harvest control rules;
3. Recommend potential MPs for both stocks that meet objectives defined under the Pacific Herring Renewal process.

1.2. OBJECTIVES USED FOR EVALUATION

Between 2015 and 2018, Fisheries and Oceans Canada (DFO) engaged in a series of objective-setting workshops with First Nations and the herring fishing industry to formulate biological and yield objectives for the fisheries. Specifically, in February 2016 the Nuu-chah-nulth Nations and Ha'wiih provided a list of objectives to the DFO for WCVI (Appendix B, Table B.1). In May 2017, the DFO *proposed* core objectives to the Integrated Herring Harvesters Planning Committee, requesting feedback from herring users, with the intention to implement these objectives (or variations thereof) in the first MSE cycle. Subsequently, the DFO and the Nuu-chah-nulth have together refined spatial objectives in Table B.1 to stock-level objectives for use herein. This process is described in Appendix B.

The first objective listed below defines the minimum spawning biomass criterion that must be respected for any MP to be considered precautionary enough to avoid harming a herring stock (i.e., an imperative conservation objective). The subsequent biomass and catch objectives are each subordinate to the conservation objective. Although we later present performance with respect to objectives 2-6 in a ranked order, such ranking is not meant to impose priorities among these objectives. Any implicit ranking is for the sole purpose of readability of the performance tables.

1.2.1. Biomass objectives

1. Avoid the limit reference point (LRP) of 0.30 B_0 with high probability over three herring generations, where "high probability" is defined as 75-95% (DFO 2009).
2. Maintain spawning stock biomass in the Healthy zone, at or above the Upper Stock Reference (USR) of 0.60 B_0, with 50% probability over three herring generations.
3. Maintain spawning stock biomass at or above a target biomass level of 0.75B_0 with 75% probability over three herring generations (WCVI only).
4. Maintain spawning stock biomass at or above a target biomass level equivalent to the average biomass from 1990-1999, with 75% probability over two herring generations (WCVI only).

1.2.2. Yield objectives

5. Subject to conservation objectives, maintain average annual variability in catch (AAV) of less than 25% over three herring generations.

6. Subject to conservation objectives, maximize the median average catch over three herring generations.

Biomass Objectives 1-4 are each cast using biological reference points. Objective 1 (conservation) operationalizes the LRP of 0.30 B_0 into a measurable objective, as per the recommendations of Kronlund et al. (2018). Biomass Objective 2 implements one of the proposed USRs, 0.60 B_0, set at twice the LRP. We also evaluated performance against two alternative USRs as described in Appendix B.

1.3. KEY UNCERTAINIES

Most elements of fishery management systems are subject to some degree of uncertainty. The consequences of uncertainty in elements such as stock assessment model errors are, as we show in this paper, potentially manageable. On the other hand, uncertainty about ecological dynamics is both difficult to quantify and difficult to manage. Challenges quantifying the uncertainty in ecological dynamics arise because stock assessment models are the main vehicle by which we study ecological dynamics since we need the models to estimate unobservable population dynamics drivers such as abundance, natural mortality, recruitment, and fishing mortality. Following from the arguments made above in Section 1.2, we develop three operating models to represent alternative hypotheses for how stock-specific rates of natural mortality change over time. The first model (constant-*M*) assumes that natural mortality has remained constant over the 1951-2017 period of exploitation (i.e., Model B above), while the alternative model allows natural mortality to vary over the same historical period (i.e., Model A above). This latter time-varying *M* operating model is further divided into two models based on assumptions about future patterns in natural mortality. In particular, we assume that either (i) future natural mortality rates will fluctuate randomly around the recent 10-year average (density-independent *M*) or (ii) that pulse natural mortality events will occur at random, but more frequently, when spawning biomass is low (density-dependent *M*). The latter hypothesis is difficult to quantify, but some empirical justification regarding potential Allee effects for herring can be found in Kronlund et al. (2018).

Natural mortality is certainly not the only key uncertainty surrounding Pacific Herring population dynamics. Like most other fish stocks, the influence of spawning stock size on recruitment, as well as contributions of oceanographic processes, are poorly understood. In this paper, we assume that stock-recruitment follows a Beverton-Holt model with parameters estimated via the constant-*M* and time-varying-*M* assessment models mentioned above. We only consider stock-recruitment parameter uncertainty (via sampling parameters and recruitment deviations from their joint Bayes posterior distribution) in these models, rather than alternative functional forms, because we aimed to limit the complexity of this first MSE cycle. For similar reasons, we do not directly consider spatial population dynamics here but, instead, reserve these processes for the next MSE cycle, although we do discuss potential implications of our results for spatially structured herring populations.

There is also significant debate about appropriate assumptions for spawn survey scaling factor q for the surface (1951-1987) and dive (1988-2017) surveys that enumerate Pacific Herring spawn deposition. As a result, two stock assessment models representing different assumptions about the dive survey q have been presented since 2011 for all five stock areas. Main attributes and limitations of both models are described in Table A.1 of the 2016 Science Response (DFO 2016). Both MPs have been peer reviewed through CSAS and both have been used to provide science advice for Pacific Herring up to 2017. The Assessment Model 2 (AM2) model has been the basis for Fisheries Management quota decisions since 2012 (DFO 2017) based on consultative processes and limitations described in Table A.1 (DFO 2016). In this paper, we base our operating models on the AM2 assumption to better understand the risks associated with continued application of this MP in the short-term. We provide a limited suite of sensitivity analyses to investigate potential implications of using Assessment Model 1 (AM1) both operating models and future assessments.

2. METHODS AND STUDY DESIGN

Simulating performance of a management procedure for herring fisheries requires three main components:

1. **an operating model** to represent both historical and future population dynamics of the stock and the sampling distributions assumed to be generating survey and age-composition data;
2. **a management procedure** consisting of (at least) past and future spawn survey index and age-composition data, a stock assessment model to estimate parameters and generate forecasts of harvestable biomass, and a harvest control rule for setting target harvest rates and catch limits; and,
3. **performance metrics** needed to compare simulated outcomes to fishery objectives.

The following sections describe how these components are modeled for BC Pacific Herring fisheries. Our model notation attempts to maintain consistent conventions for state variables and parameters across both the operating model and stock assessment model, while also making clear the differences between operating model variables, parameters estimated in stock assessment models, and variables derived from these parameter estimates. As a general rule, any parameter or variable (e.g., B_0) that does not show a "^" or "~" symbol is part of the operating model. The symbol "^" over a variable indicates a parameter (e.g., $\hat{B}_0$) or variable estimated by the stock assessment model. The combination of "^" and "~" symbols and time subscripts (e.g., $\widetilde{\hat{B}_{MSY,T}}$) indicates a quantity that is a function of estimated stock assessment model parameters while time subscripts (e.g., "T") on parameters such as the one shown above indicate an estimate of that quantity given data up to the time step indicated. Vector objects are denoted using notation such as $1{:}T$ in subscripts (e.g., $\hat{B}_{1:T}$).

2.1. OPERATING MODELS

2.1.1. Operating model scenarios

Besides uncertainty in spatial structure and dynamics of herring, natural mortality is the most critical population dynamics uncertainty affecting current herring fisheries. As noted above, we used three operating model scenarios to represent the dynamics of Pacific Herring given assumptions about temporal variability in natural mortality.

Pacific Herring dynamics in WCVI and SOG are simulated using single-sex, age-structured operating models previously described in Tables 3 and 4 of Cox et al. (2019). The structure was modified to include three commercial fleets, Food, Social and Ceremonial (FSC) fisheries, and two surveys (Table 5, OM.10-OM.15). We also replaced the growth model with empirical observations of weight-at-age (Table 5, OM.3) for the historical period. These changes were made to represent the key assumptions in the recent herring assessment model (Martell et al. 2012; Cleary et al. 2018), and to generate fleet-specific catches and age-composition data in the projection period. The operating models simulated a historical period $T_0 \leq t \leq T_1 - 1$ corresponding to 1951 - 2017, and a projection period $T_1 \leq t \leq T_2$ corresponding to 2018 – 2032 (i.e., 3 herring generations, Seber 1997).

2.1.1.1. Time-varying M operating models

The density-dependent mortality (DDM) scenario assumes that future M_t returns to the long-term average estimated to occur over the entire historical period (1951-2017; Figure 4a). The DDM process simulates low-frequency/high-mortality events when biomass drops below the LRP of 30% of B_0. Our assumption underlying this approach to density-dependent M is that the historical M estimates are derived from a cubic spline fitted to noisy data. So, it is possible that the historical M values were actually spikes that were smoothed over by the spline. Although the sample time-series is small, the peaks in M occurred in approximately 6% of years (4 out of 67 years) with the peak M being approximately 1.5 times the historical average.

This process was implemented as an additive process in two stages. First, we simulated a simple random walk beginning with the last annual estimate of *M* from the time-varying-*M* assessment model (i.e., $\widehat{M}_{2017}$) and ending at the estimated long-term average natural mortality from the historical period (i.e., the average of each $\widehat{M}_{1951:2017}$ vector in Figure 4a). Random walk annual jumps in $\log(M_t)$ had a standard deviation of $\sigma_M = 0.1$. Then, random density-dependent mortality events of $1.5M_t$ were simulated with 6% probability only when spawning biomass was below 30% of the operating model B_0.

The density-independent mortality (DIM) scenario assumes that future natural mortality rates M_t return to the average rate estimated to occur over the past 10 years (i.e., the average of $\widehat{M}_{2008:2017}$; Figure 4b). This density-independent process was implemented identically to the first random walk stage of DDM, but ended at the most recent 10-year average rate (i.e., the average of each $\widehat{M}_{2008:2017}$ vector in Figure 4a).

2.1.1.2. Constant M operating models

The average M_t rates used as the end-point of the random walk in both time-varying *M* scenarios above were calculated from the historical period for each simulation (1951-2017). A constant natural mortality (conM) scenario was used to represent an alternative view of herring stock dynamics in WCVI and SOG (Figure 4c). This scenario estimates a constant *M* for both the historical and projection period, and represents a large departure from the *status quo* assessment assumption that natural mortality is highly variable over time.

2.1.2. Operating model conditioning on historical data

Data and parameters for both time-varying-*M* and constant-*M* operating models were obtained from stock assessment data and parameter estimates for the WCVI and SOG stocks (Martell et al. 2012; Cleary et al. 2018). For the historical period, we rescaled age-2 recruitments from the herring stock assessment to age-1 recruitment in the current OM age structure via,

$$R_t^{OM} = R_{t+1}^{AM} e^{M_t} \quad .$$

Switching from age-2 to age-1 as the basis age for recruitment also required recalculating equilibrium recruitment R_0 for the stock-recruitment model, given the same steepness h and equilibrium biomass B_0 value. To match the herring stock assessment model's equilibrium assumptions, R_0 is adjusted by the historical average mortality,

$$R_0^{OM} = R_0^{AM} e^{\bar{M}_t} \quad .$$

We represented uncertainty about stock history by sampling 100 operating model parameter vectors from their joint posterior distribution obtained via Markov Chain Monte Carlo (MCMC) sampling on the 2017 assessment (using either time-varying-*M* or constant-*M*). The OM states for the historical period (Figure 3) were then initialized using MCMC draws for unfished biomass, natural mortality (Figure 4), fishing mortality (Figure 5; Figure 6, bottom), age-1 recruitment, stock-recruitment steepness, and standard errors for recruitment deviations, survey index errors, and age-composition sampling errors.

MCMC samples for each of the 100 replicates were drawn using a stratified random sampling procedure (Appendix C, Figure C.3). We stratified the joint posterior of initial mortality $M_0$and unfished biomass B_0 into 100 regions each containing 1% of the joint marginal (M_0, B_0) distribution. We defined the sample strata by first dividing the marginal distribution of initial mortality into 10 deciles of 500 points (Figure C.3, below diagonal, red lines). Within each M_0 decile, the conditional B_0 distributions were then divided into deciles in the same way, producing rectangular regions of the joint marginal that each contained 50 posterior points (Figure C.3, below diagonal, green lines). A stratification process (not random sampling) was used following the theory of Latin Hypercube Sampling which guarantees that sampling is proportional to observed percentiles as opposed to pure random sampling of 100 MCMC draws which is more sensitive to the random number seed used to initiate the sampling.

Each replicate's operating model history was conditioned on parameter values chosen by sampling randomly within each joint centile. Sampled points were expanded from the bivariate marginal to the entire, unconditional posterior by using the posterior chain index for the sampled point. This ensured that the 100 replicates were able to capture the range and covariance within the joint marginal (M_0, B_0) distribution, and helped to capture correlation between remaining variables across the posterior as a whole (Figure C.3, above diagonal). Furthermore, while there were some irregularities in the sampled marginal densities for the remaining parameters (Figure C.3, diagonal, B_{2017} and Steepness), the samples were consistently able to capture the range of joint marginal distributions (Figure C.3; below diagonal, coloured polygons).

2.2. MANAGEMENT PROCEDURES

Simulated management procedures (MPs) consist of three components: (1) a fishery data set involving time-series (t = 1, 2,…,T) of catch by fleet, a time-series of spawn index indices, and proportions-at-age in the fishery catch; (2) a stock assessment model that estimates historical biomass, recruitment, natural mortality, selectivity, and stock-recruitment parameters up to time step t, as well as operational control points derived from these parameters as required by harvest control rules (Cox et al. 2013); and (3) a harvest control rule for computing the target exploitation rate and catch limit based on stock assessment estimates of spawning biomass status relative to the estimated unfished level. These basic elements match the inputs used in the current procedure used to set annual quotas for herring. Below, we describe this “status quo” procedure in detail along with nine alternative procedures based on variations of the current one.

2.2.1. Current herring MP

All elements of the Pacific Herring management procedure have changed since the original herring harvest control rule (HCR) was tested and implemented in 1986 (Haist 1990; Hall et al. 1988). First, the survey changed in 1988 from a surface survey of herring eggs conducted from small vessels and on foot, to a dive survey that enumerates total egg deposition via subsurface eggs counts which is extrapolated into a measure of total egg deposition for each spawn bed.

Second, application of the HCR changed from using the estimated current spawning biomass as indicator of stock status (as per Hall et al. 1998), to using the forecasted spawning stock biomass (circa 1995, Schweigert et al. 1997).

Finally, the structural assumptions of the stock assessment model have varied among *inter alia* different discrete and instantaneous formulations of mortality, alternative assumptions about survey catchability *q*, empirical vs. modeled weight-at-age, and time-varying estimates of natural mortality (e.g., Haist and Stocker 1984; Stocker 1993; Haist and Schweigert 2006; Martell et al. 2012; DFO 2016).

Changes to the herring MP listed above were intended to improve either biological realism or statistical fit of the assessment model. Generally speaking, the changes were implemented without evaluation of the management consequences and prior to comprehensive simulation testing. However, previous evaluations indicated that the current herring MP (Cleary et al. 2010; Cox et al. 2019; and DFO 2015) might lack robustness across a wider range of hypotheses about Pacific Herring stock dynamics. The empirical data do not rule out the possibility that the current management procedure lacks robustness. For instance, three of the major herring stocks, WCVI, Central Coast (CC), and Haida Gwaii (HG), were below cut-off for 32%, 21%, and 46% of years, respectively, from 1986 to 2013 (DFO 2017). HG was closed to both commercial roe and spawn-on-kelp (SOK) fisheries from 2002–2018 with the single exception of 2014 (DFO 2018). Commercial roe and SOK fishing opportunities available in 2014 were not pursued following an agreement between the commercial sector and local First Nations. Similarly, the WCVI was closed to commercial fisheries in 2006, with a commercial SOK opportunity available in 2011 (though not pursued, DFO 2018).

The SOG and WCVI management areas show very different stock histories under the current assessment-management system. For example, WCVI has been closed to fishing for 9 years, but has begun to show some signs of recovery since 2015. This prolonged low production-low biomass period (Kronlund et al. 2018) raises questions about whether the egg-deposition survey accurately measures herring spawning stock biomass, whether the stock assessment model over-estimates spawning biomass, and whether the harvest control rule is conservative enough (or too conservative) for this forage species. In contrast, herring spawn biomass estimates in the SOG are now among the highest ever recorded, yet there are concerns that the spatial distribution of spawn has concentrated and that spawn has been persistently absent from some areas. In these contrasting cases, the science questions (i.e., major uncertainties) involve unexplained changes in Pacific Herring natural mortality rates estimated in stock assessment models, lack of confidence in assumptions about the spawn survey scaling parameter (catchability, q), and the effects of concentrated fishing on fine-scale Pacific Herring spatial population structure. Given these uncertainties, the effectiveness of the herring MP to rebuild the WCVI stock is unclear. Similarly, if the SOG stock biomass declines away from the current high level, will the current herring MP avoid rapid rates of decline to an unacceptable level? Proper risk management needs to anticipate the possibility of sudden declines (e.g., due to an unpredictable rapid increase in natural mortality) that leads to loss of ecosystem and user benefits. Similarly, implementing policies that have not been designed or tested for the expected conditions under which they will be used creates both conservation and economic risks.

Data requirements for the current herring MP include total BC herring landings and numbers-at-age observations from the Reduction, Seine-Roe, Gillnet-Roe, Food and Bait, and Special Use fisheries, numbers-at-age observations from the test fishery/biological sampling program, spawn index observations for Survey 1 (surface, 1951-1987) and Survey 2 (dive, 1988-2017), average weight-at-age over the time period of the assessment (seine gear only), and an assumption of maturity-at-age.

At each time step, the stock assessment component of the management procedure fits a state-space statistical catch-at-age stock assessment model (Martell et al. 2012; Cleary et al. 2018) that estimates current spawning stock biomass ($\hat{B}_T$), unfished equilibrium spawning stock biomass ($\hat{B}_0$), and a pre-fishery spawning stock biomass forecast for the following year ($\hat{B}_{T+1}$). Estimated forecast spawning biomass is used in a minimum escapement harvest control rule of the form

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

where the minimum spawning biomass escapement level (E) is defined in Table 2 for WCVI and Table 3 for SOG. FSC removals of 150 short tons (136 t) or a catch equivalent to F = 0.01 occur in each projection year, regardless of the recommended harvest rate. Note this represents FSC allocation prescribed in the Integrated Fisheries Management Plan (IFMP), not herring use reported by First Nations.

Under both the current and alternative MPs given below, we assume that the full catch (C_{T+1}) is taken each year even though, in practice, catches are often lower than the prescribed levels.

2.2.2. Alternative harvest control rules

We examined nine alternative feedback harvest control rules given by combinations of a linear-piecewise rule form (i.e., hockey-stick), target harvest rate, operational control points defining biomass-based cutoff and threshold levels, and absolute catch caps. Management procedure details for each of the WCVI and SOG fisheries are given in Table 2 and Table 3, respectively.

The first class of alternative HCRs (MP2-3) differ from MP1 by reducing the target harvest rate in Eq 1 from 20% to 10% (MP2) and, in the case of MP3, further including a cap on total catch (Table 2 and Table 3, max total allowable catch [TAC]).

The next class of alternatives (MP4-6) each change stock status used in Eq 1 from an absolute, fixed biomass level, as used historically (Schweigert et al. 1997), to 50% of the unfished biomass estimated from the assessment model. MP4 uses a 20% target harvest rate, while MP5-6 both reduce this target to 10%. MP6 further implements a catch cap (Table 2 and Table 3).

The final three harvest control rules (MP7-9) fundamentally alter the form of the rule from a combination of fixed escapement/fixed harvest rate (i.e., Eq 1) to a target harvest rate that varies as a linear-piecewise function (or hockey-stick) of estimated stock status. The hockey-stick (HS) form involves two operational control points: a lower “cutoff” control point below which the target harvest rate equals zero and an upper control point above which the target harvest rate is constant, i.e.,

Eq 2. $$C_{T+1} = \begin{cases} 0 & \text{if} \quad \hat{B}_{T+1} \le 0.3\hat{B}_0, \\ 0.2 \cdot \dfrac{\hat{B}_{T+1} - 0.3\hat{B}_0}{0.6\hat{B}_0 - 0.3\hat{B}_0} \cdot \hat{B}_{T+1} & \text{if} \quad 0.3\hat{B}_0 < \hat{B}_{T+1} \le 0.6\hat{B}_0, \\ 0.2 \cdot \hat{B}_{T+1} & \text{if} \quad 0.6\hat{B}_0 < \hat{B}_{T+1}. \end{cases}$$

All three of MP7-9 set these control points to 30% and 60%, respectively, of unfished spawning biomass estimated in the annual assessment model. MP7 aims for a target harvest rate of 20%, while MP8-9 use 10%. MP9 further implements a catch cap (Table 2 and Table 3).

Finally, MP10 is a no fishing procedure (NoFish) that demonstrates the maximum possible growth and range of natural variation in stock abundance for each stock under each operating model scenario.

3. RESULTS

3.1. OPERATING MODEL CONDITIONING

As noted earlier, time-varying-*M* and constant-*M* operating models originate from two different stock assessment model assumptions about the extent of historical variation in *M*. Fitting each of these models to the same set of historical data creates two impressions about historical patterns of population dynamics and fishing mortality, as well as two different interpretations of current stock status and productivity. Our intent here is not to become overly focused on the statistical properties of these particular models *per se*, but rather to simply treat them as equally plausible operating models for simulation. We, therefore, attempt to point out their similarities and differences so that operating model effects on management procedure performance is easier to judge from the simulation output.

3.1.1. WCVI OPERATING MODELS

Alternative operating models conditioned on historical data produce different estimates of population parameters and survey precision for WCVI herring (Table 6). As expected, the time-varying-*M* model shows an overall better fit to the data than constant-*M* based on the total negative log-likelihood (smaller values imply better fit). Allowing *M* to vary over time absorbs some variation in the spawn survey index, so that this model estimates a more precise survey index CV = 49% (i.e., τ_k^I in Table 5) compared to the constant-*M* model where the CV = 62.5%. This has implications for future data generation as the time-varying-*M* model will simulate new spawn survey data that are about 30% more precise than the constant-*M* operating model, which will, in turn, impact future assessment performance (i.e., estimates of biomass, productivity, status, etc.). Values for recruitment variability (σ_R) were similarly higher for constant-*M*, as some variation in recruitment gets attributed to variation in *M*, but the absolute difference was relatively small. Although estimated catchability for the surface survey was less than 1.0 for both models, it was 50% lower for the constant-*M* model (Table 6, $q_{4(surface)}$), mainly because of the implications described below for the productivity-biomass trade-off in parameter estimates.

Model estimates for the base natural mortality in 1951 (M_0) were nearly identical for the two operating models. The main difference for population dynamics occurred in the impression about the productivity-biomass trade-off. Productivity (i.e., stock-recruitment steepness h) and unfished equilibrium biomass (B_0) are typically inversely related (e.g., small, productive stock vs large, unproductive stock) in assessment model estimates. The time-varying-*M* model characterizes WCVI herring as relatively small ($B_0 = 48.7\ kt$) and productive ($h = 0.724$) compared to constant-*M*, which estimates a potentially large ($B_0 = 109.73\ kt$) but less productive stock ($h = 0.541$). The high steepness parameter for time-varying-*M* could arise for at least two reasons. First, it could reflect a lack of model sensitivity to the stock-recruitment relationship because this model can capture apparent variation in abundance via variation in *M* rather than recruitment. Thus, estimated steepness for time-varying-*M* would be similar to the prior mean (steepness prior $h = 0.67$). Second, allowing *M* to vary over time could break correlations between steepness and other model parameters like *M* and B_0 with the result also being similar to the prior mean. In either case, the relatively high productivity implied by the prior mean further implies that the average stock size does not need to be that large to support the historical catch; that is, the historical catch can mostly be explained by variation in production via annual deviations in *M* or recruitment. If the average stock size is small, then the spawn index catchability must then be closer to 1.0, which is consistent with the catchability estimates described above. For the constant-*M* model, estimated steepness is lower presumably because of greater model sensitivity to stock-recruitment, but this could also reflect correlations with other models parameters such as *M* and B_0. In either case, the higher unfished biomass arises because lower productivity requires a higher average biomass to support the historical production.

Differences in catchability between the two operating models lead to biomass estimates for 2017 (B_{2017}) that differ by a factor of two. On the other hand, despite all the differences given above, the two models estimate almost identical current stock status relative to their respective unfished biomasses (D_{2017}).

Estimated MSY-based biological reference points follow from the parameters given above, implying a small/productive stock for time-varying-*M* and large/unproductive stock for constant-*M*. In particular, note that, under both models, these theoretical optimal harvest rates are more than 2-5 times the rates that we test in candidate management procedures.

3.1.2. SOG OPERATING MODELS

The qualitative patterns and trade-offs in parameter estimates for SOG are practically identical to WCVI. This is not surprising given that the patterns mainly arise via properties of the stock assessment models. SOG herring *M* is not estimated to be as variable in the time-varying-*M* model compared to WCVI; therefore, most differences attributable to variability in *M* are smaller. The stock assessment data for SOG herring are also generally more extensive and more precise, which may reduce some sensitivity to assumptions.

Nevertheless, notable differences between operating models include similar baseline M (M_0) values, similar estimated stock-recruitment steepness, and nearly identical unfished biomass and MSY-based biological references points (Table 6).

For SOG, the major difference between time-varying-*M* and constant-*M* is for current estimated biomasses, which are $B_{2017} = 117.04kt$ and $B_{2017} = 59.96kt$, respectively. This pattern is opposite to the current biomass estimates in WCVI, where the time-varying-*M* model estimated much lower current biomass (Table 6). It seems as though the models are similar in their estimation of long-term average properties driven by population dynamics parameters, but differ substantially in their most recent assessment of biomass – this could be an indication of relatively robust estimation of population dynamics processes, but high sensitivity to more recent data for time-varying-*M*.

The closed-loop simulations aim to quantify long-term risks to management performance arising from these assessment model estimation properties. In this section we use 10-year retrospective analyses to show how time-varying-*M* and constant-*M* model biomass and parameter estimates change over time in response to new data and fluctuations in biomass.

Retrospective analyses of spawning biomass, natural mortality, and fishing mortality rates show how assessment model estimates change over time for WCVI (Figure 5) and SOG herring (Figure 6). The time-varying-*M* model shows little retrospective pattern for WCVI biomass, possibly because the stock is small, fishing mortality is essentially zero, and natural mortality rates are estimated to be high. The non-linear sensitivity of abundance to *M* (e.g., $N_{t+1} - N_t e^{-M}$) means that, all else being equal, biomass is more sensitive to errors in *M* when *M* is low than when *M* is high. The retrospective pattern in *M* shows considerable variability in most recent estimates, but a lack of persistent positive or negative bias. The stronger link between *M* and long-term biomass in the constant-*M* model produces a more persistent over-estimation of spawning biomass growth for WCVI (Figure 5, top right). That is, as long-term constant M estimates decrease over time, the average biomass increases.

Retrospective patterns in assessment model estimates for SOG are opposite to WCVI. In particular, the larger stock size generates more sensitivity of biomass estimates to variation in estimated *M* and other parameters (Figure 6, top left). Although the time-varying-*M* biomass estimates are generally unbiased, large over-estimates can occur. In contrast, the constant-*M* model shows a persistent negative bias in biomass estimates. These are not driven by changes in constant *M*, however, since those estimates are very stable. The systematic under-estimates probably arise from retrospective patterns in estimated recruitment.

3.2. SIMULATION MODEL DYNAMICS

In each section below, we first present closed-loop simulation model output for a single replicate to illustrate spawning biomass dynamics, retrospective assessment model estimates, and harvest rate dynamics in relation to management procedure targets for both WCVI and SOG stocks. The WCVI example uses the time-varying-*M* operating model and density-dependent-*M* (DDM) scenario since this scenario actually involves enough future fishing to demonstrate management procedure behaviour. In contrast, we use the low current biomass scenario derived from the constant-*M* operating model for SOG since a biomass over-estimation is the key short-term risk to this stock. Note that all MP implementations use the time-varying-*M* assessment model for annual assessments. We apply three different MPs to each operating model where the random errors in *M*, survey indices, age-composition, and recruitment are all identical. Thus, the simulation dynamics show only the effects of changes in MP target harvest rates and catch caps.

The example single simulation replicates are then followed by summaries of 100 simulation replicates for the same MPs and scenarios, but for spawning biomass depletion (biomass relative to unfished), catch, and realized harvest rates (i.e., the true proportion of fish harvested rather than estimated). These larger biomass and catch samples are used to derive final performance metrics for the evaluation in Section 3.3.

3.2.1. WCVI

For WCVI, we applied the current HCR with the 20% harvest rate (minE18.8_HR.2), the current HCR with a 10% harvest rate (minE18.8_HR.1), and the 10% harvest rate with a 2,000 t cap on catch (minE18.8_HR.1_cap2) (Figure 7). For this DDM scenario replicate, the median natural mortality rate in 2017 started higher than the long-term average and decreased toward the long-term average over the projection period as shown earlier in Figure 4a (WCVI). Thus, natural mortality in this simulation replicate decreases over the projection period (Figure 7, middle row), causing biomass to increase such that fisheries are opened under all three MPs. Under this particular simulation trial, the current MP (Figure 7, left column) assessment errors are very large and lead to harvest rates exceeding the 20% for most of the projection period and occasionally greater than 40%. Although biomass assessments indicate the stock is above $0.30B_0$, the actual spawning biomass is maintained very near this level.

Reducing the target harvest rate in the MP directly reduces biomass sensitivity to positive assessment biases (Figure 7, middle column). Thus, the spawning biomass grows to well-above the $0.30B_0$ level as harvest rates realized by the stock are generally less than 35%.

Finally, a lower harvest rate combined with a 2,000 t cap on total catch further reduces sensitivity to assessments errors (Figure 7, right column). In this MP, the stock grows to near unfished levels as harvest rates are consistently maintained below 20%.

Outcomes for 100 simulations for the same scenario-MP combinations generally mimic the single-replicate examples (Figure 8). Although the current MP (Figure 8, left column) leads to relatively slow growth in median biomass over the projection period, it also maintains a relatively high proportion of biomass levels below the LRP at $0.3B_0$. Catch increases over time, but is highly variable from year-to-year. Reducing the target harvest rate to 10% (Figure 8, middle column) increases the long-term growth trend, and moves more of the biomass envelope above the LRP. Adding a catch cap (Figure 8, right column) has little impact on biomass in the short-term, while further increasing the biomass growth trend in the long-term.

3.2.2. SOG

For SOG herring, we applied the current HCR with the 20% harvest rate (minE21.2_HR.2), the estimated 50% cutoff MP with a 20% harvest rate (minE.5B0_HR.2), and the 30-60% B_0 hockey-stick HCR with 20% target harvest rate (HS30-60_HR.2) (Figure 9) under the constant-*M* scenario. Under this conM scenario, the natural mortality rate was constant over both the historical and projection periods. Therefore, all changes in biomass arise only from changes in recruitment and fishing mortality.

The most striking feature shown in this particular simulation trial is the occasional, but severe over-estimates of biomass under all MPs (since they all use the same time-varying-*M* assessment model) (Figure 9, top row). These errors are driven by large under-estimation errors in *M* as shown in Figure 9 (middle row). Although the time-varying-*M* assessment model actually does a good job of estimating historical *M* up to about year 2006, the most recent values can be systematically biased to a large degree. Under-estimating *M* leads to biomass over-estimation, realized harvest rates well in excess of their 20% target, and a subsequent drop in spawning biomass. The flexibility in the time-varying-*M* model seems to allow for a rapid update of estimated *M* (provided the data are precise enough to have detected it) back to relatively unbiased values and subsequent unbiased estimates of biomass. Therefore, the model doesn't seem to promote long periods of severe over-fishing. Nevertheless, realized harvest rates on the stock fluctuate from just under the target 20% to almost 60% due to these assessment error feedbacks. In the case of the 50% B_0 cutoff and hockey-stick HCRs, the fisheries are actually closed when the assessment errors are corrected (Figure 9, bottom row, middle and right columns).

Despite the occasional large assessment errors, all three MP variants are able to maintain the spawning stock biomass above 30% of B_0 greater than in 90% of the time (Figure 10, top row). The current MP (Figure 10, left column) maintains less volatility in catch and never closes the commercial fisheries under this scenario. Harvest rates realized by the stock under the current MP are generally higher than the target 20%, and typically maintained between 15-40%. The 50% B_0 and hockey-stick MPs have more variable catch, mainly because of the higher cutoff and ramped target harvest rate, respectively. Although the median annual yields follow similar trajectories to the current MP, fishery closures occur and/or low catch year occur in these cases.

Of the three operating models, the constant-*M* scenario presents the greatest challenge to the MPs and the current MP appears to present the greatest risk, even though the overall level of risk is low (i.e., judging by the low proportion of simulation replicates with $B < 0.3B_0$, Figure 10).

3.3. MANAGEMENT PROCEDURE EVALUATION

3.3.1. WCVI

As noted above, management procedure performance is more sensitive to operating model assumptions for WCVI compared to SOG because the operating models differ more in their estimation of stock productivity and natural mortality dynamics. For instance, in the absence of fishing (i.e., the NoFish MP), spawning biomass meets the Conservation Objective (Obj 1) in 88%, 78%, and 94% of simulation trials for DDM, DIM, and conM scenarios, respectively (Table 6). However, under the DIM scenario especially, where future natural mortality is assumed to remain near the recent 10-year average, there seems to be little to no scope for even the most conservatively managed fisheries to operate as no MPs met the Conservation Objective (Obj 1), nor the other Biomass Objectives (Obj 2-4).

Under the DDM and conM scenarios, several MPs were able to meet the Conservation Objective (Obj 1), while fewer met Biomass Objectives 2-4. When comparing MP performance between Obj 2 and Obj 3, the latter specifies both a higher biomass threshold (i.e., $0.75B_0$) and a higher probability threshold (i.e., >75%), which means that any MP failing to meet Obj 2 will automatically fail to meet Obj 3. Objective 2 was the most difficult for MPs to meet across all operating model scenarios (Table 7).

As expected, MPs with 10% maximum harvest rates maintained higher average spawning biomass than MPs with 20% maximum harvest rates regardless of the form of harvest control rule or presence of a catch cap. For instance, each harvest control rule form was represented in the top three most conservative MPs under each scenario (Table 7; MP3, MP6, and MP9). Similarly, all three HCR forms were represented in the next grouping of three most conservative MPs, as long as they each used 10% maximum harvest rates. The current MP and HS30-60 forms with 20% maximum harvest rate were then the least conservative in two of the three operating model scenarios.

For the WCVI stock, MPs with 2,000 t catch caps maintained the highest spawning biomasses because their effective harvest rates were further reduced as the caps limited the absolute impact of assessment errors. Furthermore, MPs with these catch caps were the only MPs to meet Objectives 1 and 2 for the DDM and conM scenarios (Table 7).

For yield objectives, only MPs with 10% maximum harvest rates and catch caps were able to maintain catch variability near or below 25% probably because the lower effective harvest rates maintained higher average biomass, which resulted in lower frequency of assessment outcomes below the cutoffs. The trade-off, of course, is in substantially lower average yields that were 50-60% of yield obtained for non-capped and/or 20% maximum harvest rate MPs (Table 7). The 50% B_0 form of HCR (i.e., minE.5B0) resulted in the most frequent fishery closures; however, this did not result in substantially more biomass or yield than other HCR forms.

The pattern of MP performance against alternative USRs within Objective 2 was qualitatively similar across scenarios to those described above. However, no procedure, including no fishing, maintained spawning biomass above the alternative USR derived from a historical period of average production (Table 7, last column).

3.3.2. SOG

Patterns of MP performance for SOG herring were similar to those observed for WCVI. In particular, the 10% maximum harvest rate MPs with catch caps maintained the highest biomass levels, although the catch caps had little overall impact. All MPs achieve the Conservation Objective (Obj 1) by maintaining spawning biomass above the LRP with greater than 90% probability under all operating model scenarios. However, all three MPs with 20% maximum harvest rates failed to achieve Objective 2 under the conM scenario (Table 7). This probably occurs because the higher harvest rate magnifies the impact of assessment estimation errors in M as described in Section 3.2.2.

Under the DDM and DIM scenarios, the 10% maximum harvest rate MPs with catch caps maintained annual variability in yield less than the threshold 25% (Objective 5), while the current MP maintained variability at 27-28% across all scenarios. As expected, the 10% maximum harvest rate MPs obtained yields that were 50-60% of the yield for 20% maximum harvest rate MPs.

The current herring MP never closed SOG herring fisheries under any operating model scenario. For most other MPs, closures occurred 0-9% (Table 8) of the time with the highest occurrence being the 50% B_0 MP with 20% harvest rate under the conM scenario. Reasons for this higher rate of closure are described in Section 3.2.2.

In contrast to WCVI, MPs met Objective 2 with alternative USRs in almost all cases. The only exception occurred where the current MP failed (by 2%) to maintain spawning biomass above the biomass during an Average Productive Biomass period under the conM scenario (last column in Table 8).

4. DISCUSSION

Pacific Herring fisheries face challenging questions at almost all steps of the harvest decision-making process (as well as many other areas involved in managing fisheries). Most of these questions arise from a lack of clear scientific understanding about fish population structure, dynamics, and abundance, as well as a healthy skepticism about the ability of complicated stock assessment models to resolve these issues. However, by developing explicit conservation, spawning biomass, and yield objectives, via collaborations in part with First Nations and industry stakeholders, fishery managers have established the conditions needed to conduct a structured scientific investigation of expected management performance in the presence of uncertainty. In this paper, we evaluated the ability of proposed management procedures to meet these quantitative conservation, biomass, and yield objectives despite considerable uncertainty about underlying dynamics and stock size at any particular decision point in time. Although we cannot guarantee actual performance of any management procedures we evaluated, our scientific evaluation is able to draw two types of conclusions. First, we can determine whether certain MPs may or may not be rejected based on failure to meet objectives under the particular simulation scenarios we examined. Second, where no MPs could feasibly maintain fisheries, we can identify the specific uncertainty that contributed to the failure and corresponding need for future research.

For WCVI herring, our simulation results show that the current management procedure (minE18.8_HR.2) would fail to meet spawning biomass conservation objectives under most circumstances we examined. Reducing the maximum harvest rate to 10% and capping fishery quotas at a maximum 2,000 t would reduce the effective harvest rate and protect against periods of low productivity and stock assessment over-estimates of abundance when they occur. In two of the three scenarios we examined, where natural mortality remains near the long-term historical average (i.e., by decreasing or staying constant), these types of MPs would meet Biomass Objectives 1 (conservation) and 2, but not Objective 3 as it is more stringent. Any fisheries that occurred would be relatively small with average annual yields less than 2,000 t and closures 7-25% of the time. If natural mortality has fluctuated historically and, in future, remains near the recent 10-year average, then no MP would provide consistent fisheries besides those required for food, social, and ceremonial purposes. One might argue that this density-independent-M operating model presents an arbitrary future projection because we could have chosen a wider range or alternative future values than the recent 10-year average. With the density-dependent-M scenario, M decreases to the long-term average, and we found several acceptable MPs in that case. Natural mortality estimated by the time-varying-M operating models is also currently trending downward (last 10-years), so any continuation of this trend would result in performance improvements beyond those obtained under density-dependent-M. Therefore, some MPs must have acceptable probabilities of achieving Objectives 1 and 2 for density-independent-M somewhere between the recent 10-year average M and the long-term average M. Thus, in the short-term, we could further examine sensitivity of management performance to future density-independent-M in this range.

It appears that no MP for WCVI herring fisheries could meet Objective 3 under any scenario. The natural variability of recruitment alone (even when *M* is constant) is enough to limit the proportion of years in which the stock is greater than 75% of B_0 even in the absence of fishing. Only MPs with catch caps were able to meet Objective 2.

For SOG herring, the current MP (minE21.2_HR.2) was generally robust across all scenarios we examined. It, along with two other 20% maximum harvest rate MPs, only failed to meet Objective 3 in the case where historical and future natural mortality is constant (whereas the annual stock assessment assumes it is time-varying). The consequences of meeting Objective 1, but not Objective 2 under one particular scenario, implies that the SOG stock may fluctuate between 30% and 60% of the unfished level, but should rarely drop below 30% of B_0. Natural mortality rates seem to be relatively stable over time for the SOG stock regardless of whether we assume they are time-varying or constant in the operating models. A relatively low and stable *M* implies a yield-maximizing harvest rate greater than 50%. Therefore, a maximum harvest rate of 20% leaves an adequate margin for assessment errors, at least in terms of meeting the stated objectives. This result for SOG is consistent with previous evaluations of the current MP that found it performed well (>90% probability B > LRP) across a range of operating model scenarios and possible future states for this stock area (Hall et al. 1988; Cox et al. 2019) and under assumptions of high productivity (only) (Cleary et al. 2010).

Versions of the hockey-stick harvest control rule have been recommended as a precautionary HCR for many fisheries around the world (Punt et al. 2014); however, our results indicate that HCR form is not necessarily the most important feature of a precautionary management procedure. In fact, we demonstrated that the maximum target harvest rate is more important since stock assessment errors are multiplied by this rate. So, doubling the harvest rate doubles the errors when they occur and this, combined with the asymmetric loss of over-fishing, leads to persistent conservation challenges. The maximum harvest rate sets the overall scale of fishing impacts in relation to average productivity and, therefore, is the key driver of long-term dynamics. Absolute caps on quotas serve a similar purpose in limiting the effective harvest rate on the stock and, especially, the negative impact of over-estimation errors when the stock is small such as occurred for WCVI herring in our simulations. Appropriately scaled catch caps may be a real benefit in rebuilding fisheries where assessment errors could have long-lasting impacts. The catch caps we included in MPs for the larger SOG herring stock were too high to generate much effect; however, caps in the range 20-25,000 t on the current MP could potentially eliminate the failure to meet Objective 2 under the DIM scenario for this stock, making the modified current MP appear robust under all scenarios we examined. Such a cap would further reduce inter-annual catch variability to less than the maximum 25% suggested by stakeholders.

4.1. LIMITATIONS AND FUTURE WORK

The stock-recruitment steepness parameter affects long-term stock productivity and, therefore, our perception about the potential effectiveness of management procedures. In particular, steepness affects the buffer between the theoretical optimal harvest rates (i.e., U_{MSY}) and the maximum harvest rates used in MPs to meet both conservation and yield objectives in the presence of uncertainty. For SOG, even harvest rates that were, due to assessment errors, double the intended 20% maximum were still well below the theoretical U_{MSY} values of 50-53% given in Table 6 for each operating model. However, long-term variation in steepness or biases in the operating model estimates themselves would reduce this gap, thereby reducing realized conservation performance. Future work should therefore test sensitivity of SOG MPs to alternative prior assumptions about stock-recruitment steepness, as well as variability over time, in the operating models.

Our results showed that assessment model errors were a key driver of conservation performance. Thus, future research could examine the assessment method in greater detail, in particular, attempting to find ways of reducing biomass estimation and forecasting errors. For instance, the current assessment uses a particular cubic-spline parameterization of time-varying-*M* that could induce some bias, especially if the number of spline nodes is not increased over time. Keeping the spline nodes fixed at the current number of 12 flattens the spline over time, which induces lags and increasingly biased estimates. A simpler random walk in *M* approach, which we have tested in other work, would eliminate this effect and provide better long-term estimation performance. There is also continuing concern about fixing catchability as currently done in the AM2 component of the MPs we examined. It is relatively straightforward to substitute AM1 as an assessment method in MP evaluations however we avoided AM1 in this set of trials for two main reasons. First, including AM1 would require additional operating models parameterized via AM1. Second, the assessment errors we showed for AM2, which effectively fixes dive survey catchability to 1.0, were often very large and we expect AM1 to have even higher variability in abundance estimates. This is because catchability adds another free parameter in that model, which would allow changes in the overall population scale at each assessment. The benefit of allowing such additional variability is questionable because AM1 is largely dependent on the catchability prior as there is little to no information about catchability in the herring spawn survey data for any herring stock (Cleary et al. 2018).

4.2. SPATIAL POPULATION DYNAMICS

Spatial population structure and dynamics of Pacific Herring is a key uncertainty that we aim to examine in future cycles of MSE research. Appendix A presents an initial summary of spatially disaggregated abundance data for WCVI and SOG herring stocks from which the next MSE steps will be derived. Implications of spatial structure may include, *inter alia*, spatial population dynamics, sequential fisheries, fishing season timing and duration, and fine-scale spatial objectives of interest to First Nations and local communities. Without taking population spatial structure into account, localized harvest rates may exceed sustainable harvest rates even where the aggregate harvest rate appears buffered by precautionary measures such as lower maximum harvest rates and catch caps. For instance, Benson et al. (2015) showed that interactions among spatial population productivity and abundance, fishing season timing and duration, and fishing power combine to determine the importance of spatial structure in long-term management performance.

Future research could also examine the feasibility and performance of data-based management procedures for herring, especially where fine-scale spatial operating models are used to examine MP performance in the presence of uncertainty about spatial population structure and dynamics. Modelling fine-scale population structure would have two predictable effects on the data used in either data-based or model-based management procedures. First, if overall sampling intensity remains the same over the whole area (e.g., WCVI), spawn survey indices and age-composition data at smaller scales would be more imprecise (i.e., more variable) because of smaller sample sizes. Second, apparent process error in abundance due to fluctuations in local recruitment, productivity, and possibly *M* would also be higher because the index data are not aggregated to large-scales where positive and negative deviations average out. Stock assessment models, therefore, may or may not improve at smaller spatial scales. If small sub-areas are treated independently, they may become less biased as the data better reflect local dynamics. However, it is also inevitable that reduced data quality would reduce model effectiveness in terms of both precision and bias (Johnson and Cox 2019). On the other hand, spatial hierarchical assessment models may provide a compromise between treating stocks independently and aggregating (Johnson and Cox 2019; Thorson et al. 2015; Berger et al. 2017). Thus, even though operating models and management could potentially be done at smaller scales in theory, it may not reduce risks in practice without some additional compensating adjustments to the management procedures as determined via simulation testing.

5. RECOMMENDATIONS

Our results identified several management procedures that could meet fishery objectives at the aggregate-stock level across a range of operating model scenarios, parameter uncertainty, and future assessment estimation errors. For SOG herring, the current management procedure met the Conservation Objective (Obj 1) in all cases and only failed to meet Objective 2 under a constant-*M* scenario. A slight modification to either the maximum harvest rate or a catch cap would likely suffice to meet Objectives 1 and 2 (and all 3 candidate USRs), as well as Objective 3 across all of the operating models we examined.

For WCVI herring, management procedures with 10% maximum harvest rates and 2,000 t catch caps could meet Objectives 1 and 2 as long as future natural mortality rates don't increase to more than the 2008-2017 average. In the presence of a catch cap, harvest rates realized by the stock were maintained well below 20% and often below the maximum 10%. Such MPs could ensure defensibility of on-going management advice while safeguarding against heavy depletion in the short-term as the further strategic MSE work progresses (Butterworth and Geromont 2001).

Nevertheless, it appears that even the best-performing MPs for WCVI are still sensitive to a plausible uncertainty regarding future natural mortality rates. This implies a need for follow-up work revising the most promising MPs until this sensitivity is eliminated. For instance, one option would be to augment, e.g., the HS30-60_HR.1_cap2 MP with a trend criterion that ensures a stable growing stock prior to re-opening fisheries. Such a criterion could be invoked when the stock has recently been assessed between 30% and 60% of estimated B_0. Such a criterion would perform more like the NoFishing MP when the stock is low, adding robustness uncertainty about underlying productivity.

Another option is a slow-up MP in which the user specifies the number of years required for the stock projection to be above a threshold (e.g., minimum escapement level) before a harvest rate can be applied. To demonstrate, we added a slow-up rule to the best performing MP for WCVI (minE.5B0_HR.1_cap2). This analysis appears in Appendix C.

Finally, we recommend further exploration of modelling approaches for depensatory natural mortality for future operating model scenarios. This may include Allee effects and/ or role of predator biomass or consumption rates on depensation.

6. ACKNOWLEDGMENTS

We thank Trevor Branch and Paul Regular for sharing their time and expertise in reviewing the working paper, and all of the participants for their constructive engagement in the RPR process. We thank Bruce Patten (meeting chair) and Lisa Christensen and Ann Mariscak for providing CSAS meeting support.

7. TABLES

Table 1. Performance statistics calculated for each management procedure/scenario combination. All performance indicators are calculated over 3 generations from the first year of the projections (2018 - 2032). The indicator function is defined by $I(X\ is\ TRUE) = 1$ and $I(X\ is\ FALSE) = 0$.

Objective	Description	Probability or Statistic	Definition
Objective 1	Proportion of projection years where spawning biomass exceeds $0.3B_0$.	$P(B > 0.3B_0)$	$P(B > .3B_0) = \frac{\sum_{r=1}^{100} \left[\sum_{2018}^{2032} I(B_{r,t} > 0.3B_{r,0}) \right]}{100 \cdot 15}$
Objective 2	Proportion of projection years where spawning biomass exceeds *USR*	$P(B > USR)$	$P(B > USR) = \frac{\sum_{r=1}^{100} \left[\sum_{2018}^{2032} I(B_{r,t} > USR) \right]}{100 \cdot 15}$
Objective 3	Proportion of projection years where spawning biomass exceeds $0.75B_0$.	$P(B > 0.75B_0)$	$P(B > .75B_0) = \frac{\sum_{r=1}^{100} \left[\sum_{2018}^{2032} I(B_{r,t} > 0.75B_{r,0}) \right]}{100 \cdot 15}$
Objective 4	Proportion of projection years where spawning biomass exceeds reference biomass $\overline{B}_{1990:1999}$	$P(B > \overline{B}_{1990:1999})$	$P(B > \overline{B}_{1990:1999}) = \frac{\sum_{r=1}^{100} \left[\sum_{t=2018}^{2027} I(B_{r,t} > \overline{B}_{r,1990:1999}) \right]}{100 \cdot 10}$
Objective 5	Median over replicates of average annual absolute change in the landed catch	*AAV*	$AAV = \text{median}_r \frac{\sum_{t=2018}^{2032} \lvert C_{r,t} - C_{r,t-1} \rvert}{\sum_{t=2018}^{2032} C_{r,t}}$
Objective 6	Median over replicates of mean annual landed catch	$\overline{C}$	$\bar{C} = \text{median}_r \frac{\sum_{t=2018}^{2032} C_{r,t}}{15}$

Table 2. Candidate management procedures used for the WCVI Herring fishery. Values in Cutoff column are used in place of E in Eq 1, Section 2.2.1. Upper control points are not defined for minimum escapement (minE) HCR functions, as these depend only on the cutoff value and the harvest rate.

Management procedure	U_{max} (HR)	max TAC	HCR Function	Cutoff	Upper Control Point	Label
MP1	0.2	-	minE	18,800 t	-	minE18.8_HR.2
MP2	0.1	-	minE	18,800 t	-	minE18.8_HR.1
MP3	0.1	2,000 t	minE	18,800 t	-	minE18.8_HR.1_cap2
MP4	0.2	-	minE	0.5B0	-	minE.5B0_HR.2
MP5	0.1	-	minE	0.5B0	-	minE.5B0_HR.1
MP6	0.1	2,000 t	minE	0.5B0	-	minE.5B0_HR.1_cap2
MP7	0.2	-	HS	0.3B0	0.6B0	HS30-60_HR.2
MP8	0.1	-	HS	0.3B0	0.6B0	HS30-60_HR.1
MP9	0.1	2,000 t	HS	0.3B0	0.6B0	HS30-60_HR.1_cap2
MP10	0	0	n/a	n/a	n/a	NoFish

Table 3. Candidate management procedures used for the SOG Herring fishery. Values in Cutoff column are used in place of E in Eq 1, Section 2.2.1. Upper control points are not defined for minimum escapement (minE) HCR functions, as these depend only on the cutoff value and the harvest rate.

Management procedure	U_{max} (HR)	max TAC	HCR Function	Cutoff	Upper Control Point	Label
MP1	0.2	-	minE	21,200 t	-	minE21.2_HR.2
MP2	0.1	-	minE	21,200 t	-	minE21.2_HR.1
MP3	0.1	30,000 t	minE	21,200 t	-	minE21.2_HR.1_cap30
MP4	0.2	-	minE	0.5B0	-	minE.5B0_HR.2
MP5	0.1	-	minE	0.5B0	-	minE.5B0_HR.1
MP6	0.1	30,000 t	minE	0.5B0	-	minE.5B0_HR.1_cap30
MP7	0.2	-	HS	0.3B0	0.6B0	HS30-60_HR.2
MP8	0.1	-	HS	0.3B0	0.6B0	HS30-60_HR.1
MP9	0.1	30,000 t	HS	0.3B0	0.6B0	HS30-60_HR.1_cap30
MP10	0	0	n/a	n/a	n/a	NoFish

Table 4. Notation and parameter values for the Pacific Herring operating model.

Symbol	Value	Description
T_0	1951	Initial year of the historical period
T_1	2018	Year in which simulated management procedure begins
T_2	2032	Year in which simulation ends
A	10	Number of age classes
t	$1,2,\ldots,T_2$	Time step. Corresponding year range is 1951-2032
a	1,2,...,A	Age-class index
k	1,2,...K	Fishery/gear index: 1=Reduction, 2=Seine-Roe, 3=Gillnet, 4=Survey 1 (Surface survey), 5=Survey 2 (Dive survey)
B_0	-	Unfished spawning biomass (tonnes)
h	-	Stock-recruitment function steepness
q_k	-	Spawn survey scaling parameter for k = *4,5*
τ^I_k	-	Standard deviation of observation errors for survey k = 4,5
τ^{age}_k	-	Standard deviation of logistic-normal ageing errors for fleet k
σ_R	-	Standard error of log-recruitment
M_t	-	Instantaneous natural mortality rate (/yr) in year t
σ_M	0.1	Standard error of random walk jumps in natural mortality rate
$W_{a,t}$	-	Annual observed weight-at-age in the historical period
$a_{50}^{mat}, a_{95}^{mat}$	2.26, 3.21	Age-at-50% and -95% maturity
$a_{50}^{sel,k}, a_{95}^{sel,k}$	-	Age-at-50% and -95% selectivity for each gear
S_a^k	-	Proportion selected-at-age *a* by gear-*k*
R_0	-	Unfished equilibrium recruitment

Symbol	Value	Description
ϕ	-	Unfished spawning biomass per recruit
$N_{1,a}$	-	Numbers at age in year 1 (1951), input from conditioning assessment model
$N_{t,a}$	-	Number of age *a* fish at time *t*
$\epsilon_{t,k}$	-	Uncorrelated *Normal*(0,1) observation error in log-spawn index from survey *k=4,5* at time *t*
$\eta_{t,a}^{k}$	-	Uncorrelated *Normal*(0,1) error in logistic-transformed proportions-at-age from gear *k=1,2,3* at time *t*
W_t	-	Log-normal recruitment process deviation
δ_t^X	-	*Normal*(0,1) process error component in log-natural-mortalith rate (X = M) and log-recruitment (X = R).
B_t	-	Spawning biomass in year *t*
$C_{t,k,a}$	-	Catch at age-*a* with gear-*k* in year *t*
$F_{t,k}$	-	Fully-selected fishing mortality rate for gear *k* in year *t*
$Z_{t,a}$	-	Total mortality rate in year *t* for age-*a*
$I_{t,k}$	-	Observed biomass index for gear *k = 4, 5*
$P_{t,a}^{k}$	-	Observed proportion of age class *a* herring in the sampled catch for gear *k*
$x_{t,a}^{k}$	-	Zero-centred log-residual of herring proportions-at-age *a* at time *t* in gear *k*
$u_{t,a}^{k}$	-	True proportion of age class *a* herring in the sampled catch for gear *k*

Table 5. Age-structured operating model equations defining the population dynamics and observations for Pacific Herring.

Selectivity, maturity, and weight-at-age

OM Number	Equation
OM.1	$s_a^k = \begin{cases} 0 & a=1 \\ \left(1+\exp\left[-\log(19)\left(a-a_{50}^{sel,k}\right)/\left(a_{95}^{sel,k}-a_{50}^{sel,k}\right)\right]\right)^{-1} & a>1 \end{cases}$
OM.2	$m_a = \begin{cases} 0 & a=1 \\ \left(1+\exp\left[-\log(19)\left(a-a_{50}^{mat}\right)/\left(a_{95}^{mat}-a_{50}^{mat}\right)\right]\right)^{-1} & a>1 \end{cases}$
OM.3	$w_{a,t} = \begin{cases} 0 & a=1 \\ W_{a,t} & t<T_1 \\ \dfrac{\sum_{y=1}^{T_1-1} W_{a,y}}{T_1-1} & t \ge T_1 \end{cases}$

State dynamics

OM Number	Equation
OM.4	$\phi = \sum_a w_{a,T_1} m_a e^{-(a-1)\bar{M}_t}$
OM.5	$R_0 = B_0 / \phi$
OM.6	$N_{t,1} = \begin{cases} R_t^{OM} & t<T_1 \\ \dfrac{4R_0^{OM} B_{t-1}}{B_0(1-h)+(5h-1)B_{t-1}} e^{\sigma_R \cdot d_t^R - 0.5\sigma_R^2} & t \ge T_1 \end{cases}$
OM.7	$N_{t,a} = \begin{cases} N_{t-1,a-1} e^{-Z_{t-1,a-1}} & 2 \le a \le A-1 \quad t>1 \\ N_{t-1,a-1} e^{-Z_{t-1,a-1}} + N_{t-1,a} e^{-Z_{t-1,a}} & a=A \quad t>1 \end{cases}$

OM Number	Equation
OM.8	$B_t = \sum_{a=1}^{A} m_a w_{a,t} N_{t,a} e^{-Z_{t,a}}$
OM.9	$M_t = \begin{cases} M_1 & t = 1, \\ M_{t-1.} e^{\sigma_M \delta_t^M - \sigma_M^2/2} & t > 1 \end{cases}$
OM.10	$C_{t,k,a} = w_{a,t} N_{t,a} \frac{s_a^k F_{t,k}}{Z_{t,a}} \left[1 - e^{-Z_{t,a}}\right]$
OM.11	$Z_{t,a} = M_t + \sum_{k=1}^{k=3} s_a^k F_{t,k}$

Observation models

OM Number	Equation
OM.12	$I_{t,k} = q_k \left(\sum_{a=1}^{A} m_a w_{a,t} N_{a,t} e^{-Z_{t,a}} \right) e^{\tau_k^I \epsilon_{t,k} - \tau_k^2/2}$
OM.13	$u_{t,a}^k = \frac{N_{t,a} s_a^k e^{Z_{t,a}}}{\sum_j N_{t,j} s_j^k e^{Z_{t,j}}}$
OM.14	$x_{t,a}^k = \log u_{t,a}^k + \tau_P^k \eta_{t,a}^k - \frac{1}{A} \sum_{j=1}^{A} \left[\log u_{t,j}^k + \tau_k^{age} \eta_{t,a}^k \right]$
OM.15	$p_{a,t}^k = \exp\left[x_{t,a}^k\right] \Big/ \sum_{j=1}^{A} \exp\left[x_{t,a}^k\right]$

Table 6. Herring operating model properties arising from fits to historical data. For each stock 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 second 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 ($\overline{M}$), unfished spawning biomass (B_0), spawning stock biomass in 2017 (B_{2017}), spawning stock depletion ($D_{2017} = B_{2017}/B_0$), biomass that produces the theoretical maximum sustainable yield (B_{MSY}), maximum sustainable yield (MSY), and the harvest rate that achieves maximum sustainable yield ($U_{MSY} = MSY/(B_{MSY} + MSY)$). 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	$\overline{M}$	B_0	B_{2017}	D_{2017}	B_{MSY}	MSY	U_{MSY}
WCVI	Time-varying	-740.161	0.490	0.728	0.826	0.724	0.632	0.578	48.729	18.836	0.393	11.313	13.303	0.540
		-	0.041	0.054	0.087	0.076	0.189	0.029	7.504	6.665	0.145	-	-	-
WCVI	Constant	-597.286	0.625	0.885	0.455	0.541	0.663	-	109.733	36.882	0.366	34.184	29.918	0.422
		-	0.049	0.063	0.051	0.070	0.020	-	35.633	7.275	0.128	-	-	-
SOG	Time-varying	-1421.41	0.432	0.686	1.019	0.739	0.494	0.543	145.867	117.039	0.828	33.261	37.655	0.531
		-	0.040	0.053	0.095	0.084	0.177	0.028	31.610	31.766	0.260	-	-	-
SOG	Constant	-1299.94	0.459	0.713	0.798	0.666	0.610	-	146.556	59.961	0.419	38.449	38.449	0.507
		-	0.038	0.052	0.045	0.085	0.012	-	27.012	11.098	0.097	-	-	-

Table 7. Management procedure performance for the West Coast of Vancouver Island stock. Performance criteria are calculated over 3 generations (15 years) from the start of the projection period for all objectives except Biomass Objective 4, which is calculated over 2 generations (10 years, Table 1). Management procedures are ordered within each scenario by performance achieving the Conservation Objective (Obj1), and then ranked in order of Objectives 2-6, where ranking is for the sole purpose of readability of the performance tables and is not meant to impose priorities between Objectives 2-6.

			Biomass Objectives				**Yield Objectives**			**Obj 2 with Alternative USR**	
			Obj 1 (LRP)	**Obj 2**	**Obj 3**	**Obj 4**	**Obj 5 (Catch Variability)**	**Obj 6 (Average Yield)**	**Prob. closures**	**Historical Average Biomass**	**Average Productive Biomass**
		Criterion	**> 75%**	**>50%**	**>75%**	**>75%**	**< 25%**	**max**	**min**	**>50%**	**>50%**
Scenario	**MP**	**Label**	**P(Bt > .3B0)**	**P(Bt > .6B0)**	**P(Bt > .75B0)**	**P(Bt > B90s)**	**medAAV**	**medAveCatch**	**P(Ct < 650t)**	**P(Bt > Bave)**	**P(Bt > Bave-prod)**
WCVI_DDM	10	NoFish	88%	61%	46%	42%	-	0.13	100%	61%	40%
WCVI_DDM	6	minE.5B0_HR.1_cap2	87%	55%	39%	38%	16.49	1.72	25%	55%	34%
WCVI_DDM	9	HS30-60_HR.1_cap2	86%	54%	39%	37%	13.14	1.86	14%	54%	34%
WCVI_DDM	3	minE18.8_HR.1_cap2	86%	54%	38%	37%	8.26	1.85	17%	54%	34%
WCVI_DDM	5	minE.5B0_HR.1	86%	47%	32%	32%	39.07	3.63	27%	47%	27%
WCVI_DDM	8	HS30-60_HR.1	84%	46%	31%	31%	36.33	3.78	14%	46%	26%
WCVI_DDM	2	minE18.8_HR.1	84%	46%	31%	31%	34.32	3.79	18%	46%	27%
WCVI_DDM	4	minE.5B0_HR.2	78%	33%	20%	22%	47.42	6.23	29%	32%	16%
WCVI_DDM	**1**	**minE18.8_HR.2**	**75%**	**30%**	**19%**	**21%**	**41.28**	**6.66**	**21%**	**30%**	**15%**
WCVI_DDM	7	HS30-60_HR.2	74%	30%	19%	21%	40.31	6.56	14%	30%	15%
WCVI_DIM	10	NoFish	78%	39%	27%	32%	-	0.13	100%	40%	23%
WCVI_DIM	6	minE.5B0_HR.1_cap2	74%	35%	23%	28%	29.43	1.52	34%	35%	20%
WCVI_DIM	3	minE18.8_HR.1_cap2	73%	34%	22%	28%	21.35	1.74	26%	34%	19%
WCVI_DIM	9	HS30-60_HR.1_cap2	73%	34%	23%	28%	18.63	1.73	21%	34%	19%
WCVI_DIM	5	minE.5B0_HR.1	69%	28%	17%	23%	49.49	2.69	37%	28%	14%
WCVI_DIM	8	HS30-60_HR.1	68%	28%	17%	23%	40.85	2.97	22%	27%	14%
WCVI_DIM	2	minE18.8_HR.1	68%	27%	17%	23%	41.17	3.08	28%	27%	14%
WCVI_DIM	4	minE.5B0_HR.2	60%	19%	11%	17%	60.48	4.48	39%	20%	8%
WCVI_DIM	**1**	**minE18.8_HR.2**	**56%**	**18%**	**10%**	**16%**	**47.74**	**5.06**	**30%**	**18%**	**8%**
WCVI_DIM	7	HS30-60_HR.2	56%	18%	10%	16%	47.27	5.06	20%	18%	8%

			Biomass Objectives				Yield Objectives			Obj 2 with Alternative USR	
			Obj 1 (LRP)	Obj 2	Obj 3	Obj 4	Obj 5 (Catch Variability)	Obj 6 (Average Yield)	Prob. closures	Historical Average Biomass	Average Productive Biomass
		Criterion	> 75%	>50%	>75%	>75%	< 25%	max	min	>50%	>50%
Scenario	**MP**	**Label**	**P(Bt > .3B0)**	**P(Bt > .6B0)**	**P(Bt > .75B0)**	**P(Bt > B90s)**	**medAAV**	**medAveCatch**	**P(Ct < 650t)**	**P(Bt > Bave)**	**P(Bt > Bave-prod)**
WCVI_conM	10	NoFish	94%	58%	40%	92%	-	0.13	100%	74%	73%
WCVI_conM	6	minE.5B0_HR.1_cap2	91%	53%	36%	88%	7.12	1.98	8%	70%	68%
WCVI_conM	3	minE18.8_HR.1_cap2	91%	53%	36%	88%	7.12	1.98	7%	70%	68%
WCVI_conM	9	HS30-60_HR.1_cap2	91%	53%	36%	88%	7.10	1.98	7%	70%	68%
WCVI_conM	5	minE.5B0_HR.1	87%	38%	25%	83%	29.47	7.68	9%	59%	57%
WCVI_conM	8	HS30-60_HR.1	86%	38%	24%	83%	29.40	7.71	7%	58%	57%
WCVI_conM	2	minE18.8_HR.1	86%	38%	24%	83%	28.89	7.73	7%	59%	56%
WCVI_conM	4	minE.5B0_HR.2	73%	23%	13%	70%	31.30	13.09	10%	41%	39%
WCVI_conM	7	HS30-60_HR.2	72%	23%	13%	69%	30.70	13.23	7%	40%	38%
WCVI_conM	**1**	**minE18.8_HR.2**	**72%**	**23%**	**13%**	**69%**	**30.46**	**13.30**	**8%**	**40%**	**38%**

Table 8. Management procedure performance for the Strait of Georgia stock. 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), and then ranked in order of Objectives 2-6, where ranking is for the sole purpose of readability of the performance tables and is not meant to impose priorities between Objectives 2-6.

			Biomass Objective		**Yield Objectives**			**Obj 2 with Alternative USR**	
			Obj 1 (LRP)	**Obj 2**	**Obj 5 (Catch**	**Obj 6 (Average**	**Prob. Closures**	**Historical Average**	**Average Productive**
		Criterion	**> 75%**	**>50%**	**< 25%**	**max**	**min**	**>50%**	**>50%**
Scenario	**MP**	**Label**	**P(Bt > .3B0)**	**P(Bt > .6B0)**	**medAAV**	**medAveCatch**	**P(Ct < 650t)**	**P(Bt > Bave)**	**P(Bt > Bave-prod)**
SOG_DDM	10	NoFish	100%	97%	-	0.14	100%	99%	98%
SOG_DDM	3	minE21.2_HR.1_cap30	99%	92%	22.56	21.48	0%	97%	93%
SOG_DDM	9	HS30-60_HR.1_cap30	99%	92%	22.98	21.48	0%	98%	93%
SOG_DDM	6	minE.5B0_HR.1_cap30	99%	92%	23.50	21.48	2%	98%	93%
SOG_DDM	8	HS30-60_HR.1	99%	92%	30.09	23.44	0%	98%	93%
SOG_DDM	5	minE.5B0_HR.1	99%	92%	30.32	23.44	2%	98%	93%
SOG_DDM	2	minE21.2_HR.1	99%	91%	29.64	23.44	0%	97%	93%
SOG_DDM	4	minE.5B0_HR.2	98%	79%	28.35	39.87	3%	92%	79%
SOG_DDM	7	HS30-60_HR.2	98%	78%	27.83	39.87	0%	92%	78%
SOG_DDM	**1**	**minE21.2_HR.2**	**97%**	**78%**	**26.97**	**39.87**	**0%**	**91%**	**78%**
SOG_DIM	10	NoFish	99%	98%	-	0.14	100%	99%	98%
SOG_DIM	6	minE.5B0_HR.1_cap30	99%	93%	22.94	22.63	2%	98%	94%
SOG_DIM	3	minE21.2_HR.1_cap30	99%	93%	22.94	22.63	0%	98%	94%
SOG_DIM	9	HS30-60_HR.1_cap30	99%	93%	22.94	22.63	0%	98%	94%
SOG_DIM	2	minE21.2_HR.1	99%	93%	29.63	24.88	0%	98%	94%
SOG_DIM	8	HS30-60_HR.1	99%	93%	29.68	24.88	0%	98%	94%
SOG_DIM	5	minE.5B0_HR.1	99%	93%	29.95	24.88	2%	98%	94%
SOG_DIM	4	minE.5B0_HR.2	98%	85%	28.73	43.92	3%	95%	86%
SOG_DIM	7	HS30-60_HR.2	97%	85%	27.97	43.92	1%	94%	85%
SOG_DIM	**1**	**minE21.2_HR.2**	**97%**	**84%**	**27.14**	**43.92**	**0%**	**94%**	**85%**

			Biomass Objective		Yield Objectives			Obj 2 with Alternative USR	
			Obj 1 (LRP)	Obj 2	Obj 5 (Catch	Obj 6 (Average	Prob. Closures	Historical Average	Average Productive
		Criterion	> 75%	>50%	< 25%	max	min	>50%	>50%
Scenario	**MP**	**Label**	**P(Bt > .3B0)**	**P(Bt > .6B0)**	**medAAV**	**medAveCatch**	**P(Ct < 650t)**	**P(Bt > Bave)**	**P(Bt > Bave-prod)**
SOG_conM	10	NoFish	100%	84%	-	0.14	100%	97%	93%
SOG_conM	3	minE21.2_HR.1_cap30	99%	60%	33.18	13.79	0%	87%	75%
SOG_conM	2	minE21.2_HR.1	99%	60%	33.54	13.80	0%	87%	75%
SOG_conM	9	HS30-60_HR.1_cap30	99%	60%	35.22	13.56	1%	88%	75%
SOG_conM	8	HS30-60_HR.1	99%	60%	36.11	13.56	1%	88%	75%
SOG_conM	6	minE.5B0_HR.1_cap30	99%	60%	36.19	13.43	6%	88%	76%
SOG_conM	5	minE.5B0_HR.1	99%	60%	37.27	13.43	6%	88%	76%
SOG_conM	4	minE.5B0_HR.2	93%	35%	38.63	23.31	9%	67%	52%
SOG_conM	7	HS30-60_HR.2	92%	33%	34.28	23.76	1%	65%	50%
SOG_conM	**1**	**minE21.2_HR.2**	**91%**	**31%**	**28.27**	**24.08**	**0%**	**62%**	**48%**

8. FIGURES

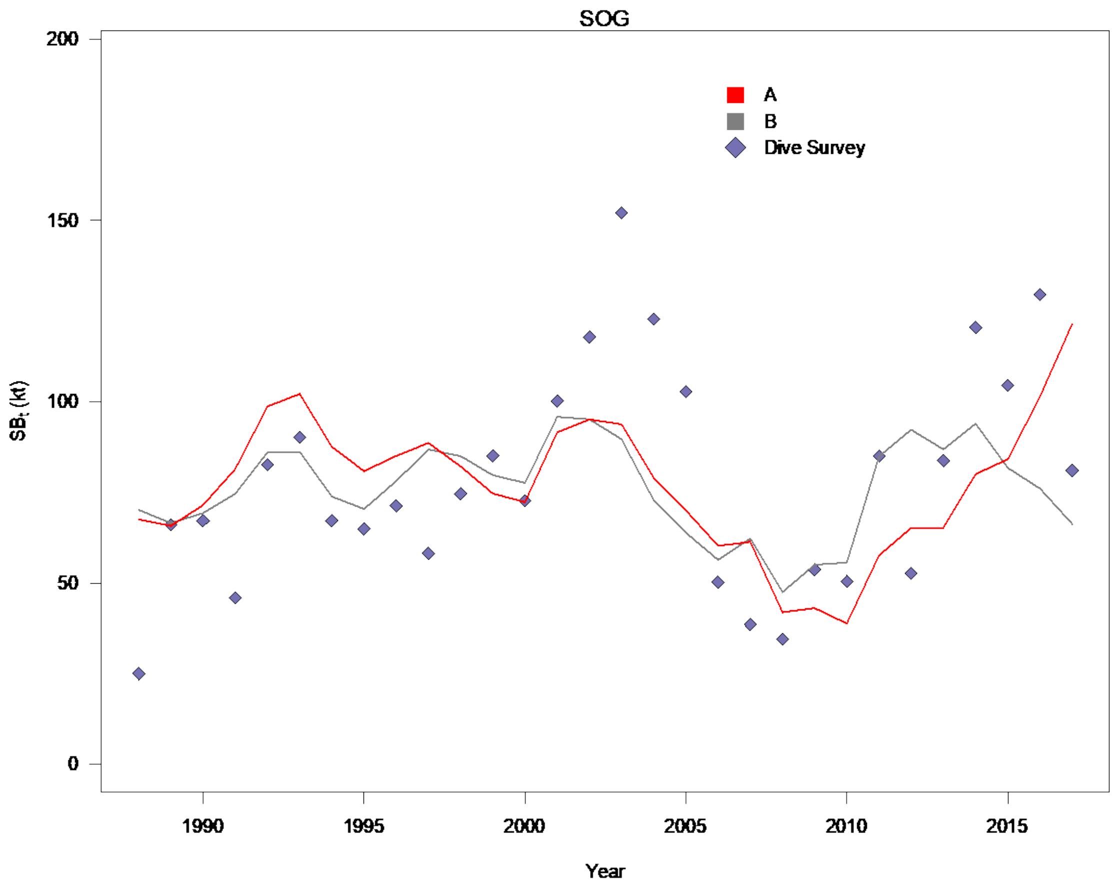

Figure 1. Spawning biomass posterior distributions from the herring stock assessment model under a time-varying M assumption (A) and a constant M assumption (B). Shaded regions show the central 95% of the distribution, and lines show the median values. Purple diamonds show the absolute spawn index observations from the dive survey.

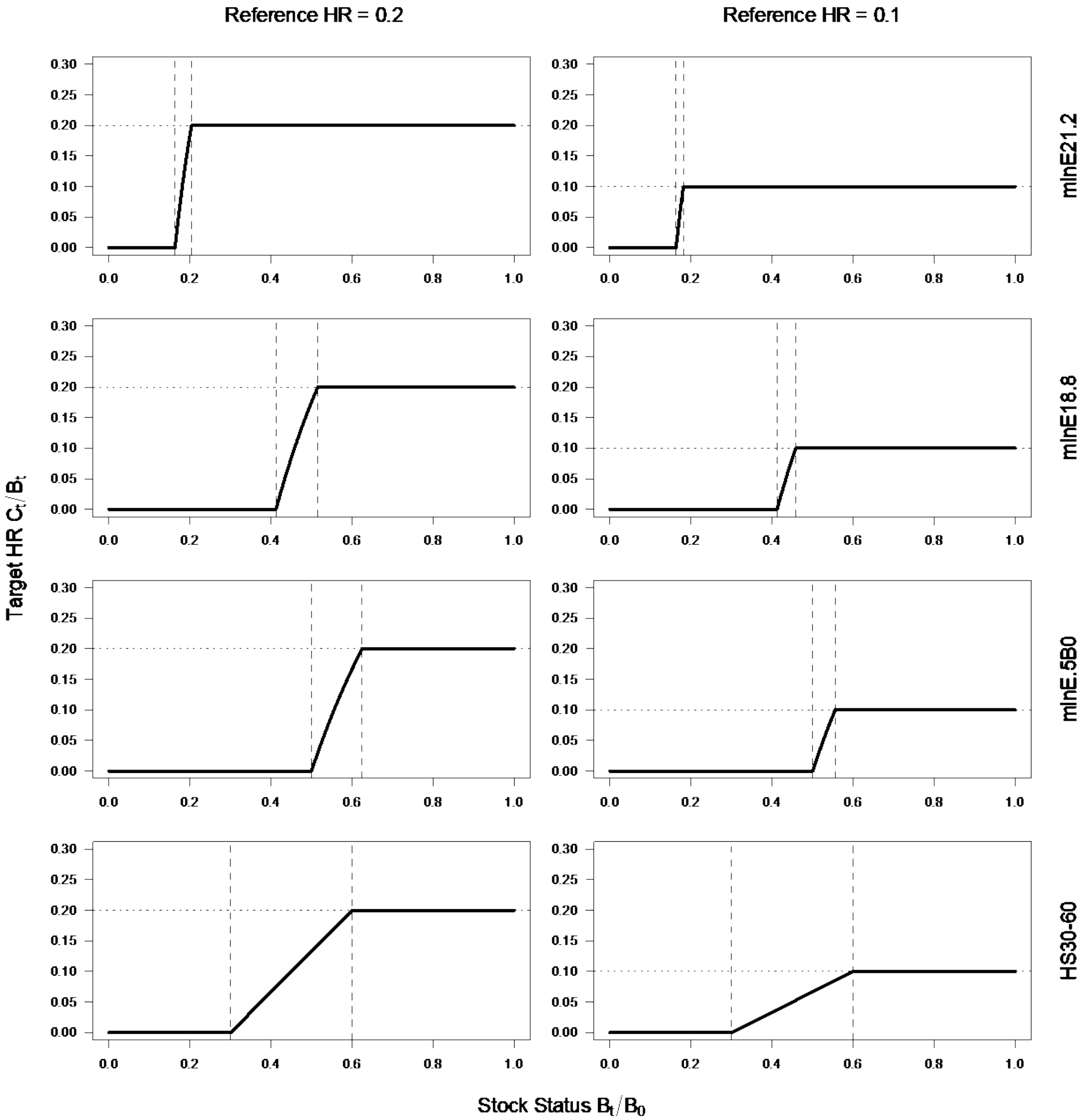

Figure 2. Harvest control rule diagrams showing the functional relationship between harvest rate and stock status for each management procedure. The first row shows the harvest control rule for the minE21.2 procedures for SOG herring MP1 - MP3 (with stock status scaled to OM B0), the second row shows the rule minE18.8 procedures for WCVI herring MP1 - MP3 (also scaled to OM B_0), the third row is the rule for the minE.5B_0 procedures MP4 - MP6, and the fourth row shows the rule for the HS30-60 procedures MP7 - MP9.

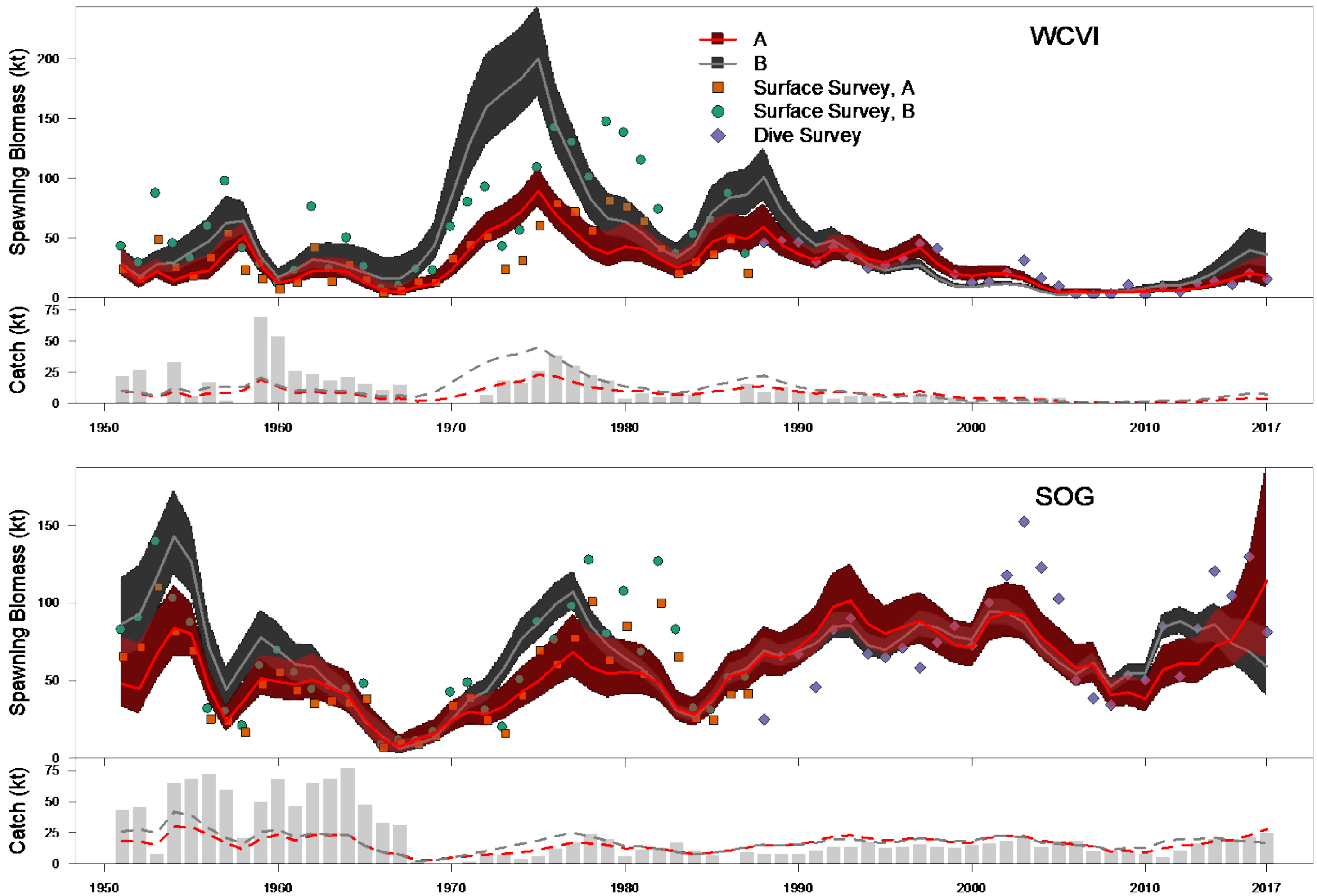

Figure 3. Assessment model estimates of spawning biomass under time-varying M (A) and constant M (B) assumptions for WCVI herring (top) and SoG herring (bottom) since 1951. Shaded regions show the central 95% of the posterior biomass distributions, and the solid lines show the median. Points in the spawning 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).

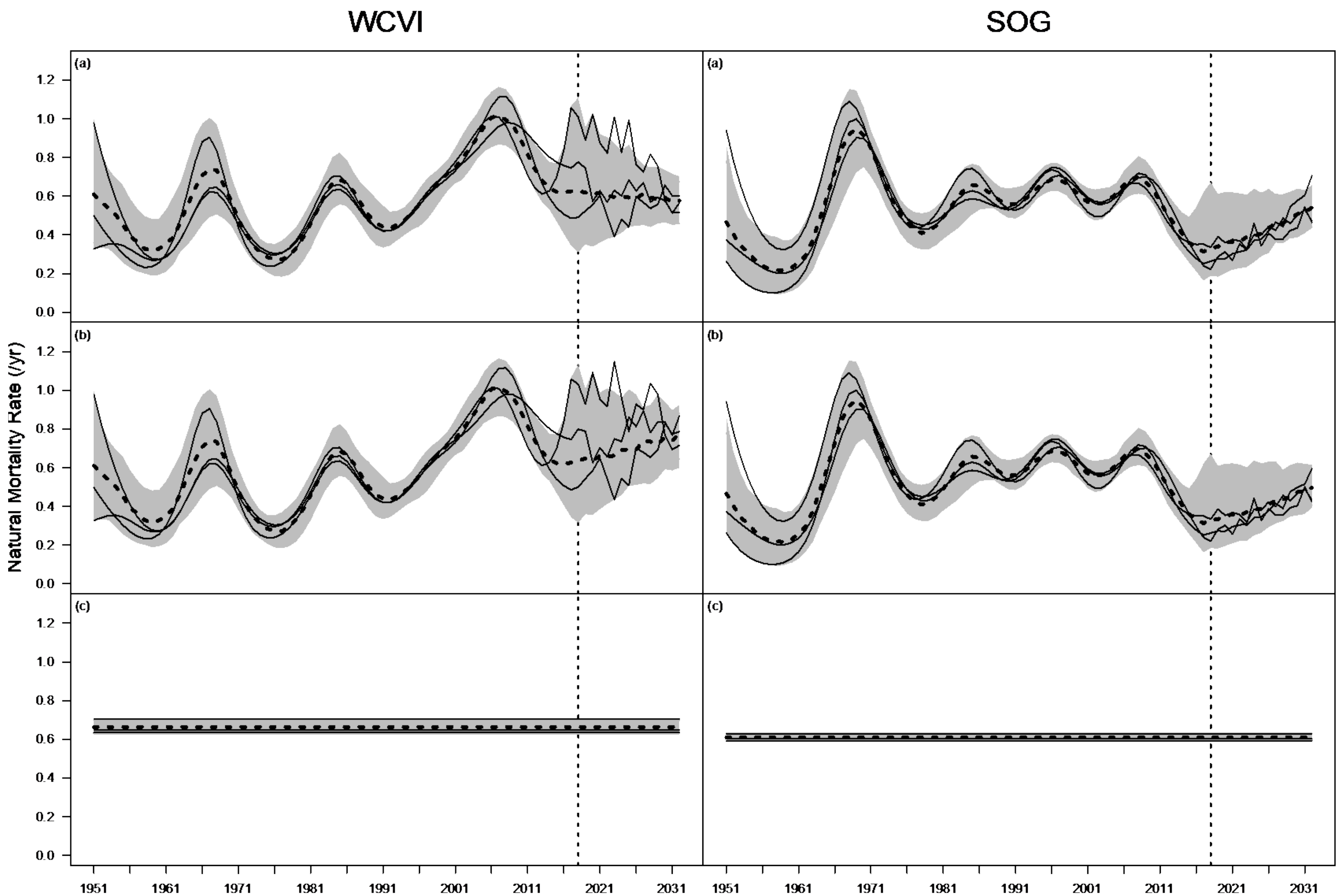

Figure 4. Simulation envelopes for time varying natural mortality in the density dependent scenario (a), density independent scenario (b), and constant M scenario (c) for WCVI and SOG herring stocks. The historical time period is shown from 1951-2017. The vertical dotted line at 2018 denotes the start 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.

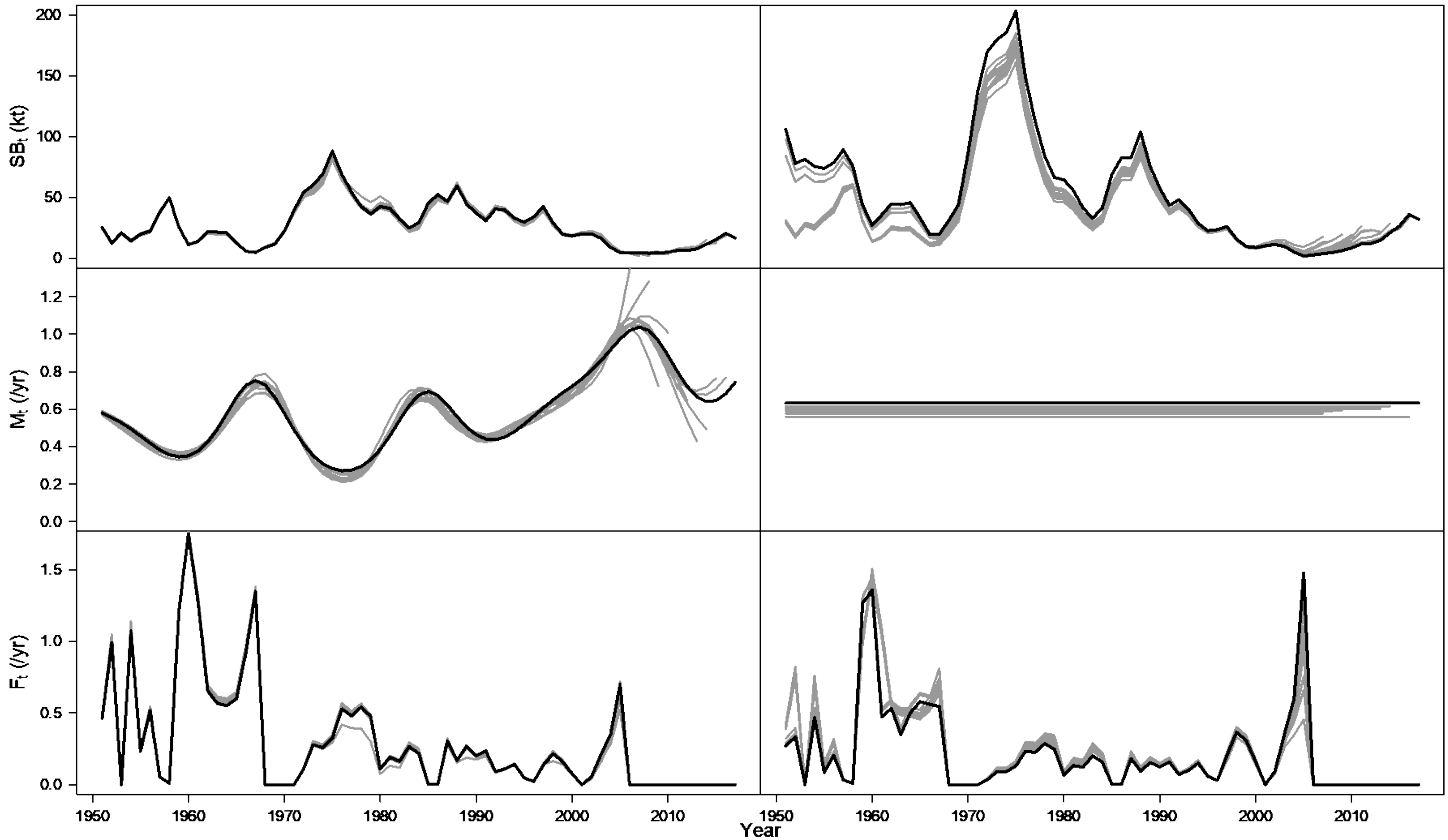

Figure 5. Retrospective (10-years) maximum likelihood estimates of WCVI herring spawning biomass (top), natural mortality M (middle) and fishing mortality F (bottom) using time-varying-M (left hand column) and constant-M,(right hand column) models. Grey lines show retrospective estimates from 2007 - 2016, while the thick black line shows the reference trajectory estimated using all data up to 2017.

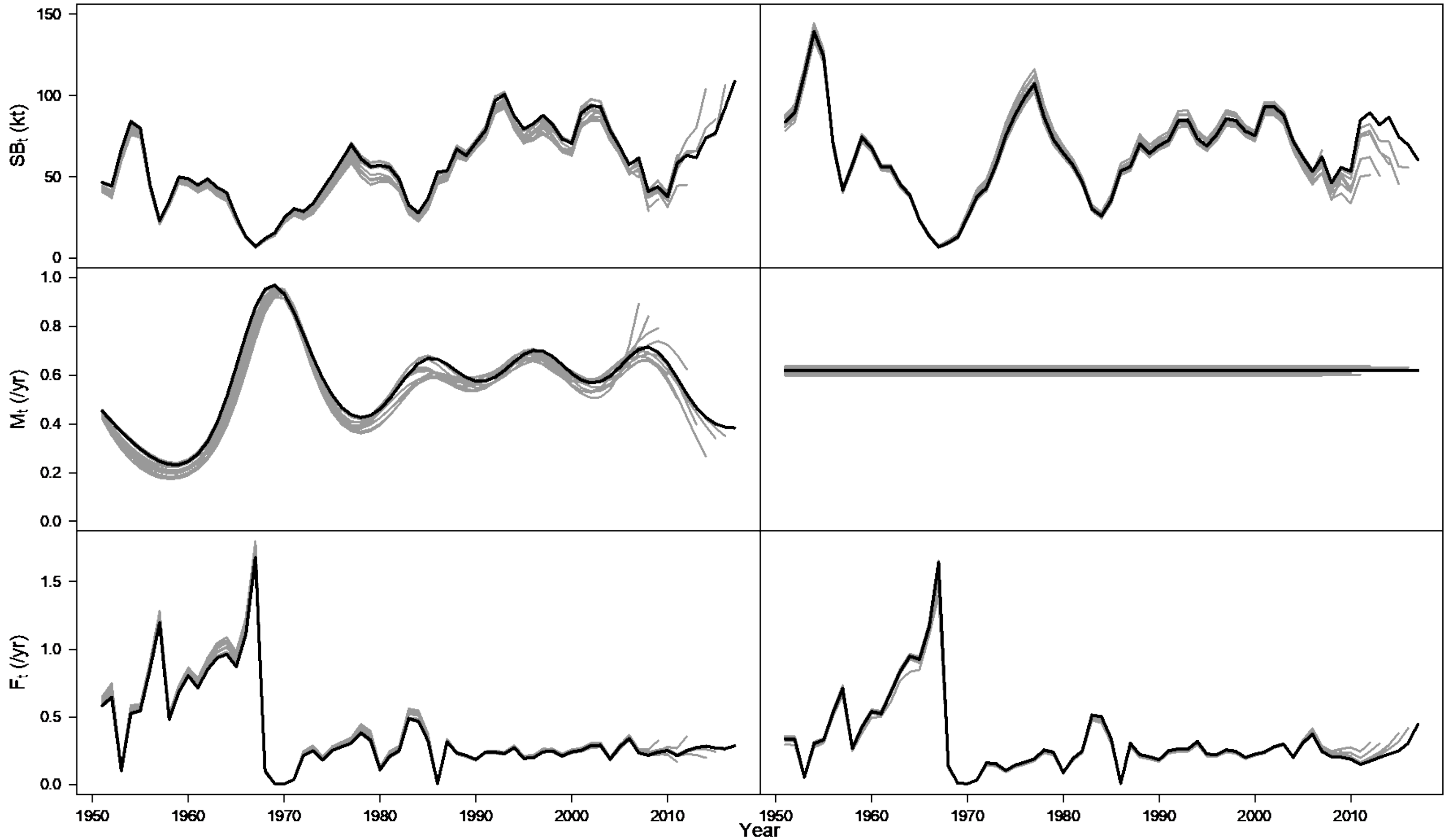

Figure 6. Retrospective (10-years) maximum likelihood estimates of SOG herring spawning biomass (top), natural mortality M (middle) and fishing mortality F (bottom) using time-varying-M (left hand column) and constant-M,(right hand column) models. Grey lines show retrospective estimates from 2007 - 2016, while the thick black line shows the reference trajectory estimated using all data up to 2017.

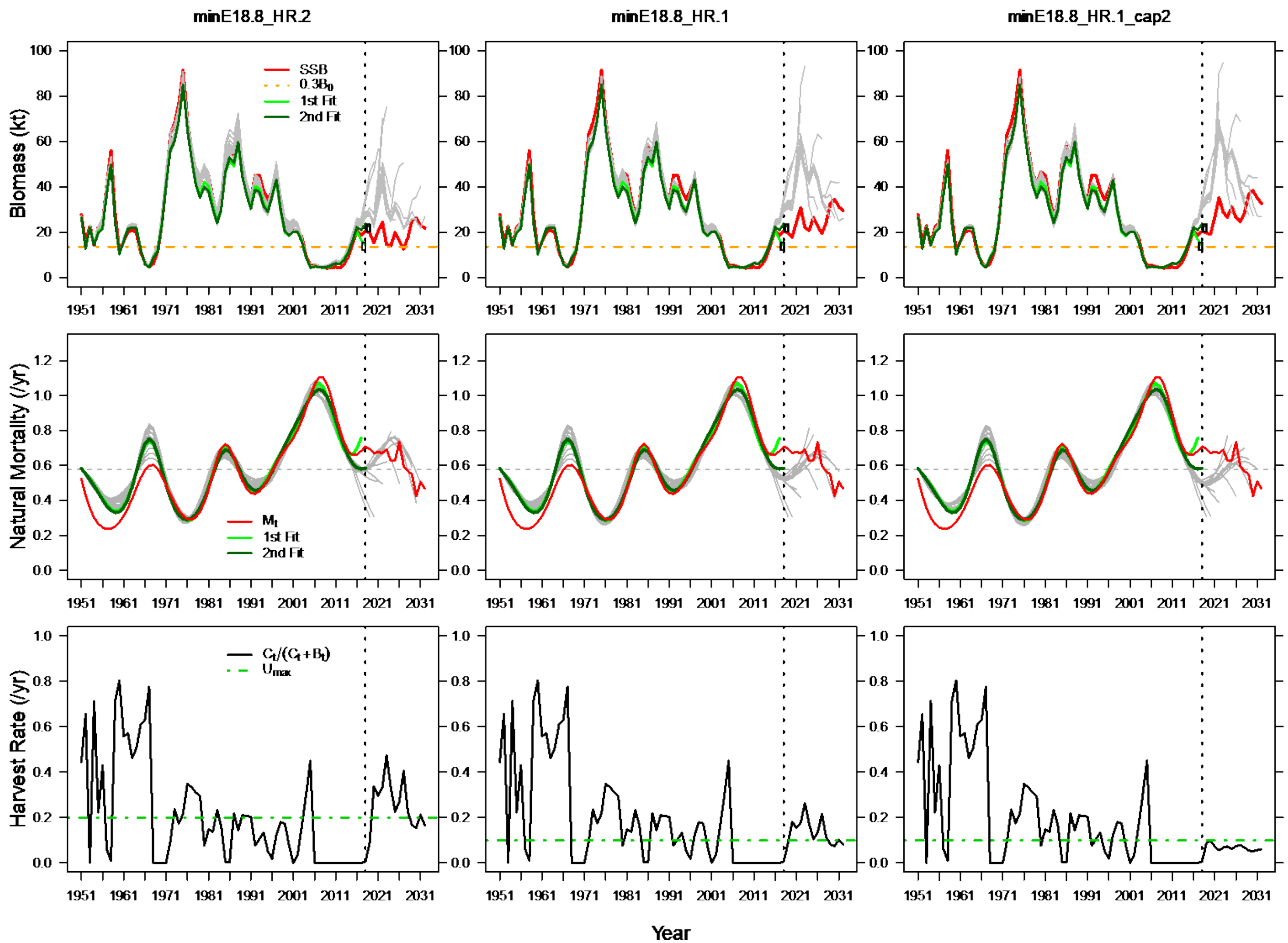

Figure 7. WCVI herring spawning biomass (top row), natural mortality (middle row) and harvest rate (bottom row, catch divided by spawning biomass) for a single WCVI_DDM scenario replicate. Columns show the management procedures minE18.8_HR.2 (left), minE18.8_HR.1 (middle) and minE18.8_HR.1_cap2 (right). In the top two rows, the red line shows the operating model values, while the green and grey lines show assessment model estimates in the projection period. The grey horizontal dashed line in the second row shows the average M value. In the bottom row, only the operating model harvest rate is shown.

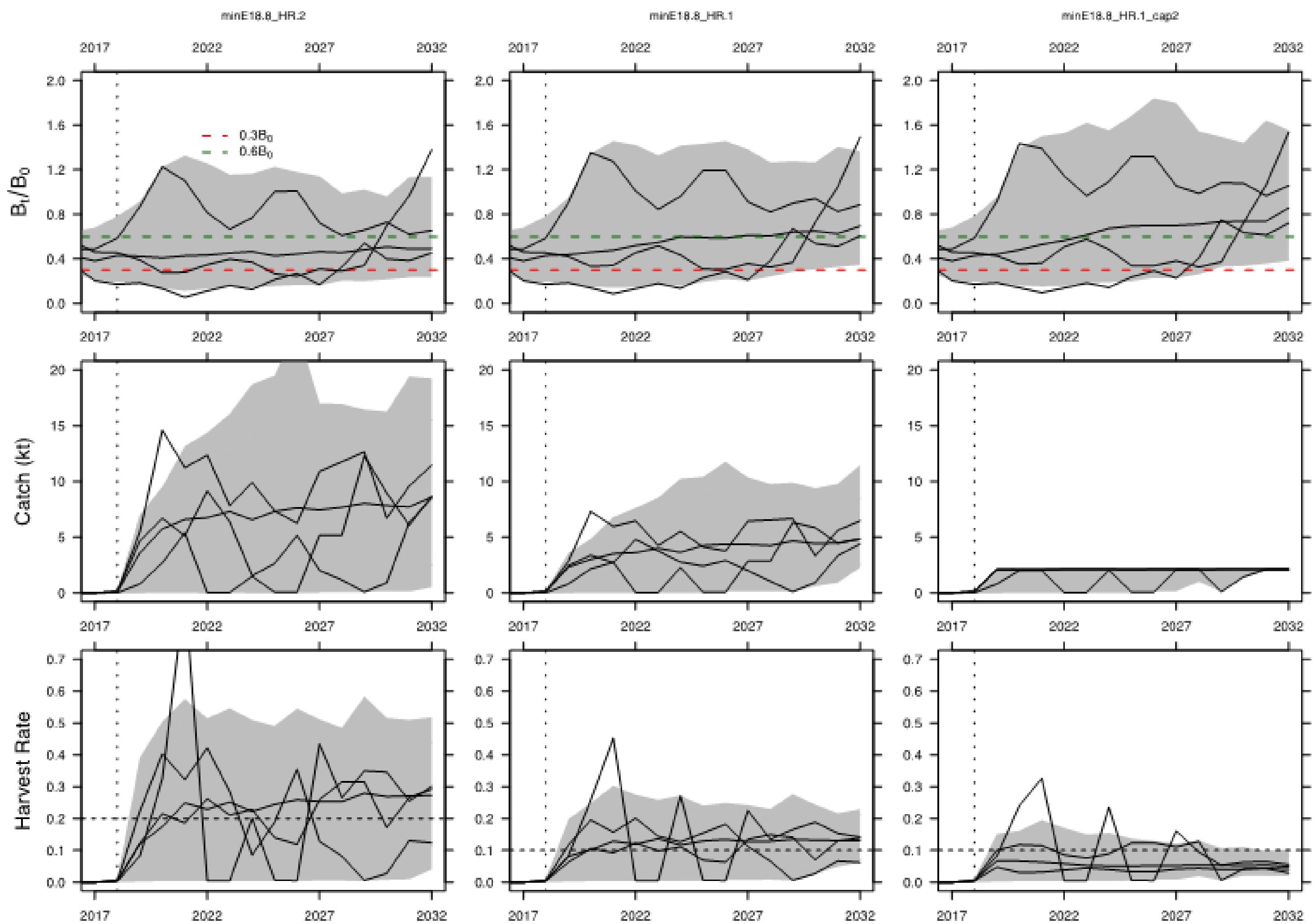

Figure 8. Depletion (top row), catch (middle), and harvest rate (bottom row) simulation envelopes for WCVI herring under the current MP (minE18.8_HR.2), current MP with 10% harvest rate (minE18.8_HR.1), and the current MP with 10% harvest rate and catch cap (minE18.8_HR.1_cap2) under the density dependent natural mortality (DDM) 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 2018 denotes the beginning of the projection period, and the horizontal dashed lines show .3B0 (red) and .6B0 (green).

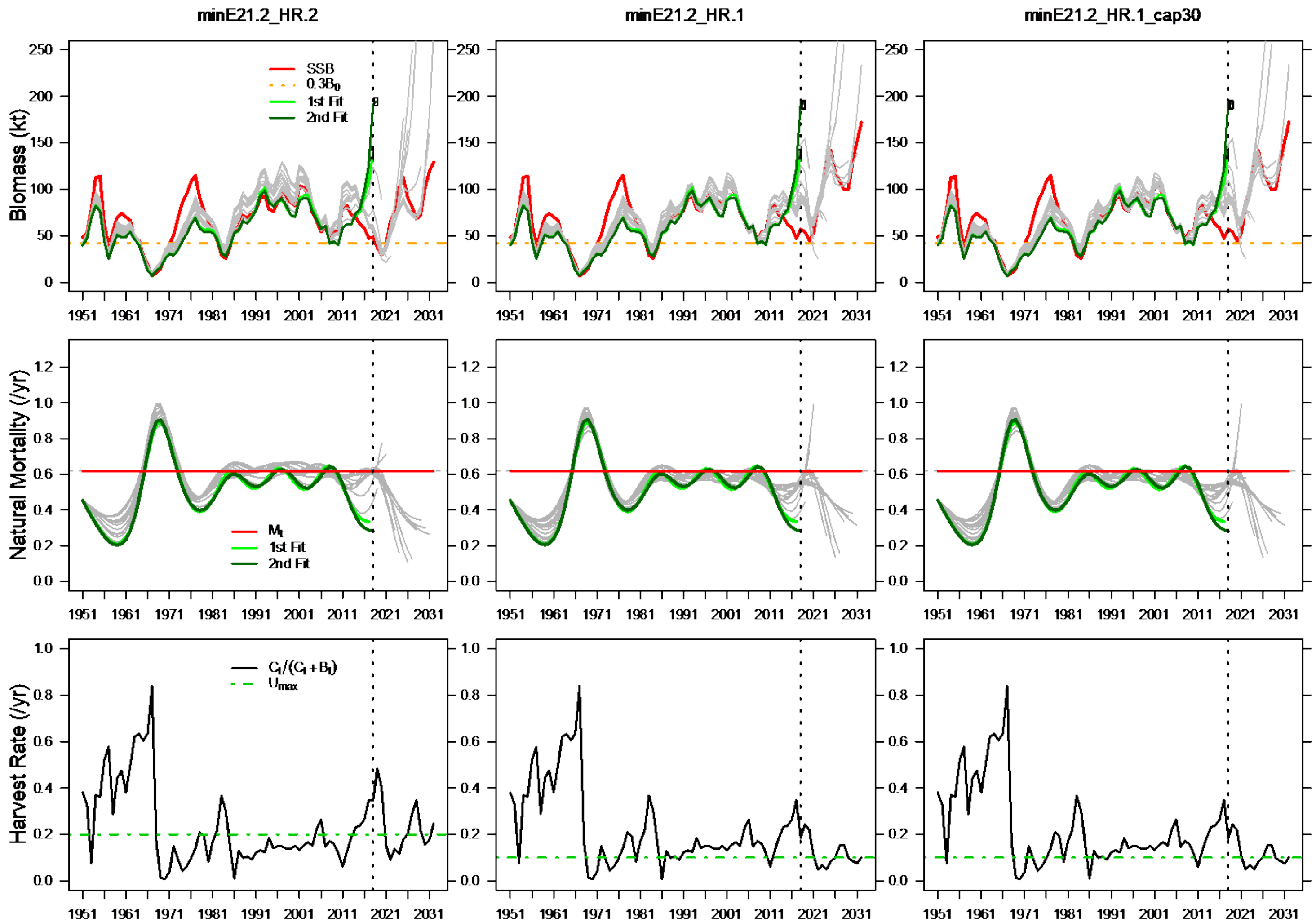

Figure 9. SoG herring spawning biomass (top row), natural mortality (middle row) and harvest rate (bottom row, catch divided by spawning biomass) for a single SOG_conM scenario replicate. Columns show the management procedures minE21.2_HR.2 (left), minE21.2_HR.1 (middle) and minE21.2_HR.1_cap30 (right). In the top two rows, the red line shows the operating model values, while the green and grey lines show assessment model estimates in the projection period. The grey horizontal dashed line in the second row shows the average M value. In the bottom row, only the operating model harvest rate is shown. Harvest rates are bigger than 1.0 preceding the 1966 crash, where the catch contained a lot of immature individuals.

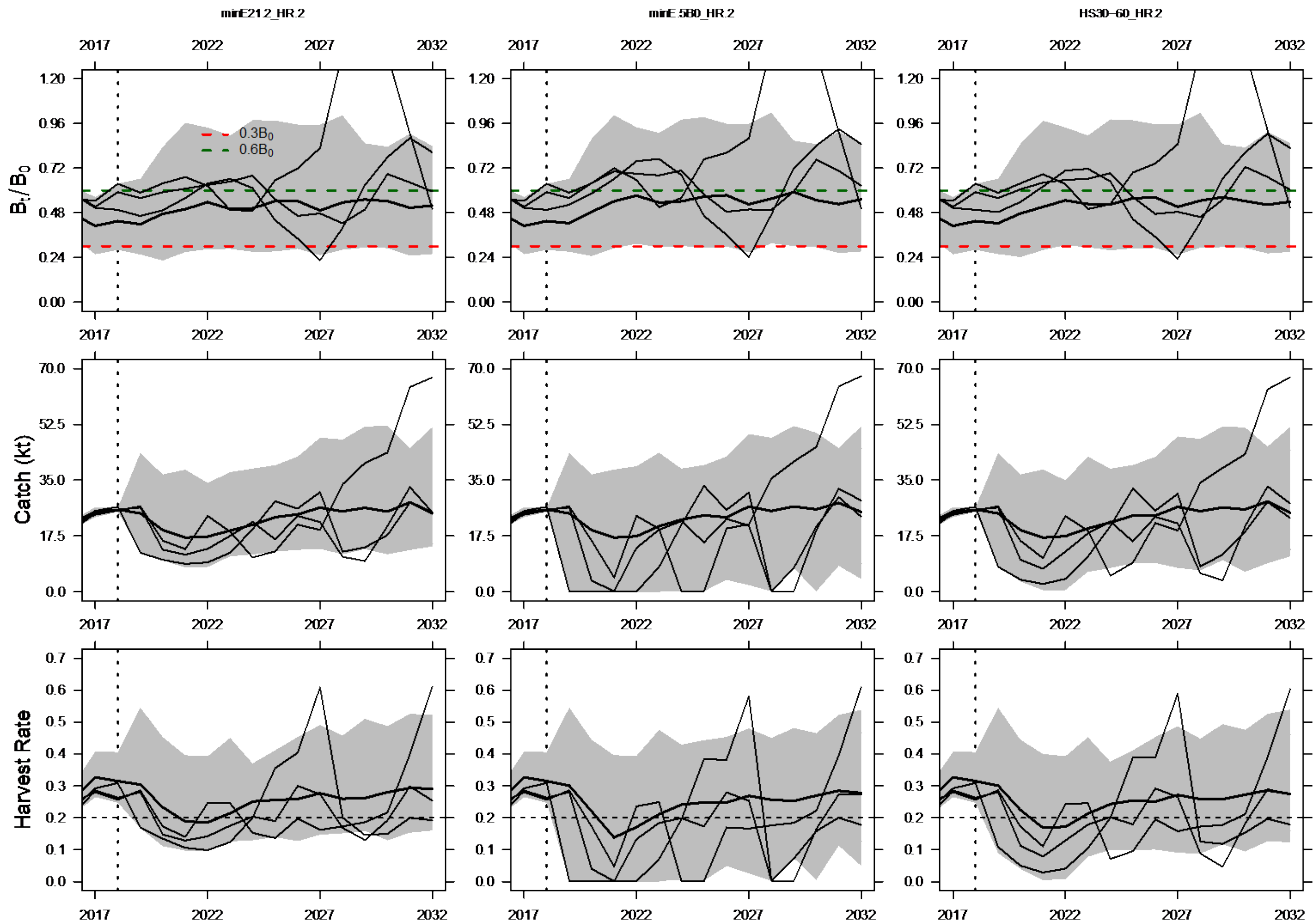

Figure 10. Depletion (top row), catch (middle), and harvest rate (bottom row) simulation envelopes for SOG herring under the current MP (minE21.2_HR.2), a minimum escapement rule with estimated cutoff (minE.5B0_HR.2), and the hockey stick model with a 20% harvest rate (HS30-60_HR.2) under the constant 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 2018 denotes the beginning of the projection period, and the horizontal dashed lines show .3B0 (red) and .6B0 (green).

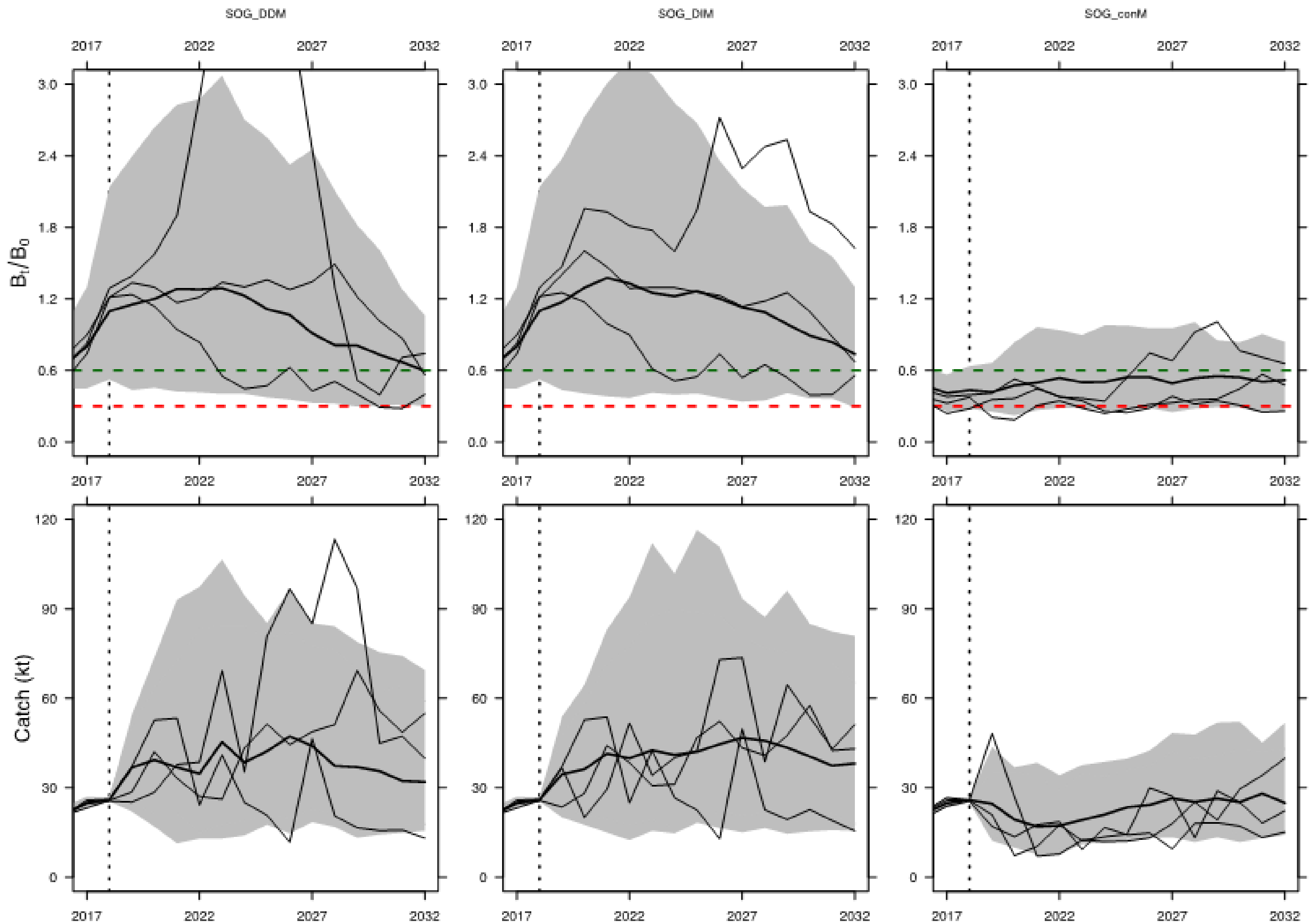

Figure 11. Depletion and catch simulation envelopes for SOG herring under the current MP (minE21.2_HR.2) under the three operating model scenarios over a 3-generation (15 year) projection period. Grey areas show the central 95% of simulated trajectories, the heavy black line shows the median of all 100 replicates, and the thin black lines show randomly chosen trajectories for 3 individual replicates. The vertical dotted line in 2018 denotes the beginning of the projection period, and the horizontal dashed lines show .3B0 (red) and .6B0 (green).

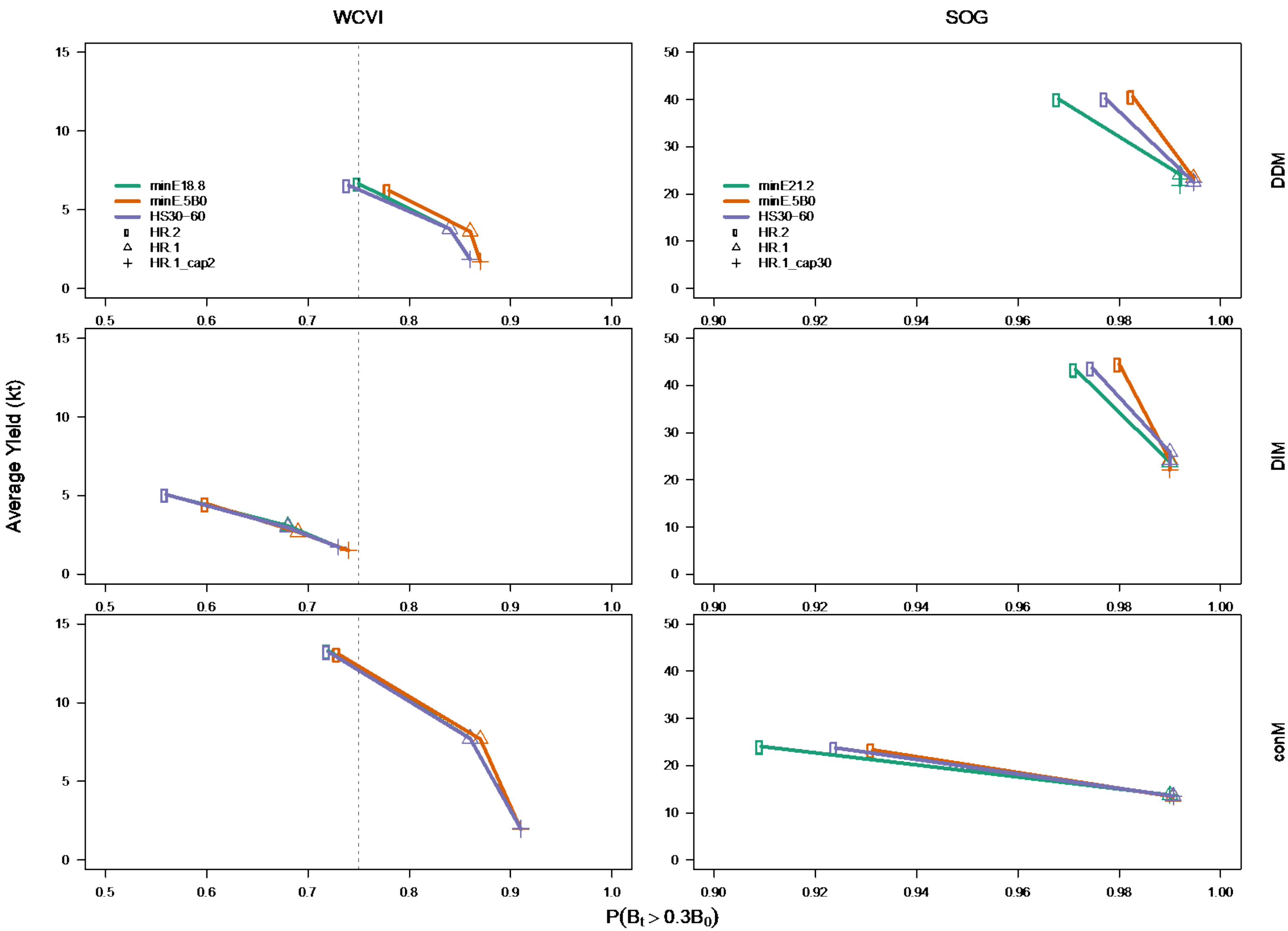

Figure 12. Trade-offs between the probability of exceeding the limit reference point (x-axis) and average yield (y-axis) over the projection period. Columns show WCVI (left) and SOG (right), while rows show the M scenarios (DDM, DIM and conM from the top). Vertical dashed line denotes P = 0.75. Line and point colours indicate the harvest control rule function, while point shapes show the harvest rates and caps. Note the different x- and y-axis scales between WCVI and SOG.

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APPENDIX A. WCVI AND SOG PACIFIC HERRING STOCKS

Pacific Herring (*Clupea pallasii*) is a pelagic species migrating between inshore spawning and offshore feeding areas of the North Pacific Ocean. Herring distribution in the eastern Pacific Ocean ranges from California to the Beaufort Sea. In British Columbia (BC) herring are managed based on five major and two minor stock areas. The five major BC herring stocks are Haida Gwaii, Prince Rupert District, Central Coast, Strait of Georgia (SOG), and West Coast of Vancouver Island (WCVI), while the two minor herring stocks are Area 2W and Area 27 (Figure A.1). These management areas are supported in part by the results of multi-year tagging and genetic studies (Hourston 1982, Beacham et al. 2008, Flostrand et al. 2009).

Although BC herring are assessed and managed as five major and two minor stocks, there remains substantial uncertainty about the spatial structure at both fine and large (coast-wide spatial scales). Hypotheses about herring stock structure include: a metapopulation structure, whereby migratory herring in all major stock areas comprise a single metapopulation, referred to as BC Primary Spawners (Beacham et al. 2008); population contingents, with connectivity among complex herring sub-populations or "stocklets" (as explored in Benson et al. 2015); and spatially discrete, locally adapted populations that exhibit site fidelity and/or natal homing (as described by local First Nations, and evident in genetically distinct stocks in Cherry Point, Portage Inlet, Metlakatla, and Skidegate Inlet, Beacham et al. 2008). As a result, there remains substantial uncertainty about the appropriate scale of management, as well as appropriate conservation and fishery objectives for Pacific Herring. For example, objectives provided by First Nations focus on biomass limits and rebuilding targets at a local spatial scale, while broad conversations about objectives with the commercial fishing industry reflect a coast-wide perspective of the fishery. To provide a common basis for future discussion, this Appendix provides a basic overview of herring stocks in the SOG and WCVI, including stock boundaries, trends and stock status, spawn distribution, fishing areas, and First Nations traditional use.

A.1. WEST COAST VANCOUVER ISLAND

Stock boundaries: The west coast of Vancouver Island (WCVI) assessment region encompasses Statistical Areas 23 to 25 (Figure A.2). The DFO provides annual estimates of spawning biomass and one-year biomass projections for the aggregate WCVI herring stock using a statistical catch age model, described in Cleary et al. (2018). WCVI First Nations identify 9 spatial areas within Stat Areas 23-25 as being biologically significant and important for FSC access (Figure A.2). However the availability of biological data varies considerably among these 9 areas making it difficult to identify and compare data trends, thus we have limited the discussion of spatial data for WCVI to the level of Stat Area.

Stock status: The WCVI stock is characterized by a recent period of prolonged low productivity and low biomass - consistent with biomass levels of serious harm (Kronlund et al. 2018). Beginning in 2015, spawning biomass shows possible signs of an increasing trend (DFO 2018, Cleary et al. 2018). The 2017 stock assessment estimates the median spawning biomass as 17,742 tonnes (90^{th}%ile: 9,719–30,650), with current stock estimated at 37% of the unfished level (DFO 2018; Cleary et al. 2018). Together, WCVI and SOG herring make up the southern BC herring stocks. These stocks share feeding grounds in the summer and fall, that is, following spring spawning, non-juvenile herring from the SOG migrate to the west coast of Vancouver Island, mixing with WCVI herring in offshore feeding areas (Hourston and Haegele 1980). Spawning biomass on the WCVI has been in decline since the late 1980s, with lowest biomasses observed from 2004-2013, whereas during this same time period the proportion of spawning between the southern herring stocks has increased for the SoG over the same three decades (Figure A.3).

Spawn distribution: From the mid-1970s through mid-1990s, herring spawn consistently occurred throughout Stat Areas 23, 24, and 25 (Table A.1). As the spawning biomass declined in the late-1990s, biomass declined and disappeared in Stat Area 24 (Vargas Is). Areas 23 (Barkley) and 25 (Nuuchatlitz) experienced declines throughout the 1990s and 2000s (Figure A.4). In the recent period of prolonged low productivity and low biomass (2005-2014) spawn biomass declined in all areas, with the lowest proportion of spawn occurring in Stat Area 24 (Table A.1). WCVI First Nations have identified a 'reference period' from 1990 to 1999 that indicates a period of time during which Nations experienced successful FSC fisheries. In years since this reference period, spawning biomass has fluctuated around the mean biomass of the reference period in Stat Area 25, and below the mean biomass of the reference period in Stat Areas 23 and 24 (Figure A.5). Note the impacts of changes to survey effort from change in survey methodology are unknown (Figure A.5).

Fishing and fleets: Reliable annual records of commercial herring fisheries for the WCVI begin in 1951, however the DFO reports commercial fisheries back to the 1920s. Modern-day herring seine-roe and gillnet-roe fisheries began in 1972 and were developed to supply Japanese roe markets. In the late 1980s, catches in WCVI were ~40% of the coastwide catch, declining to 10% by 1997, and averaging 10-15% until the last commercial roe fishery in 2005 (Figure A.6).

Fishing areas: Specific areas where commercial roe fisheries have historically occurred are described in the annual Records of Management (B.Spence, pers.comm.[1]).

First Nations traditional use: Herring are a socio-cultural and nutritionally important species for WCVI First Nations. Traditional means of harvesting herring include harvest of herring spawn (adhered to kelp), placement of hemlock or cedar boughs in key spawning areas for spawn-on-boughs, and harvest of whole herring through beach seining, trapping, or jigging. The key concerns expressed by WCVI First Nations have been access to herring in their traditional territories and stock health. The Nuu-chah-nulth Nations have reported the absence of spawning in many of their traditional harvest areas, or, when spawning does occur, suspended boughs yield only 1-3 layers of spawn, which is not sufficient to meet Food, Social, and Ceremonial needs. Following traditional management practices, boughs with only a few layers of spawn are left in the water to allow herring larvae to hatch. In addition to the nutritional value of herring as a food source, the absence of herring spawn impacts the Nations social and cultural connection to the land and sea, and the ability to teach harvesting methods to younger generations and share harvest amongst families and maintain established trade and barter relationships with other Nations.

A.2. STRAIT OF GEORGIA HERRING

Stock boundaries: Stock boundaries for SOG herring include all of Statistical Areas 14 to 19, 28, and 29 (excluding Section 293), Deepwater Bay (Section 132), and Okisollo Channel (Section 135). The DFO provides annual estimates of spawning biomass and one-year biomass projections for the aggregate SOG herring stock using a statistical catch age model, described in Cleary et al. (2018). Following input from SOG First Nations in 2016, we also present herring biomass delineated into 4 Groups: Lazo (Sections 132, 135, and 141), 14&17 (Sections 142, 143, 171, and 172), SDodd (173, 181, 182, 191, 192, and 193), ESOG (151, 152, 161, 162, 163, 164, 165, 280, 291, and 292, Figure A.7). The 4 Groups represent spatial areas important for First Nations Food, Social and Ceremonial (FSC) access, however we do not yet understand whether these groups are of biological relevance. In the SOG, Statistical Areas (Stat Area) are

[1] Brenda Spence, Fisheries and Oceans Canada

primarily considered to be management boundaries and not of biological relevance, thus we do not present spawning biomass for the individual Stat Area.

Stock status: The 2017 stock assessment estimates the median posterior spawning biomass at 114,626 tonnes (90th percentile: 70,478–176,690), with current stock estimated at 81% of the unfished level (DFO 2018; Cleary et al. 2018). Since the 1990, spawning biomass in the SOG represents 53% of the total estimated spawning biomass across the 5 BC stocks (Figure A.3).

Spawn distribution: For the past two decades herring spawning activity (egg deposition) has been largely concentrated from Nanaimo to Comox (Group 14&17). In 2017, 81% of herring spawn deposition occurred in Group 14&17, similar to the recent 10-year average of 83%. The past two decades has seen a northward concentration of herring spawning in the SOG (into 14&17), with virtually an absence of spawn deposition along the eastern Strait of Georgia (ESOG) and below Nanaimo (SDodd; Table A.2 and Figure A.8).

Fishing and fleets: Reliable annual records of commercial herring fisheries in the SOG begin in 1951, however the DFO reports commercial fisheries back to the 1920s. Modern-day herring seine-roe and gillnet-roe fisheries began in 1972 and were developed to supply Japanese roe markets. Since the 1990, 58% of the coastwide herring catch has been fished in the SOG (Figure A.6), reflecting the fact that the SOG spawning biomass represents 53% of the total coastwide spawning biomass (Figure A.3). Beginning in the mid-2000s, the herring industry began exploring new markets for whole herring and as such, in the past 6 years (2011 onwards), approximately 1/3rd of the SOG annual quota has been allocated to the Food and Bait seine fishery, with the other 2/3rd split between the seine-roe and gillnet-roe fleets.

Fishing areas: Specific areas where commercial fisheries are permitted to operate are formally described in the annual IFMP (DFO 2017). Generally, the spatial distribution of the commercial roe herring fisheries in the SOG over the past 20-years is Sections 141-143, 172, 173, occurring late February – early April, and, from 2011 onwards FB fisheries occur in Sections 141-143, 172, 173, and 291, November through February.

First Nations traditional use: Herring are a socio-cultural and nutritionally important species for SOG First Nations. Traditional means of harvesting herring include harvest of herring spawn (adhered to kelp), placement of hemlock or cedar boughs in key spawning areas for spawn-on-boughs, and harvest of whole herring through beach seining, rakes and jigging. The key concerns expressed by SOG First Nations have been access to herring in their traditional territories, stock health, and broader ecosystem impacts of low herring abundance on other species such a lingcod and sea birds. The limited spawn activity and herring abundance in the eastern portion of the SOG and the east side of Vancouver Island (south of Nanaimo) in recent years has impacted successful harvest First Nations in those areas, such as the Hul'qumi'num Nations and Tla'amin Nations. In addition to the loss of the nutritional value of herring and other reliant species as a food source, the absence of herring spawn impacts the Nations' social and cultural connection to the land and sea, and the ability to teach harvesting methods to younger generations and share harvest amongst families.

A.3. TABLES

Table A.1. Proportion of spawn index by Statistical Area for the West Coast of Vancouver Island major stock assessment region.

Year	23	24	25
1951	0.177	0.121	0.702
1952	0.629	0.148	0.223
1953	0.262	0.061	0.676
1954	0.292	0.089	0.619
1955	0.316	0.095	0.589
1956	0.426	0.015	0.559
1957	0.174	0.010	0.816
1958	0.432	0.127	0.442
1959	0.131	0.261	0.608
1960	0.486	0.374	0.140
1961	0.330	0.408	0.262
1962	0.609	0.026	0.365
1963	0.639	0.256	0.105
1964	0.225	0.478	0.297
1965	0.239	0.259	0.503
1966	0.301	0.296	0.403
1967	0.111	0.130	0.759
1968	0.379	0.090	0.531
1969	0.558	0.058	0.384
1970	0.381	0.343	0.276
1971	0.489	0.265	0.246
1972	0.252	0.283	0.465
1973	0.378	0.196	0.426
1974	0.342	0.491	0.167
1975	0.238	0.542	0.220
1976	0.498	0.364	0.139
1977	0.619	0.291	0.091
1978	0.251	0.394	0.355
1979	0.366	0.462	0.173
1980	0.307	0.571	0.122
1981	0.315	0.532	0.153
1982	0.440	0.219	0.341
1983	0.488	0.120	0.391
1984	0.285	0.617	0.098
1985	0.579	0.356	0.065
1986	0.730	0.116	0.154
1987	0.001	0.524	0.476
1988	0.337	0.453	0.210
1989	0.511	0.424	0.066
1990	0.403	0.464	0.134
1991	0.680	0.228	0.092
1992	0.376	0.490	0.134
1993	0.575	0.299	0.126
1994	0.523	0.213	0.264
1995	0.434	0.315	0.251
1996	0.347	0.459	0.194
1997	0.562	0.314	0.124
1998	0.257	0.648	0.095
1999	0.226	0.338	0.436
2000	0.376	0.115	0.509

Year	23	24	25
2001	0.159	0.192	0.649
2002	0.705	0.099	0.195
2003	0.185	0.081	0.735
2004	0.379	0.094	0.527
2005	0.412	0.090	0.499
2006	0.580	0.248	0.172
2007	0.791	0.209	0.000
2008	0.677	0.200	0.122
2009	0.547	0.125	0.328
2010	0.446	0.079	0.475
2011	0.267	0.299	0.434
2012	0.069	0.368	0.563
2013	0.335	0.061	0.604
2014	0.631	0.093	0.276
2015	0.372	0.185	0.442
2016	0.577	0.266	0.157
2017	0.335	0.097	0.568

Table A.2. Proportion of spawn index by Group for the Strait of Georgia major stock assessment region. Legend: '14&17' is Statistical Areas 14 and 17 (excluding Section 173); 'ESoG' is eastern Strait of Georgia; 'Lazo' is above Cape Lazo; and 'SDodd' is South of Dodd Narrows.

Year	14&17	ESoG	Lazo	SDodd
1951	0.879	0.055	0.018	0.048
1952	0.778	0.056	0.028	0.138
1953	0.619	0.046	0.019	0.316
1954	0.505	0.075	0.011	0.409
1955	0.555	0.067	0.119	0.259
1956	0.667	0.070	0.034	0.229
1957	0.812	0.091	0.006	0.091
1958	0.409	0.181	0.035	0.376
1959	0.695	0.054	0.059	0.192
1960	0.489	0.110	0.302	0.099
1961	0.397	0.272	0.188	0.143
1962	0.574	0.303	0.049	0.075
1963	0.438	0.402	0.071	0.090
1964	0.510	0.138	0.271	0.081
1965	0.415	0.243	0.322	0.021
1966	0.063	0.703	0.080	0.154
1967	0.216	0.495	0.158	0.131
1968	0.417	0.362	0.021	0.200
1969	0.145	0.609	0.098	0.147
1970	0.334	0.385	0.129	0.152
1971	0.356	0.253	0.271	0.120
1972	0.387	0.221	0.264	0.128
1973	0.344	0.271	0.090	0.294
1974	0.737	0.043	0.034	0.185
1975	0.675	0.096	0.081	0.148
1976	0.737	0.065	0.069	0.128
1977	0.866	0.031	0.072	0.031
1978	0.895	0.015	0.033	0.058
1979	0.656	0.131	0.060	0.153
1980	0.782	0.033	0.114	0.071
1981	0.792	0.035	0.059	0.114
1982	0.871	0.022	0.077	0.030

Year	14&17	ESoG	Lazo	SDodd
1983	0.640	0.022	0.246	0.093
1984	0.571	0.064	0.003	0.362
1985	0.582	0.119	0.003	0.296
1986	0.853	0.012	0.001	0.135
1987	0.664	0.032	0.097	0.206
1988	0.741	0.039	0.000	0.220
1989	0.934	0.013	0.001	0.052
1990	0.722	0.004	0.065	0.210
1991	0.925	0.000	0.000	0.075
1992	0.882	0.004	0.045	0.069
1993	0.856	0.000	0.012	0.132
1994	0.899	0.000	0.033	0.068
1995	0.943	0.000	0.000	0.057
1996	0.980	0.001	0.002	0.017
1997	0.947	0.001	0.000	0.052
1998	0.972	0.017	0.000	0.011
1999	0.821	0.000	0.120	0.060
2000	0.952	0.009	0.003	0.036
2001	0.721	0.024	0.207	0.047
2002	0.651	0.000	0.309	0.040
2003	0.872	0.011	0.000	0.117
2004	0.915	0.014	0.029	0.042
2005	0.926	0.005	0.006	0.063
2006	0.898	0.000	0.000	0.102
2007	0.967	0.000	0.000	0.033
2008	0.861	0.000	0.011	0.128
2009	0.921	0.000	0.000	0.079
2010	0.886	0.000	0.002	0.112
2011	0.984	0.000	0.000	0.016
2012	0.855	0.009	0.084	0.052
2013	0.928	0.000	0.055	0.016
2014	0.758	0.020	0.212	0.010
2015	0.525	0.014	0.354	0.106
2016	0.902	0.000	0.090	0.009
2017	0.806	0.000	0.194	0.000

A.4. FIGURES

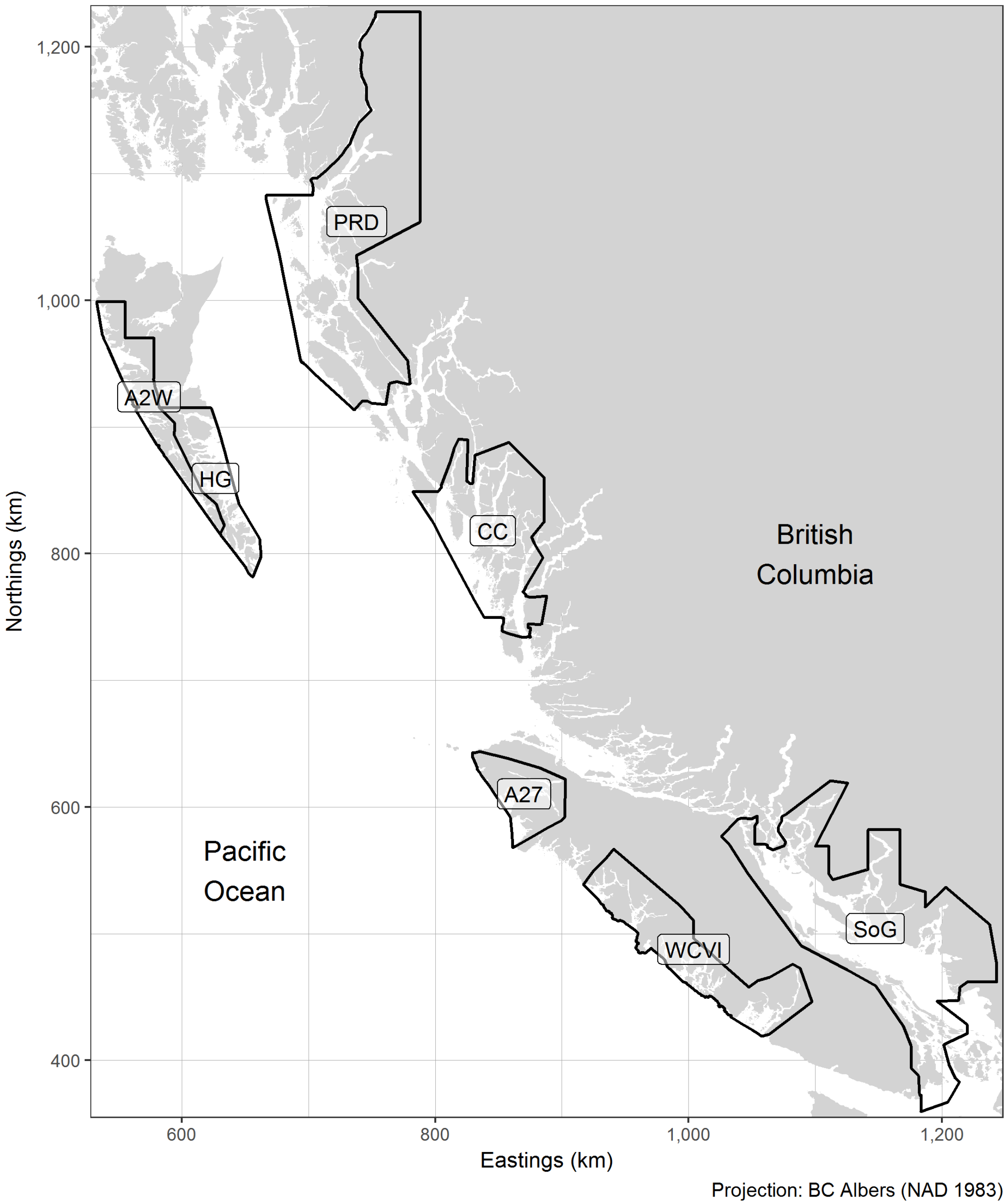

Figure A.1. Boundaries for the Pacific Herring stock assessment regions (SARs) in British Columbia: there are 5 major SARs (HG, PRD, CC, SoG, and WCVI), and 2 minor SARs (A27 and A2W). Units: kilometres (km).

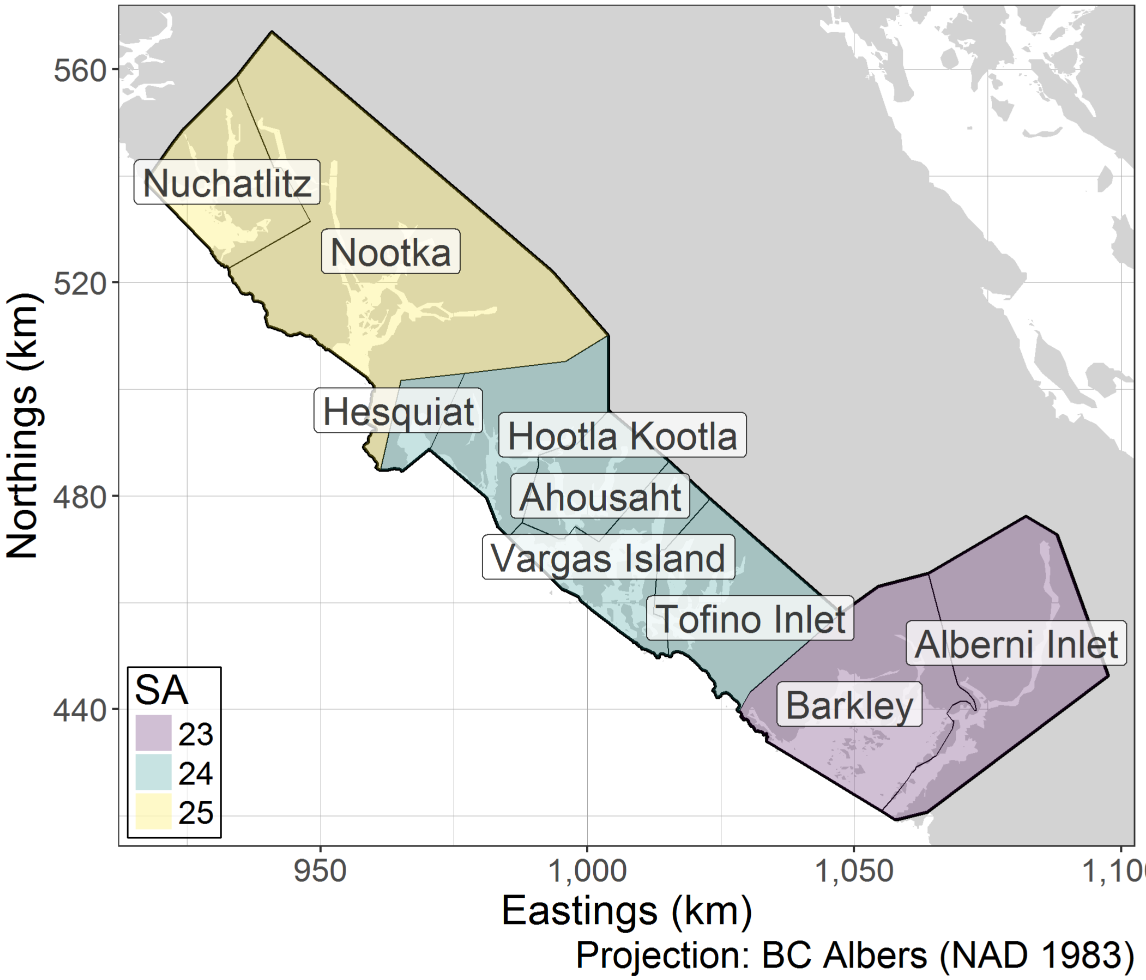

Figure A.2. Boundaries for the West Coast of Vancouver Island major stock assessment region (thick lines), associated Groups (thin lines), and associated Statistical Areas (SA). Units: kilometres (km).

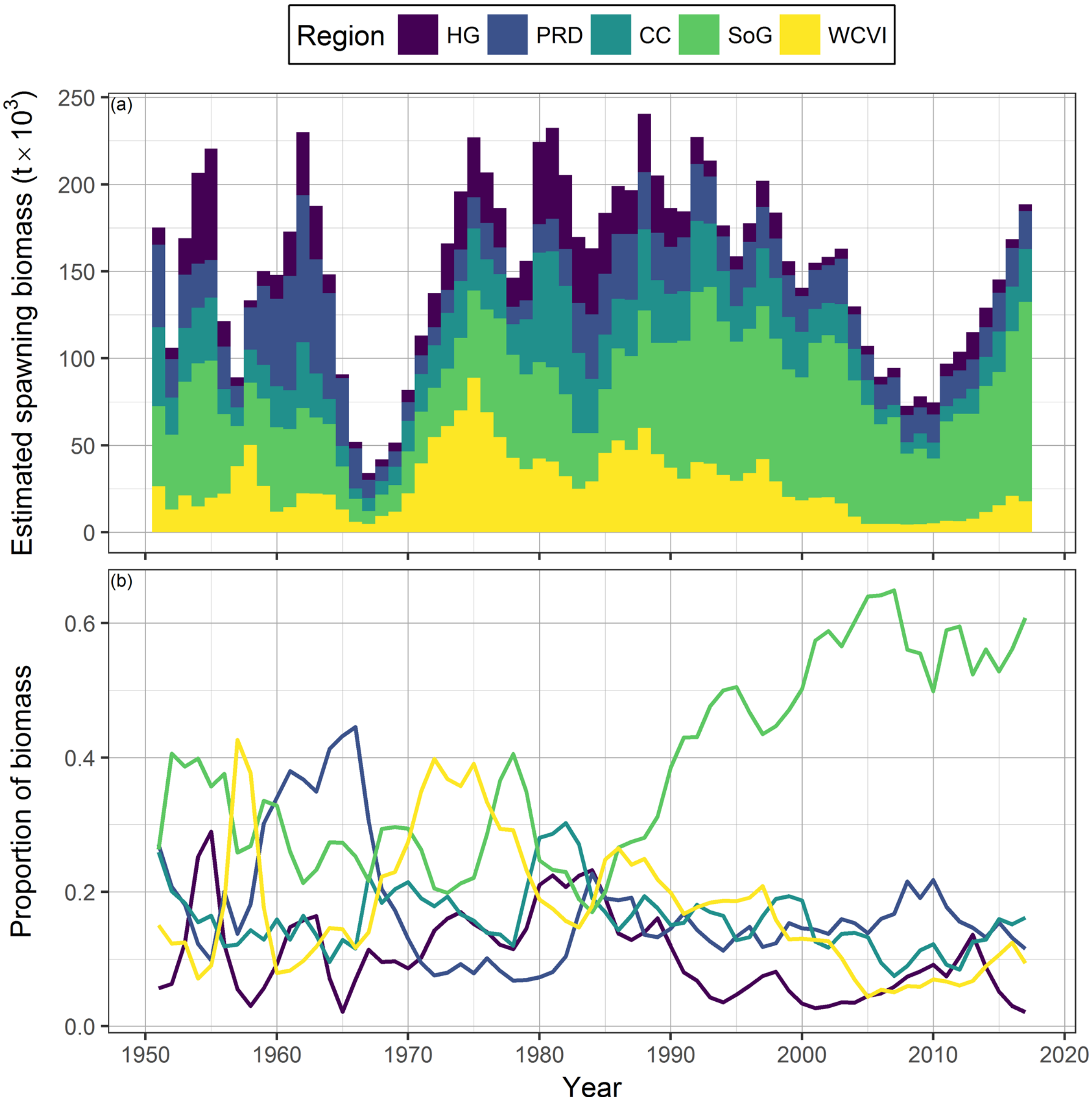

Figure A.3. Coastwide estimated Pacific Herring spawning biomass from 1951 to 2017 in thousands of tonnes (median posterior estimates; t x 10^3; panel a), and proportion of spawning biomass (b) by stock assessment region.

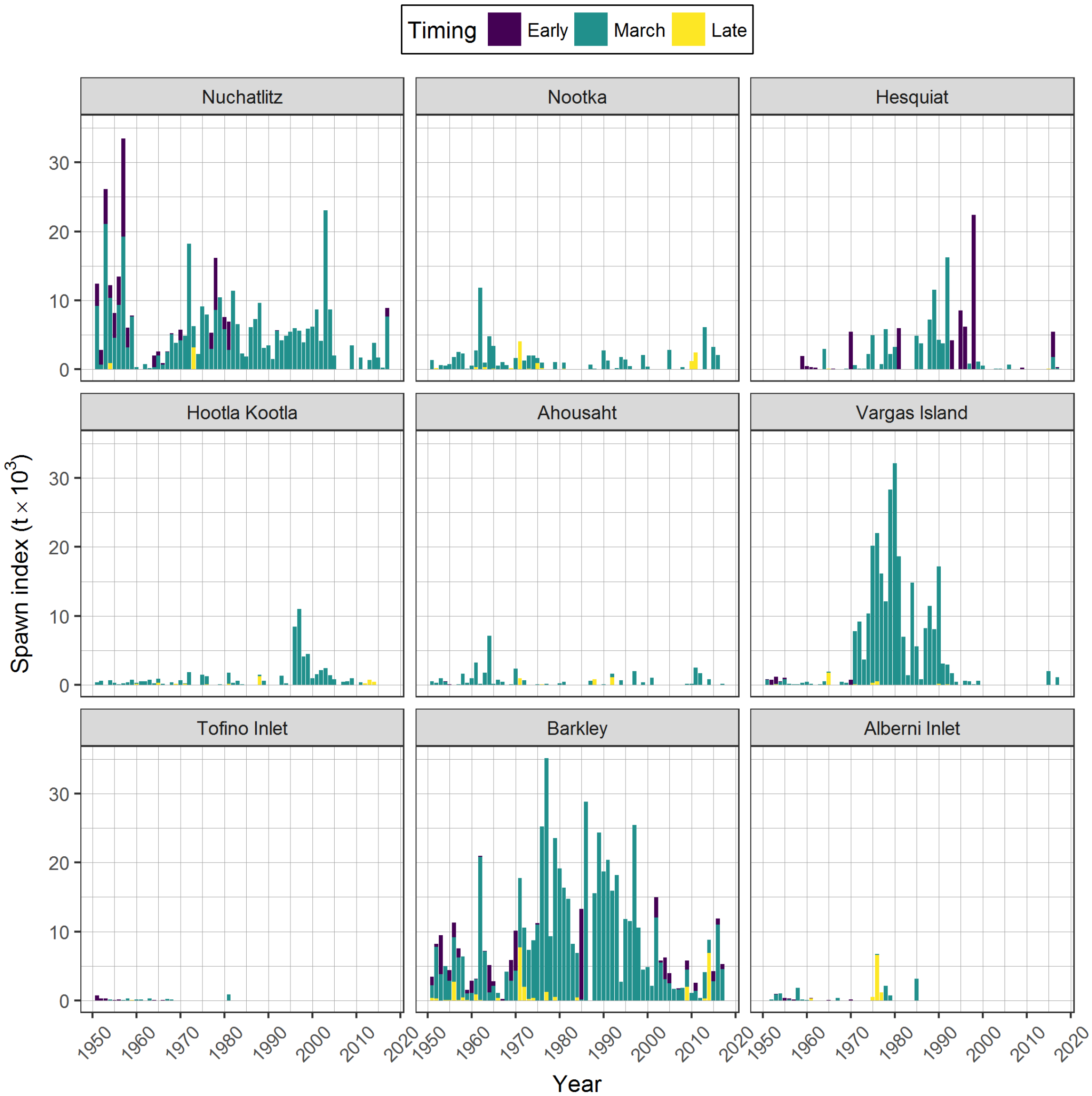

Figure A.4. Spawn index (I_t) for the West Coast of Vancouver Island stock assessment region from 1951 to 2017 in thousands of tonnes (t x 10^3) by Group. Legend: 'Early' indicates spawn that starts before March; 'March' indicates spawn that starts in March; and 'Late' indicates spawn that starts after March.

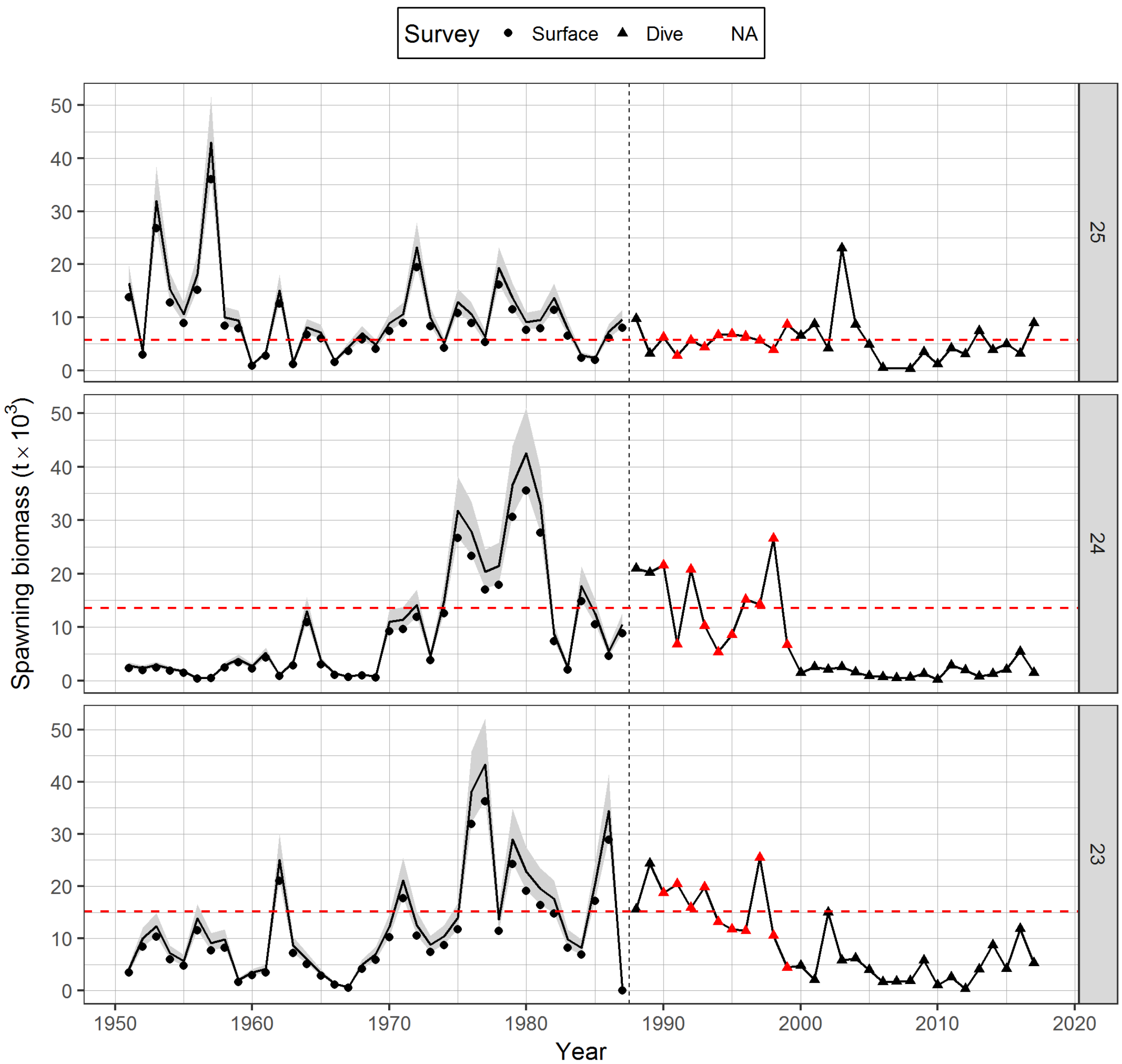

Figure A.5. Spawning biomass (MPD estimates; I_t/q; lines) and spawn index (points) for the West Coast of Vancouver Island major stock assessment region from 1951 to 2017 in thousands of tonnes (t x 10^3) by Statistical Area. The shaded area indicates the 90% confidence interval in spawning biomass (I_t/q), the vertical dashed line indicates the transition from the surface survey period (1951 to 1987) to the dive survey period (1988 to 2017), and the red horizontal dashed line indicates the mean spawning biomass during the reference period (1990 to 1999; red points).

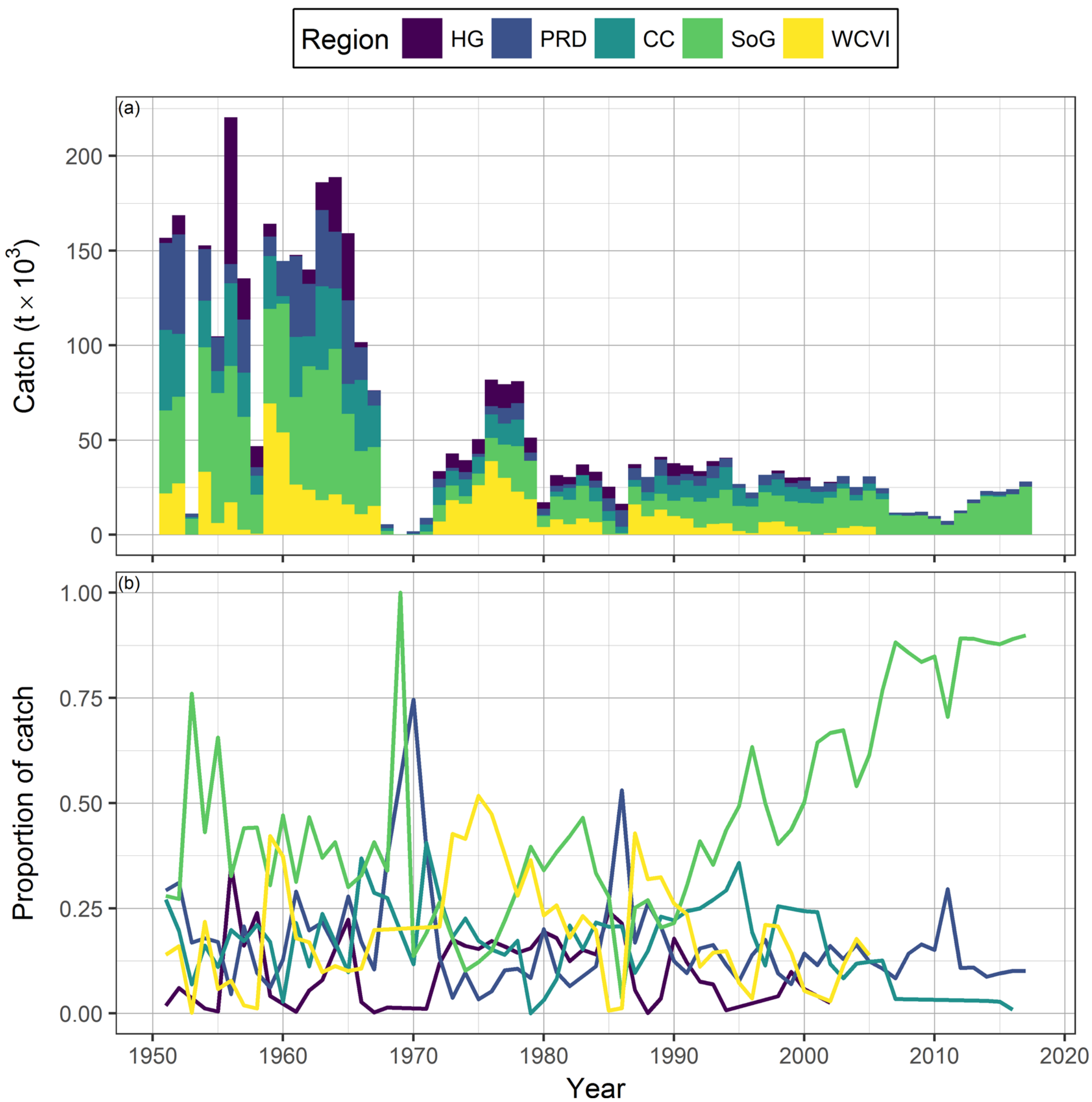

Figure A.6. Coastwide Pacific Herring catch from 1951 to 2017 in thousands of tonnes (t x 10^3; panel a), and proportion of catch (b) by stock assessment region.

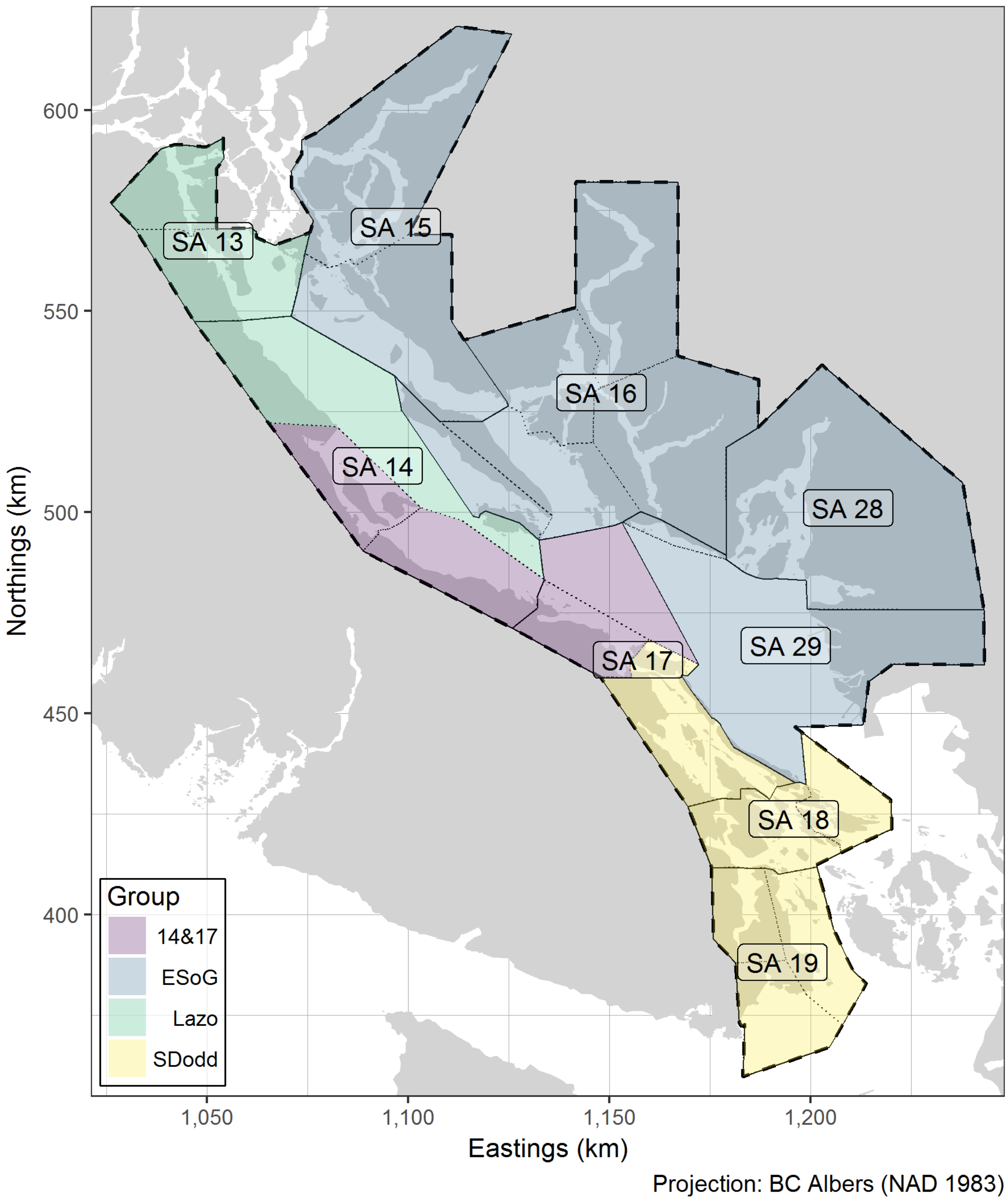

Figure A.7. Boundaries for the Strait of Georgia major stock assessment region (thick dashed lines), associated Statistical Areas (SA; thin solid lines), and associated Sections (thin dotted lines). Units: kilometres (km). Legend: '14&17' is Statistical Areas 14 and 17 (excluding Section 173); 'ESoG' is eastern Strait of Georgia; 'Lazo' is above Cape Lazo; and 'SDodd' is South of Dodd Narrows.

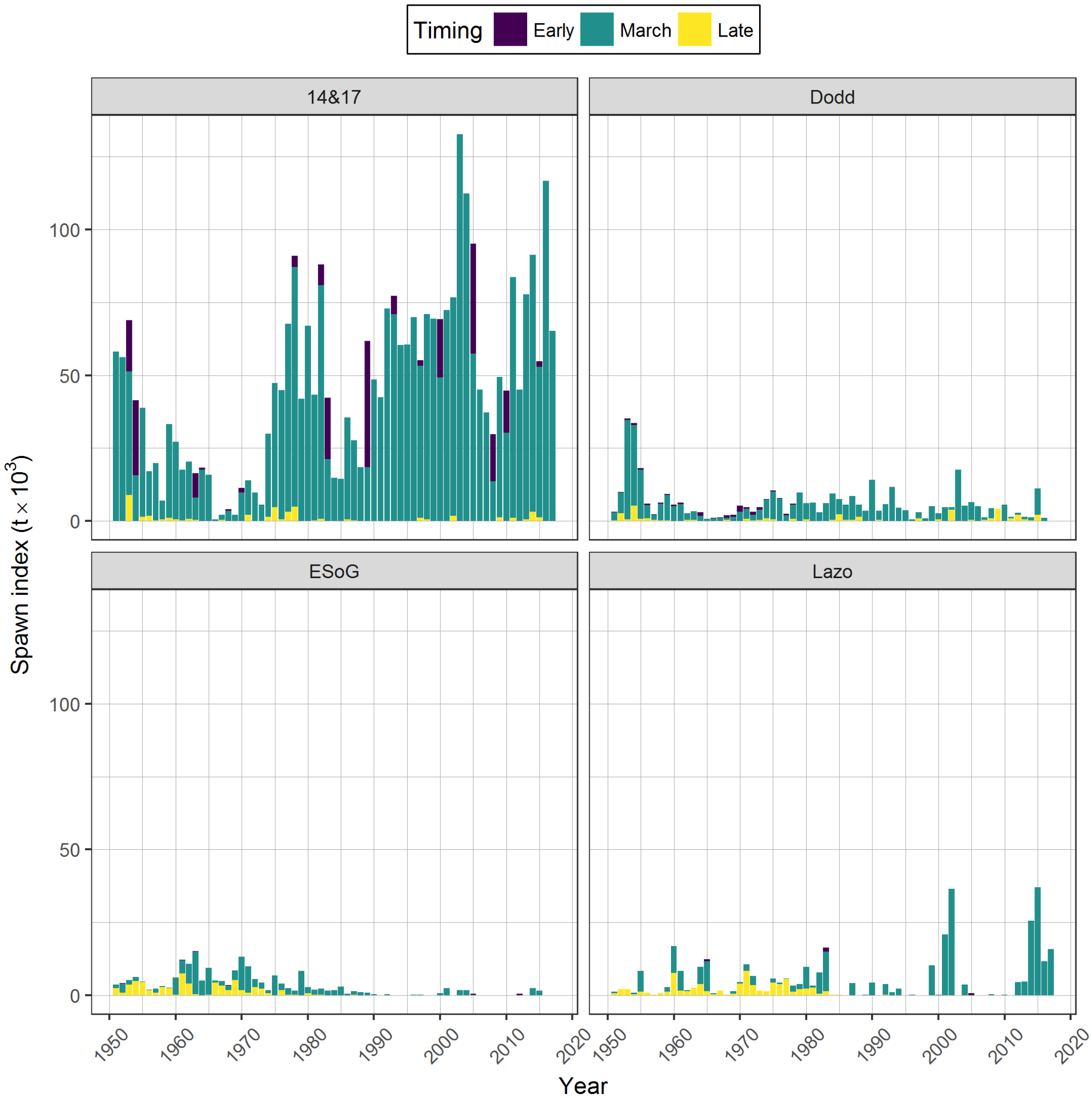

Figure A.8. Spawn index (I_t) for the Strait of Georgia stock assessment region from 1951 to 2017 in thousands of tonnes (t x 10^3) by Group. Legend: 'Early' indicates spawn that starts before March; 'March' indicates spawn that starts in March; 'Late' indicates spawn that starts after March; '14&17' is Statistical Areas 14 and 17 (excluding Section 173); 'ESoG' is eastern Strait of Georgia; 'Lazo' is above Cape Lazo; and 'SDodd' is South of Dodd Narrows.

APPENDIX B. DESCRIPTION OF OBJECTIVE-SETTING PROCESS

B.1. WCVI–CONSULTATIONS AND OBJECTIVES

DFO first met with the Nuu-chah-nulth (NCN) Nations to introduce the management strategy evaluation (MSE) process in the spring of 2015. Discussion of objectives for Pacific Herring occurred again in the summer of 2015, following with the Uu-a-thluk Joint Technical Working Group developed an extensive list of objectives which were then endorsed by the Council of Ha'wiih. The NCN objectives were presented to the DFO in February 2016.

The NCN objectives are organized into four categories: governance, economic, ecological, and socio-cultural. Within each category, measurable or operational objectives are nested within goals, with 1-3 goals per category (Table B.1). Many of the NCN objectives consider smaller, geographic spatial areas than the WCVI aggregate stock. Because the current operating model does not represent finer scale spatial dynamics of herring, implementing NCN objectives within the MSE process was a multistep process. First, DFO and NCN met to discuss and understand the NCN objectives for herring, and second, we worked together to identify ways to operationalize some of the measurable objectives for the first MSE cycle.

For example, though discussions, we understood that Objectives 2.3 and 8.2 (Table B.1) are both measurable objectives cast at the level of Statistical Area. It was agreed that the NCNs target biomass of 15,000 t in each of Stat Area 23, 24, 25, could be expanded to the entire WCVI stock with 45,000 t representing a biomass level reflective of 'healthy' herring stocks. Based on the current stock assessment model (Cleary et al. 2018), 45,000 t also corresponds to ~75% of the unfished spawning biomass. Thus, the objective was recast in terms of the aggregate WCVI stock and the following wording was agreed to:

Maintain spawning stock biomass at biomass target of $0.75B_0$, with 75% probability over a time frame of three generations (15 years).

The target biomass of 45,000 t also corresponds to the average biomass from 1990-1999, a 10-year period which the NCN describe the stocks as healthy and robust and where Nations had access to WCVI herring as FSC in their territories. From this, the following objective was developed:

Maintain spawning stock biomass at or above a target biomass level equivalent to the average biomass from 1990-1999, with 75% probability over two herring generations.

These examples appear in the Introduction as Objectives 3 and 4.

B.2. REFERENCE POINTS

Based on findings of Cox et al. (2019) and Kronlund et al. (2018), we include biological reference points based on unfished equilibrium spawning biomass, B_0 in the objectives. A limit reference point (LRP) of $0.3B_0$ is included in Objective 1, and candidate upper stock reference (USR) points based on B_0 and average spawning biomass are defined for Objectives 2 and 3 (see next section).

B.3. CORE OBJECTIVES PROPOSED BY DFO

In May 2017, the DFO proposed five core measurable objectives, each of which could be investigated for any of the five stocks (at the aggregate spatial scale) as part of the first MSE cycle. These are:

1. Avoid LRP of 0.30 B_0 with 90% probability over a timeframe of two herring generations (i.e.10 years).

2. Maintain spawning stock biomass in the healthy zone, at or above the USR, with 50% probability over a timeframe of two generations.
3. When the spawning stock biomass falls below the upper stock reference (USR) (i.e. within the cautious zone), limit the probability of decline over the subsequent 10 years from very low (5%, when at the LRP) to moderate (50%, when at the USR).
4. Subject to conservation objectives, maintain 15-year average annual variability in catch (AAV) of less than 25%.
5. Subject to conservation objectives, maximize the median average catch over the first 15 projection years.

Based on preliminary simulation results, the proposed objectives have been modified and are listed in the Introduction as Objectives 1, 2, 5, and 6.

In addition, DFO proposed three measurable USR objectives to be considered in the MSE process (Figure B.1):

1. $\overline{SB}$: average median estimated spawning biomass from 1951 to 2017;
2. $\overline{SB}_{\text{prod}}$: average median estimated spawning biomass for the productive period (1988 to 2016 for SoG, and 1988 to 1996 for WCVI); and
3. $0.6SB_0$: where B_0 is the estimated unfished biomass.

B.4. TABLES

Table B.1. Nuu-chah-nulth (NCN) Nations objectives. Objectives are organized into four categories: governance, economic, ecological, and socio-cultural. Each category has one or more goals, and each goal has one or more specific objective, categorized as either measurable or operational.

Categories	Goals	Objectives	Measurable	Operational
Governance	1) Have smaller scale management areas for the WCVI Area. (Geographic scale of management)	1.1) Three independent stock areas by 2018 for the WCVI area 100% of the time. The herring stock areas are based on DFO statistical areas – 23, 24 and 25.	-	x
		1.2) By 2018, Area 26 is managed as an independent minor stock area, 100% of the time.	-	x
		1.3) By 2018, TACs are developed and managed independently in Management Areas 23-25, 100% of the time.	-	x
		1.4) By 2018, in-season assessment information will be used to adjust TACs, fisheries and fishing plans as appropriate 100% of the time.	-	x
	2) Protect Nuu-chah-nulth's rights based (Aboriginal and Treaty rights and priority access) fisheries	2.1) By 2017, no WCVI Food & Bait herring fisheries until Nuu-chah-nulth have been consulted and accommodated each year 100% of the time.	-	x
		2.2) Only rights based herring fisheries in that part of Area 26 referred to as the Maa-nulth Domestic Fishing Area, 100% of the time.	-	x
		2.3) By 2018, regular commercial fisheries can only occur in a management area if the forecast and in-season return is greater than 15,000 tonnes for that management area 90% of the time.	x	x
		2.4) By 2018, no regular commercial herring fisheries except SOK in the Nations preferred rights based herring harvesting areas (as identified by the Nations pre-season) 90% of the time.	-	x
		2.5) By 2018, all regular commercial herring seine fisheries in Management areas 23-25 must start once the roe yield exceeds 10% , 90% of the time.	X	x

Categories	Goals	Objectives	Measurable	Operational
	3) Resources are available for Nuu-chah-nulth to participate significantly in the assessment activities in each Management Area (Participation in management).	3.1) By 2018, herring assessment training is provided to each Nuu-chah-nulth Nation each year, 100% of the time.	-	x
		3.2) By 2018, Nuu-chah-nulth will be contracted to collect herring spawn information and collect biosamples from each management area 100% of the time.	-	x
		3.3) By 2018, qualified Nuu-chah-nulth divers will be given preference for participating in the annual herring spawn dive surveys, 100% of the time.	-	x
Economic	4) Sufficient resources are available for science and management activities (Costs of management and science)	4.1) By 2018, DFO annually budgets sufficient resources to management and science activities for WCVI herring populations 100% of the time.	-	x
		4.2) By 2018, DFO supports and funds alternative methods to collect herring spawn data such as using dedicated small crews in small boats to collect herring biosamples when and where appropriate 100% of the time.	-	x
		4.3) By 2018, when abundance is sufficient to support economic fisheries, a portion of the TAC will be used to offset some of the management and science costs, 100% of the time.	-	x
		4.4) By 2019, an accurate and cost effective method to convert SOK/SOB to whole herring will be developed and used to assess WCVI SOK/SOB fisheries 100% of the time.	-	x
		4.5) WCVI herring populations are rebuilt to healthy and sustainable levels capable of supporting successful SOB and SOK fisheries in most years *added Aug 2017	x	-
Ecological	5) Broad distribution of spawning within Nuu-chah-nulth territories (Distribution of spawn)	5.1) Herring spawn covering at least 70% of pre-1960's spawn coverage areas as per DFO herring spawn area data, by 2025 at least 75% of the time.	x	-
	6) Rebuild stock structure and distribution of spawn in the WCVI herring populations (Stock structure).	6.1) By 2020 begin herring transplants in areas 23-26 annually, for a minimum of 20 years.	-	X
		6.2) By 2018, spawning at new or sites that have not been used for 3 years or more, are not to be	-	X

Categories	Goals	Objectives	Measurable	Operational
		exploited by non- rights based fisheries, until spawning occurs in the new areas 3 out 4 years, 100% of time.		
		6.3) By 2018, 10% of the habitat in the historic spawning areas will be assessed annually, 95% of the time.	-	x
		6.4) By 2019, 50% of the assessed habitat in the historic spawning areas willed be modified to support spawning herring or receive transplants 95% of the time.	-	x
		6.5) By 2025, 50% of the transplants and habitat modifications will be assessed for success or failure annually a 100% of the time for 10 years.	-	x
	7) Assess and manage the impact of marine mammal predation on herring spawn and whole herring in the WCVI area (Stock productivity).	7.1) By 2018, predation on herring and herring spawn by marine mammals must be assessed in each management area (23, 24, 25 and 26) and factored in to each area's assessment and forecast 100% of the time.	-	x
		7.2) By 2020 a marine mammal predator management plan for Areas 23-26 to protect spawning herring and herring spawn will be developed and used to manage spawning herring, 100% of the time.	-	x
		7.3) By 2020, predation by marine mammals on spawning herring in Areas 23-26 will be reduced by 50%, 75% of the time.	-	x
Socio-cultural	8) Enough herring to achieve an average of 12 layers of eggs in a spawn (Local access and Food and traditional use).	8.1) By 2017, the cut-off for each of the management areas 23-25 is 15,000 tonnes, 100% of the time.	x	-
		8.2) Minimum of 15,000 tonnes of herring per management area (23-25) by 2025 75% of the time	x	-

B.5. FIGURES

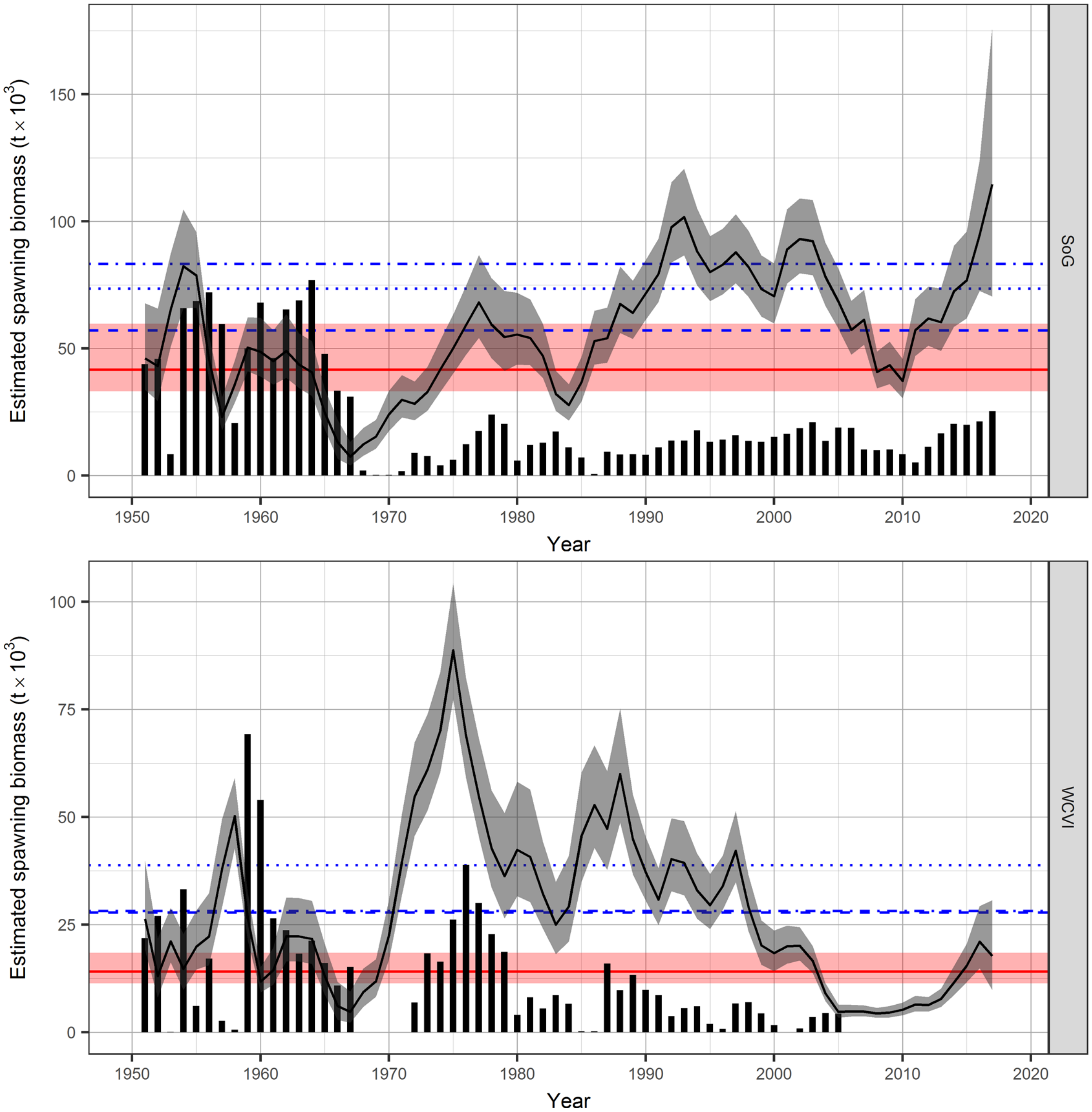

Figure B.1. Estimated spawning biomass (SB_t) for each year t in thousands of metric tonnes (t x 10^3) by region. Line and shaded area indicate median and 90% credible interval, respectively. Time series of vertical lines indicates commercial catch, excluding spawn on kelp (SOK). Red lines indicate medians and red shading indicates 90% credible interval for the limit reference point (LRP), $0.3B_0$, where B_0 is the estimated unfished biomass. Blue lines indicate proposed upper stock references (USR): dashed lines are average median estimated spawning biomass from 1951 to 2017; dotted lines are average median estimated spawning biomass for the productive period (1988 to 2016 for SoG, and 1988 to 1996 for WCVI); and dot-dash lines are $0.6B_0$ (median values).

APPENDIX C. SUPPLEMENTARY MATERIAL

C.1. WCVI SLOW-UP MANAGEMENT PROCEDURE EVALUATION

C.1.1. Description

We tested an alternative, more precautionary MP for the WCVI stock. This "slow-up" rule only simulates a commercial fishery when the assessment model's estimated spawning biomass is above the harvest control rule's lower control point for the last *k* years including the 1 year ahead forecast. This is referred to as the slow-up window. For example, if we used the minE18.8 harvest control rule and *k = 3*, the rule would only allow fishing in 2020 if Bt > 18.8 for all of 2018, 2019, and the projection in 2020. If the slow-up biomass condition is satisfied, then the harvest control rule would be applied as usual to the biomass forecast for 2020.

There are a couple of benefits to this rule over trend based precautionary harvest rule. First, this rule doesn't require the choice of a trend threshold, only the choice of a time-window to consider. Second, it benefits from the correction of large assessment errors in later years; when a positively biased forecast error is revised down within k years, the fishery will be closed if the revised biomass is beneath the lower control point.

We added a slow-up rule to the best performing MP for WCVI, which was the capped 10% harvest rate with minimum escapement and a relative cutoff (minE.5B0_HR.1_cap2). This MP passed the limit reference point criterion on the depensatory M (depM) and constant M (conM) scenarios but failed by 1 percentage point in the density independent M (depM) scenario, keeping biomass above 0.3B0 74% of the time. We tested slow-up MPs with slow-up window lengths ranging from k = 2 to k = 5. Note that the base MP without the slow-up rule corresponds to k = 1.

C.1.2. Results and discussion

As expected, we found the slow-up MP improves the base MP conservation performance under all scenarios. Over the range of slow-up window lengths we tested, the conservation performance increases by one percentage point over the base MP (Table C.1). There is a trade-off between conservation performance and fishing opportunities, with the probability of closures increasing with the size of the window for windows of at least 2 years.

Benefits of the slow-up rule have a diminishing return for this MP. For the constant M scenario, there is no improvement in the limit reference point performance after the addition of one year to the stock status window (k=2). In contrast, no improvement in the LRP performance accrues until k=5 for the depensatory M scenario. The DIM scenario has a large dip in conservation performance when k=2, and then adds another percentage point at k=5 to reach 72%, which is still worse than the same MP without a slow-up condition (Table 7, WCVI_DDM).

The sub-linear growth in LRP performance as the size of the slow-up window increases may be because there is a small gap between the conservation performance without a slow-up rule and the absence of fishing. Indeed, under the depensatory M scenario, the 5 year slow-up window has the same conservation performance as the NoFish scenario (compare Table C.1 with Table 7). For the density independent M and constant M scenario, there are 4 percentage points and 3 percentage points, respectively, between the minE.5B0_HR.1_cap2 MP and the conservation performance in the absence of fishing. Therefore, the NoFish conservation performance will act as an asymptotic limit, and as the slow-up window increases conservation performance will take smaller steps towards the limit.

Despite a more strict condition on opening the fishery, in some cases the slow-up MP reduce the number of closures by protecting the spawning stock from recruitment overfishing caused by assessment errors. As expected, the slow-up rule tends to produce a higher proportion of years with TACs below 650t, which we used as a minimum viable commercial TAC, and that proportion increases from 2 years to 5 years above the lower control point. The general increase in closures is caused by positively biased assessment errors being revised down during the slow-up window, leading to a "bang-bang" style fishery in some replicates (Figure C.1); however, the change in probability of closure depends on the scenario. In the depensatory M scenario, the probability of closure decreases when increasing to a slow-up window of 2 years, and the probability of closure is still lower than the base MP for a slow-up window of 3 years.

*Table C.1. Management procedure performance for the West Coast of Vancouver Island stock. Performance criteria are calculated over 3 generations (15 years) from the start of the projection period for all objectives except Biomass Objective 4, which is calculated over 2 generations (10 years). Management procedures are ordered within each scenario by performance achieving the Conservation Objective (Obj1), and then ranked in order of Objectives 2-6, where ranking is for the sole purpose of readability of the performance tables and is not meant to impose priorities between Objectives 2-6. The base management procedure without a slow-up rule is shown labeled with a * for comparison, and is not ordered with the slow-up rules.*

			Biomass Objectives				Yield Objectives			Alternative USR Candidates	
			Obj 1 (LRP)	Obj 2	Obj 3	Obj 4	Obj 5 (Catch Variability)	Obj 6 (Average Yield)	Prob. closures	Historical Average Biomass	Average Productive Biomass
		Criterion	> 75%	>50%	>75%	>75%	< 25%	max	min	>50%	>50%
Scenario	**MP**	**Label**	**P(Bt > .3B0)**	**P(Bt > .6B0)**	**P(Bt > .75B0)**	**P(Bt > B90s)**	**medAAV**	**medAveCatch**	**P(Ct < 650t)**	**P(Bt > Bave)**	**P(Bt > Bave-prod)**
WCVI_DDM	4	minE.5B0_HR.1_cap2_slowUp5	88%	56%	40%	38%	8.98	1.58	32%	56%	34%
WCVI_DDM	2	minE.5B0_HR.1_cap2_slowUp3	87%	55%	39%	37%	8.52	1.84	23%	55%	34%
WCVI_DDM	1	minE.5B0_HR.1_cap2_slowUp2	87%	55%	39%	37%	8.78	1.84	21%	55%	34%
WCVI_DDM	3	minE.5B0_HR.1_cap2_slowUp4	87%	55%	39%	38%	8.9	1.72	26%	55%	34%
WCVI_DDM	*	minE.5B0_HR.1_cap2	87%	55%	39%	38%	16.49	1.72	25%	55%	34%
WCVI_DIM	4	minE.5B0_HR.1_cap2_slowUp5	75%	35%	23%	29%	24.27	1.45	42%	36%	20%
WCVI_DIM	2	minE.5B0_HR.1_cap2_slowUp3	74%	35%	23%	28%	21.78	1.66	33%	34%	20%
WCVI_DIM	3	minE.5B0_HR.1_cap2_slowUp4	74%	35%	23%	28%	22.1	1.57	37%	35%	20%
WCVI_DIM	1	minE.5B0_HR.1_cap2_slowUp2	74%	34%	23%	28%	21.21	1.67	31%	34%	20%
WCVI_DIM	*	minE.5B0_HR.1_cap2	74%	35%	23%	28%	29.43	1.52	34%	35%	20%

		Criterion	Biomass Objectives Obj 1 (LRP) > 75%	 Obj 2 >50%	 Obj 3 >75%	 Obj 4 >75%	Yield Objectives Obj 5 (Catch Variability) < 25%	 Obj 6 (Average Yield) max	 Prob. closures min	Alternative USR Candidates Historical Average Biomass >50%	 Average Productive Biomass >50%
Scenario	**MP**	**Label**	**P(Bt > .3B0)**	**P(Bt > .6B0)**	**P(Bt > .75B0)**	**P(Bt > B90s)**	**medAAV**	**medAveCatch**	**P(Ct < 650t)**	**P(Bt > Bave)**	**P(Bt > Bave-prod)**
WCVI_conM	4	minE.5B0_HR.1_cap2_slowUp5	92%	54%	37%	89%	7.63	1.85	16%	71%	68%
WCVI_conM	1	minE.5B0_HR.1_cap2_slowUp2	92%	53%	36%	88%	7.12	1.98	9%	70%	68%
WCVI_conM	2	minE.5B0_HR.1_cap2_slowUp3	92%	53%	36%	88%	7.12	1.98	9%	70%	68%
WCVI_conM	3	minE.5B0_HR.1_cap2_slowUp4	92%	53%	36%	88%	7.17	1.96	10%	70%	68%
WCVI_conM	*	minE.5B0_HR.1_cap2	91%	53%	36%	88%	7.12	1.98	8%	70%	68%

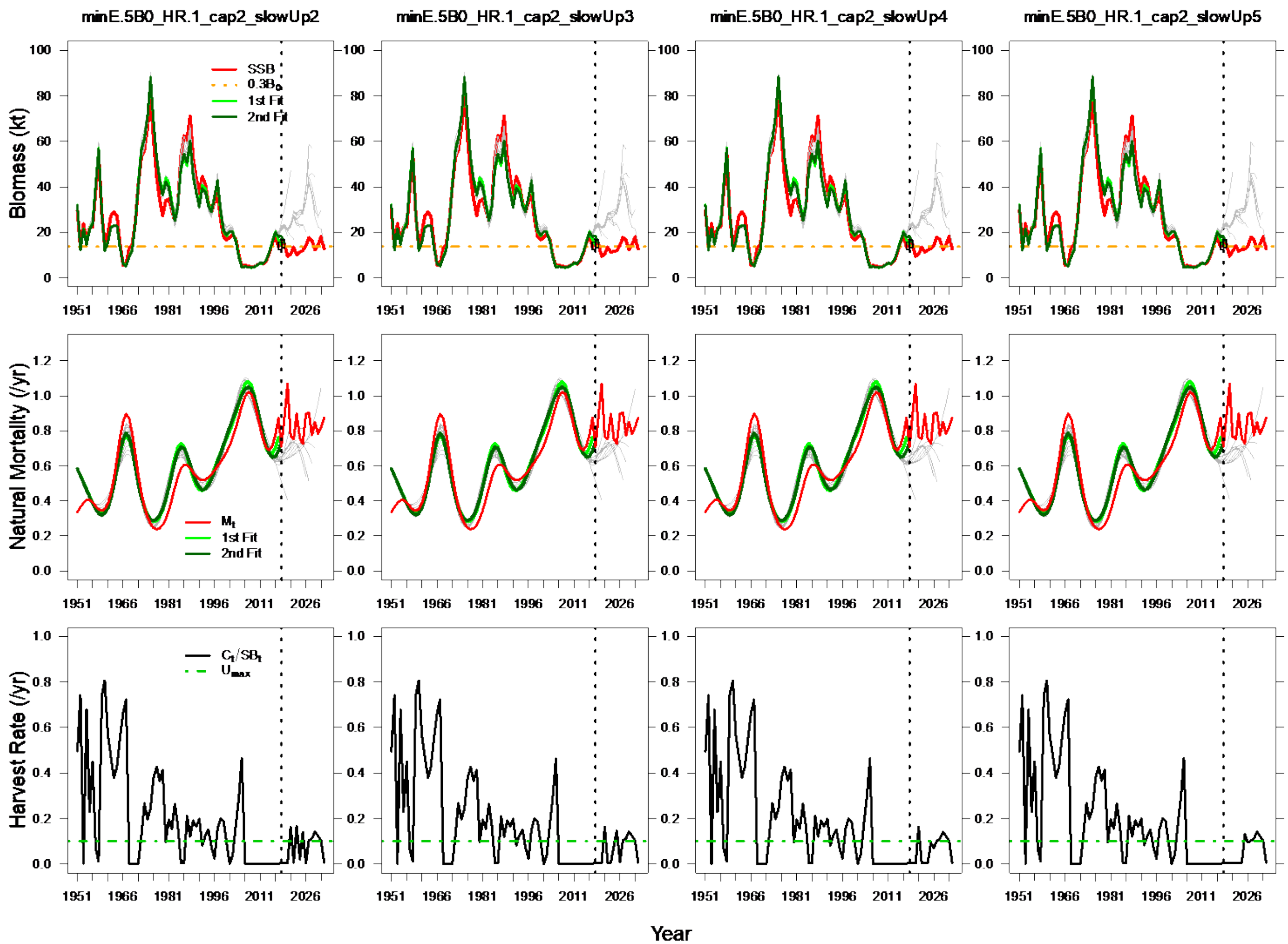

Figure C.1. WCVI herring spawning biomass (top row), natural mortality (middle row) and harvest rate (bottom row, catch divided by spawning biomass) for a single WCVI_DIM scenario replicate. Columns show the management procedures minE.5B0_HR.1_cap2_slowUpk for k=2 (left column), k = 3 (second column), k = 4 (third column), and k=5 (right hand column). In the top two rows, the red line shows the operating model values, while the green and grey lines show assessment model estimates in the projection period.

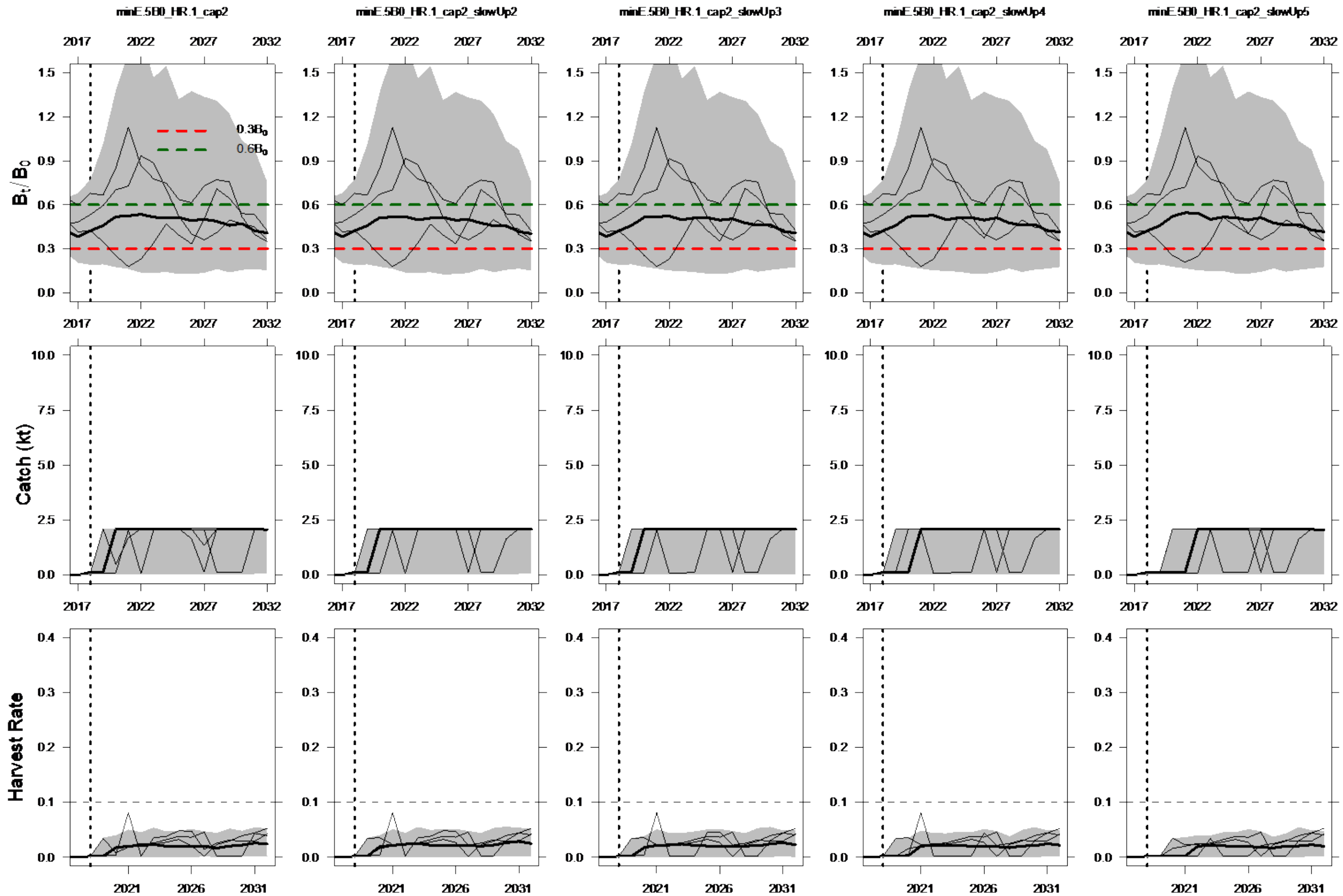

Figure C.2. Depletion (top row), catch (middle), and harvest rate (bottom row) simulation envelopes for WCVI herring under the best performing MP (minE.5B0_HR.1_cap2), and the slow-up versions of the same MP (minE.5B0_HR.1_cap2_slowUpk, k = 2, ..., 5), under the density independent natural mortality (DIM) 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 2018 denotes the beginning of the projection period, and the horizontal dashed lines show .3B0 (red) and .6B0 (green).