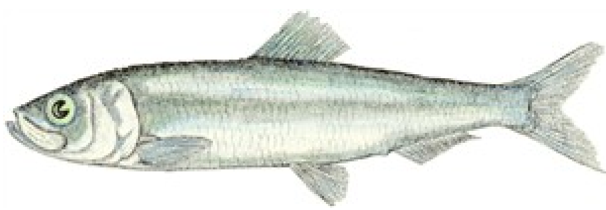
Fisheries and Oceans Canada / Pêches et Océans Canada
Ecosystems and Oceans Science / Sciences des écosystèmes et des océans

Pacific Region
Canadian Science Advisory Secretariat
Science Advisory Report 2019/001

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



Pacific Herring (Clupea pallasii). Image credit: [Fisheries and Oceans Canada](#).

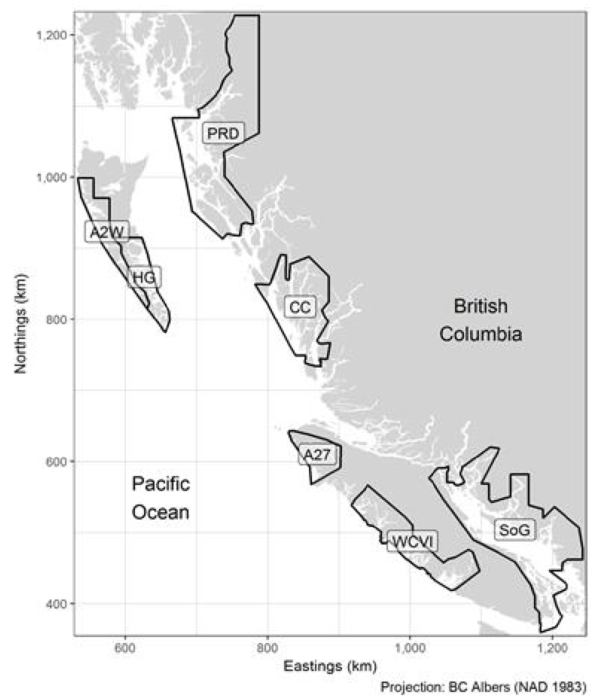


Figure 1. Boundaries for the Pacific Herring stock assessment regions (SARs) in B.C., Canada. The major SARs are Haida Gwaii (HG), Prince Rupert District (PRD), Central Coast (CC), Strait of Georgia (SOG), and West Coast of Vancouver Island (WCVI). The minor SARs are Area 27 (A27) and Area 2 West (A2W). Units: kilometres (km).

Context:

Fisheries and Oceans Canada (DFO) has committed to renewing the current management framework to address a range of challenges facing Pacific Herring stocks and fisheries in British Columbia. Renewal of the management framework includes conducting a Management Strategy Evaluation (MSE) process to evaluate the performance of candidate management procedures against a range of hypotheses about uncertain stock and fishery dynamics. The purpose of the evaluation is to identify management procedures that provide acceptable outcomes related to conservation and fishery management objectives. Selection of a preferred management procedure for each DFO fisheries *management area is an iterative process conducted with the participation of First Nations, the fishing industry, government and non-government organizations.*

This Science Advisory Report is from the July 25-26, 2018 regional peer review on Evaluation of Management Procedures for Pacific Herring (Clupea pallasii) in the Strait of Georgia and the West Coast of Vancouver Island Management Areas of British Columbia. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

SUMMARY

- Pacific Herring (*Clupea pallasii*) in British Columbia (BC) are managed based on five major stock management areas. This peer review focused on simulation testing of management procedures for two management areas, West Coast of Vancouver Island (WCVI) and Strait of Georgia (SOG) in a process known as Management Strategy Evaluation (MSE).
- Between 2015 and 2018, as part of the MSE process, 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.
- One conservation objective, three biomass objectives, and two yield objectives were developed through consultation between fishery managers, scientists, First Nations and industry stakeholders.
- Biological limit reference points for herring reflect low productivity and low biomass states associated with evidence of serious harm (Kronlund et al. 2018). The Conservation Objective defines a minimum spawning biomass (the LRP) that must be avoided with high probability for consistency with the DFO Decision-making framework (DFO 2009). Subsequent biomass and yield objectives may be ranked in priority but a ranking was not proposed here.
- Three operating models were developed to represent alternative hypotheses describing stock-specific rates of natural mortality (*M*) over time. The first model (constant-*M*) includes the assumption that natural mortality is constant over the historical and the projection time frame. The other two time-variant models (density-independent-*M*, depensatory-*M*) include the assumption that natural mortality rates vary over time, while differing in the mechanisms assumed to be driving future natural mortality rates.
- Pacific Herring dynamics for stocks in the WCVI and SOG management areas were simulated using single-sex, age-structured operating models (DFO 2015).
- Ten candidate management procedures (MP) were evaluated for both SOG and WCVI. The performance of each management procedure is ranked against the conservation objective.
- Stock status relative to biological reference points was not included in this MSE but will be provided as part of upcoming work on the status of Pacific Herring in 2018 and 2019 forecast.
- For Pacific Herring, key uncertainties include: historical and future trends in natural mortality, steepness of the stock-recruitment (SR) relationship and SR functional form, potential changes in survey coverage and sampling, an unknown relationship between herring biomass and spawn survey index (estimated by the parameter *q*), and uncertainty in spatial population dynamics.

- The three operating model scenarios presented in the working paper only differed structurally in assumptions about natural mortality, and use operating models based on an assumption that there is a direct linear relationship between the spawn survey index and spawning biomass, i.e., q=1 (Assessment Model 2, DFO 2016). This assumption (q=1) reflects the parameterization of the stock assessment model implemented by Fisheries Management for quota decisions since 2015.
- The working paper demonstrated that the Pacific Herring operating model (DFO 2015) is suitable for simulating realistic data derived from alternative hypotheses about stock and fishery dynamics for WCVI and SOG stocks.
- The sensitivity of WCVI results to future trends in natural mortality suggests additional MP modifications may be required such as criteria that the spawning stock is increasing above the cut-off prior to resuming harvest, i.e., a slow-up MP.
- For Pacific Herring, MPs that implement reductions in harvest rates and application of catch caps can reduce the risk of overharvesting. This finding is applicable to all BC Pacific Herring stocks. However, differences in future trends in abundance presented for WCVI and SOG show the importance of undertaking stock-specific selection of objectives and evaluation of MPs via simulation. Future MSE cycles are likely to result in area-specific MP design. This contrasts with the historical practice of applying the same MP design to all areas.

BACKGROUND

Pacific Herring (*Clupea pallasii*) in British Columbia (BC) are managed based on five major stock management areas: Haida Gwaii, Prince Rupert District, Central Coast, Strait of Georgia, and West Coast of Vancouver Island, and two minor stock management areas. A full CSAS review of the stock assessment model occurred in October 2017 (DFO 2018). This peer review focused on simulation testing of management procedures for West Coast of Vancouver Island (WCVI) and Strait of Georgia (SOG). These two management areas were chosen for evaluation because they exhibit contrasting stock and fishery histories, and a set of biomass and yield objectives have been identified in part through workshops with WCVI First Nations and industry participants. Experience with this Management Strategy Evaluation (MSE) process will be applied to simulation testing of management procedures for the remaining Pacific Herring stocks in a subsequent MSE cycle.

Like most fisheries around the world, managers of BC's herring 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 three decades, herring scientists and managers have 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 (HCR) to compute a catch limit for the next fishing year. 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 cut-off 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 globally, three out of five 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).

A fishery management system can be made more precautionary against poor performance despite informational uncertainties by following structured scientific principles. The main idea is to recognize the key uncertainties and then develop alternative hypotheses for experimental testing rather than in trying to find the single best explanation for past system behaviour. Alternative scientific hypotheses can be used as experimental conditions under which the expected performance of candidate management actions, or "procedures", can be evaluated. The evaluation process involves simulating the application of each candidate management procedure (MP) under each hypothesis. The MPs that perform poorly against pre-specified stock and fishery objectives are eliminated from further consideration. This process of elimination is a practical means of finding MPs that could potentially work in reality, where trade-offs are sought. Any procedure that fails to meet objectives acceptably in simulation testing is likely to fail in the real world, since the real world is more complex and uncertain than most models.

The working paper used closed-loop simulations to evaluate performance of alternative MPs given uncertainties about past and future herring stock dynamics. This work represents the first cycle of MSE under the DFO commitment to a multi-year renewal of the management framework (Pacific Herring Renewal).

ANALYSIS

Management Objectives

Between 2015 and 2018, 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. The first objective relates to stock conservation by avoiding a threshold to possible serious harm (Kronlund *et al.* 2018); this objective must be met for any MP to merit further consideration (i.e., an imperative conservation objective). The subsequent biomass and yield objectives are each subordinate to the conservation objective, Objective 1. The potential ranking of Objectives 2-6 is not identified here as they may involve trade-offs of management outcomes, e.g., the relative priority of average catch (Objective 6) and stability of catches (Objective 5).

Conservation Objective

1. Avoid the Limit Reference Point (LRP) of $0.3B_0$ with high probability over three herring generations, where "high probability" is defined as 75-95% (DFO 2009).

Biomass Objectives

2. Maintain spawning stock biomass at or above the Upper Stock Reference (USR) with at least 50% probability over three herring generations. Four candidate USRs include:
   a. $0.4B_0$, 40% of unfished equilibrium spawning biomass,
   b. $0.6B_0$, 60% of unfished equilibrium spawning biomass,
   c. B_{ave}, historical average biomass, and
   d. $B_{ave\text{-}prod}$, average biomass during a productive period (1988 to 2016 for SOG, and 1988 to 1996 for WCVI).
3. Maintain spawning stock biomass at or above a target biomass level of $0.75B_0$ (75% of unfished equilibrium spawning biomass) with at least 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 at least 75% probability over two herring generations (WCVI only).

   Yield Objectives

5. Maintain average annual variability in catch of less than 25% over three herring generations.
6. Maximize the mean average catch over three herring generations.

Operating Models

Three operating model (OM) scenarios were developed to represent alternative hypotheses for how stock-specific rates of natural mortality (*M*) change over time. The constant-*M* (conM) hypothesis applies the assumption that natural mortality is constant over the historical 1951-2017 period and in the projection period. Two alternative hypotheses allow natural mortality to vary over the same historical period. These time-varying-*M* operating models are distinguished based on assumptions about future patterns in natural mortality. In particular, the assumptions are (i) future natural mortality rates will fluctuate randomly around the recent 10-year average (DIM, density-independent-*M*) or (ii) that pulse natural mortality events will occur at random, but more frequently, when spawning biomass is below 0.3 of the unfished level (depM, depensatory-*M*).

Fitting each of the models corresponding to each hypothesis to the same set of historical data creates two hypotheses about historical patterns of population dynamics and fishing mortality (Figure 2), as well as two different interpretations of current stock status and productivity. The operating model hypotheses are treated as equally plausible for the purposes of simulating the behaviour of candidate management procedures. There is no attempt to determine which is the most likely based on statistical fit criteria.

Pacific Herring dynamics for stocks in the WCVI and SOG management areas were simulated using single-sex, age-structured operating models. The model structure included three commercial fleets (seine-roe, gillnet-roe and seine-food and bait), an allocation for Food, Social and Ceremonial fisheries, and two survey time periods. Growth was represented using observed weight at age for the historical reconstruction period. These changes were made to represent the key assumptions in the current herring assessment model, and to allow simulation of fleet-specific catches and age-composition data in the projection period. The operating models simulated the historical period from 1951-2017 and a projection period from 2018-2032 which corresponds to three Pacific Herring generations.

Data and parameters for both time-varying-*M* and constant-*M* operating models were obtained from stock assessment data and parameter posterior distributions for the WCVI and SOG stocks. Historical and future trends in natural mortality are presented in Figure 3.

Management Procedures

Management procedures control the type, frequency and precision of the simulated data. A statistical catch-at-age assessment model was used in the simulated management procedures. Nine alternative feedback harvest control rules differed by the choice of target harvest rate, operational control points where harvest rate is altered, and application of absolute catch caps. Management procedure MP1 (Table 1) is intended to mimic historical practice for the SOG and WCVI management areas. Harvest control rule diagrams showing the functional relationship between harvest rate and stock status for each management procedure are presented in

Figure 4. Results of simulations show the effects of changes in the form of the harvest control rule component of each MP.

Management Procedure Evaluation

WCVI

Management procedure performance is more sensitive to operating model assumptions for WCVI compared to SOG because of differences in the estimates of stock productivity and natural mortality dynamics. For instance, in the absence of fishing, the Conservation Objective (Objective 1) is met in 88%, 78%, and 94% of simulation trials for depM, DIM, and conM scenarios, respectively (Table 2). However, under the DIM scenario, where future natural mortality is assumed to remain near the recent 10-year average, no MPs met the Conservation Objective (Objective 1) with at least a 75% probability.

Under the depM and conM scenarios, most MPs met the Conservation Objective (Objective 1), while fewer met Biomass Objectives 2-4. When comparing MP performance between Objective 2 and Objective 3, the latter specifies both a higher biomass threshold (i.e., $0.75B_0$) and a higher probability threshold (i.e., at least 75%), which means that any MP failing to meet Objective 2 will automatically fail to meet Objective 3.

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 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 depM and conM scenarios, where the USR in Objective 2 is defined as $0.4B_0$, $0.6B_0$, or the average biomass from a historical productive period ($B_{\text{ave-prod}}$).

For yield objectives, only MPs with 10% maximum harvest rates and catch caps were able to maintain catch variability near or below 25% because lower effective harvest rates maintain higher average biomass and because the catch cap reduces the maximum catch to 2,000 t, further mitigating assessment and implementation uncertainty that could lead to over-harvest at low abundance. The trade-off is in substantially lower average yields that were 50-60% of yields obtained for non-capped and/or 20% maximum harvest rate MPs. The 50% B_0 form of HCR, both with and without a catch cap (i.e., MP5, MP6), resulted in the most frequent fishery closures (25-37% for depM and DIM).

The pattern of MP performance against alternative USRs within Objective 2 was qualitatively similar across scenarios to those described above. However, with both time-varying-*M* scenarios, no procedure, including no fishing, maintained spawning biomass above the USR derived from a historical productive period.

SOG

Patterns of MP performance for SOG herring were similar to those observed for WCVI. In particular, the 10% maximum harvest rate MPs maintained the highest biomass levels; the catch cap of 30,000 t had little overall impact. All MPs achieve the Conservation Objective (Objective 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 with USR=$0.6B_0$ (Table 3).

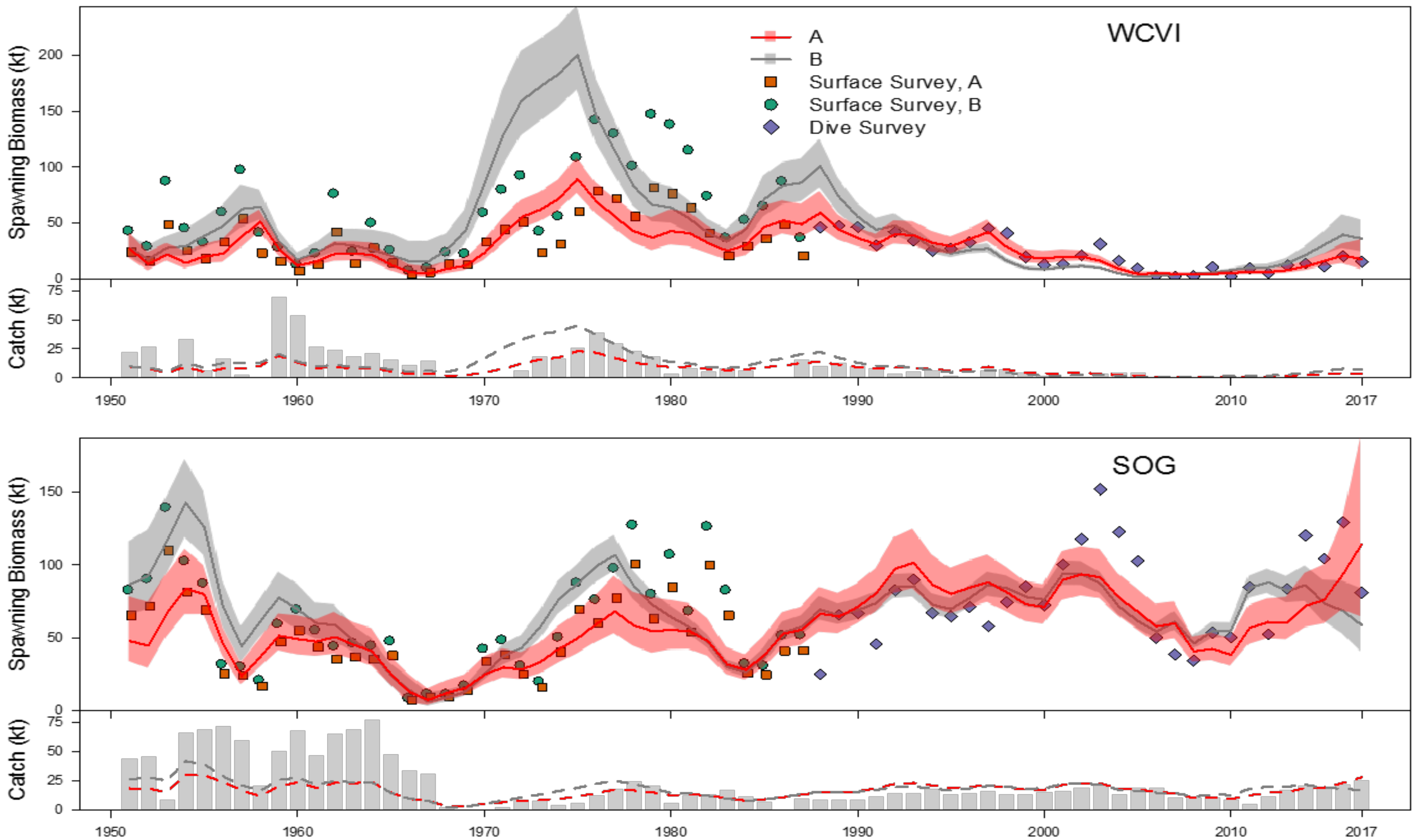


Figure 2. Assessment model estimates of spawning biomass under time-varying-M (A) and constant-M (B) assumptions for WCVI herring (top) and SOG herring (bottom) since 1951. Shaded regions show the central 95% of the posterior biomass distributions, and the solid lines show the median. Points in the spawning biomass plots show the spawn-index observations from the surface survey scaled by the time-varying-M estimate of catchability (squares), the surface survey indices scaled by the constant-M estimate of catchability (circles), and the dive survey indices (diamonds, not impacted by M scenario). 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).

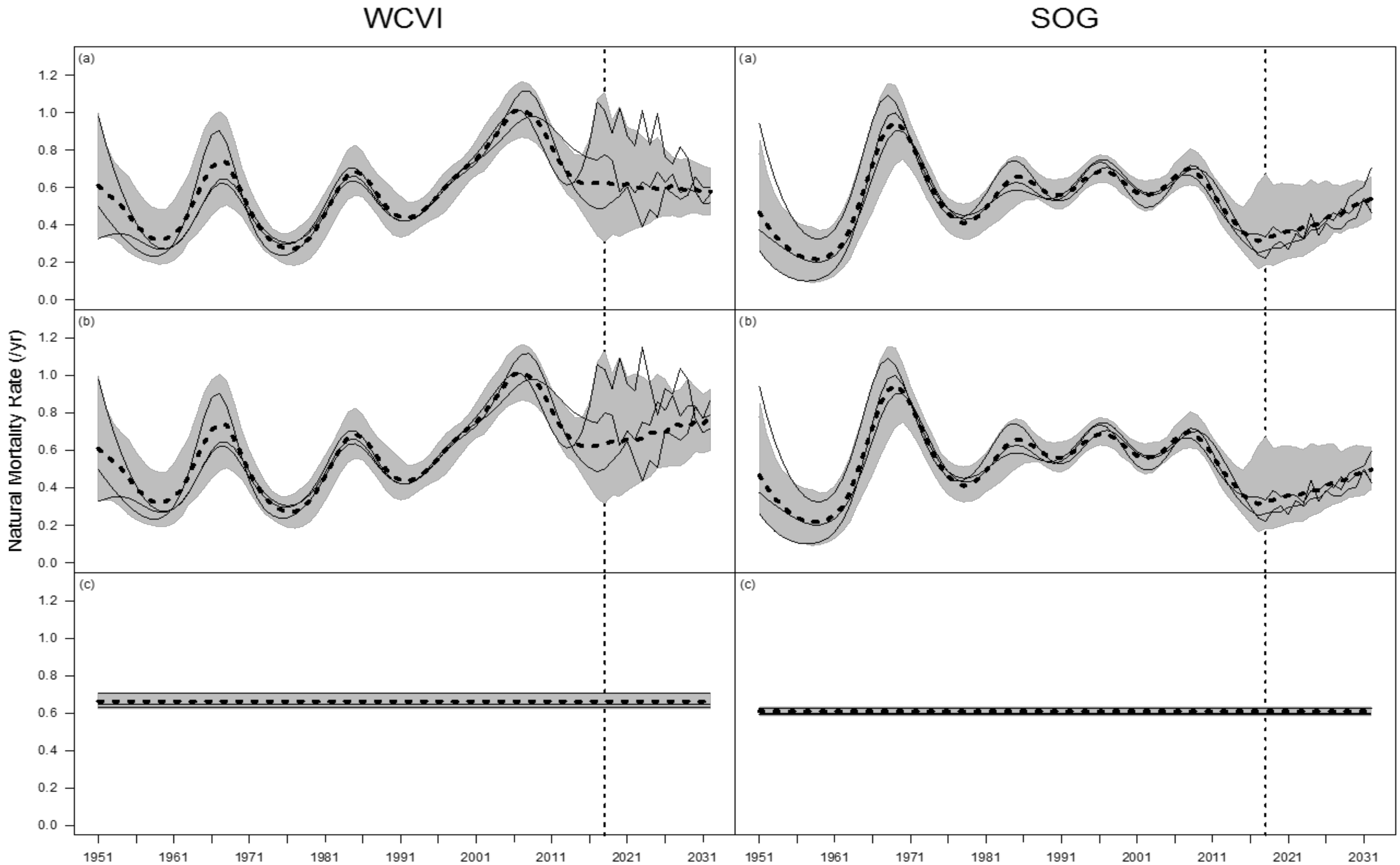


Figure 3. Simulation envelopes for time varying natural mortality in the depensatory-M scenario (a), density-independent-M scenario (b), and constant-M scenario (c) for WCVI and SOG herring stocks. The historical time period is shown from 1951-2017. The vertical dotted line at 2018 denotes the start 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 of 100 randomly selected replicates.

Table 1. Candidate management procedures used for the West Coast of Vancouver Island (WCVI) and Strait of Georgia (SOG) Pacific Herring fisheries. Upper control points (UCPs) are not defined for minimum escapement (minE) harvest control rule (HCR) functions, as these depend only on the cut-off value and the harvest rate (HR). Legend: management procedure (MP), hockey stick (HS), equilibrium spawning biomass (B_0), and tonnes (t).

MP	**U_{max} (HR)**	**Maximum Catch (t)**		**HCR Function**	**Cut-Off**		**UCP**
		WCVI	**SOG**		**WCVI**	**SOG**	
MP1	0.2	n/a	n/a	minE	18,800 t	21,200 t	n/a
MP2	0.1	n/a	n/a	minE	18,800 t	21,200 t	n/a
MP3	0.1	2,000	30,000	minE	18,800 t	21,200 t	n/a
MP4	0.2	n/a	n/a	minE	$0.5B_0$	$0.5B_0$	n/a
MP5	0.1	n/a	n/a	minE	$0.5B_0$	$0.5B_0$	n/a
MP6	0.1	2,000	30,000	minE	$0.5B_0$	$0.5B_0$	n/a
MP7	0.2	n/a	n/a	HS	$0.3B_0$	$0.3B_0$	$0.6B_0$
MP8	0.1	n/a	n/a	HS	$0.3B_0$	$0.3B_0$	$0.6B_0$
MP9	0.1	2,000	30,000	HS	$0.3B_0$	$0.3B_0$	$0.6B_0$
MP10	0	0	0	n/a	n/a	n/a	n/a

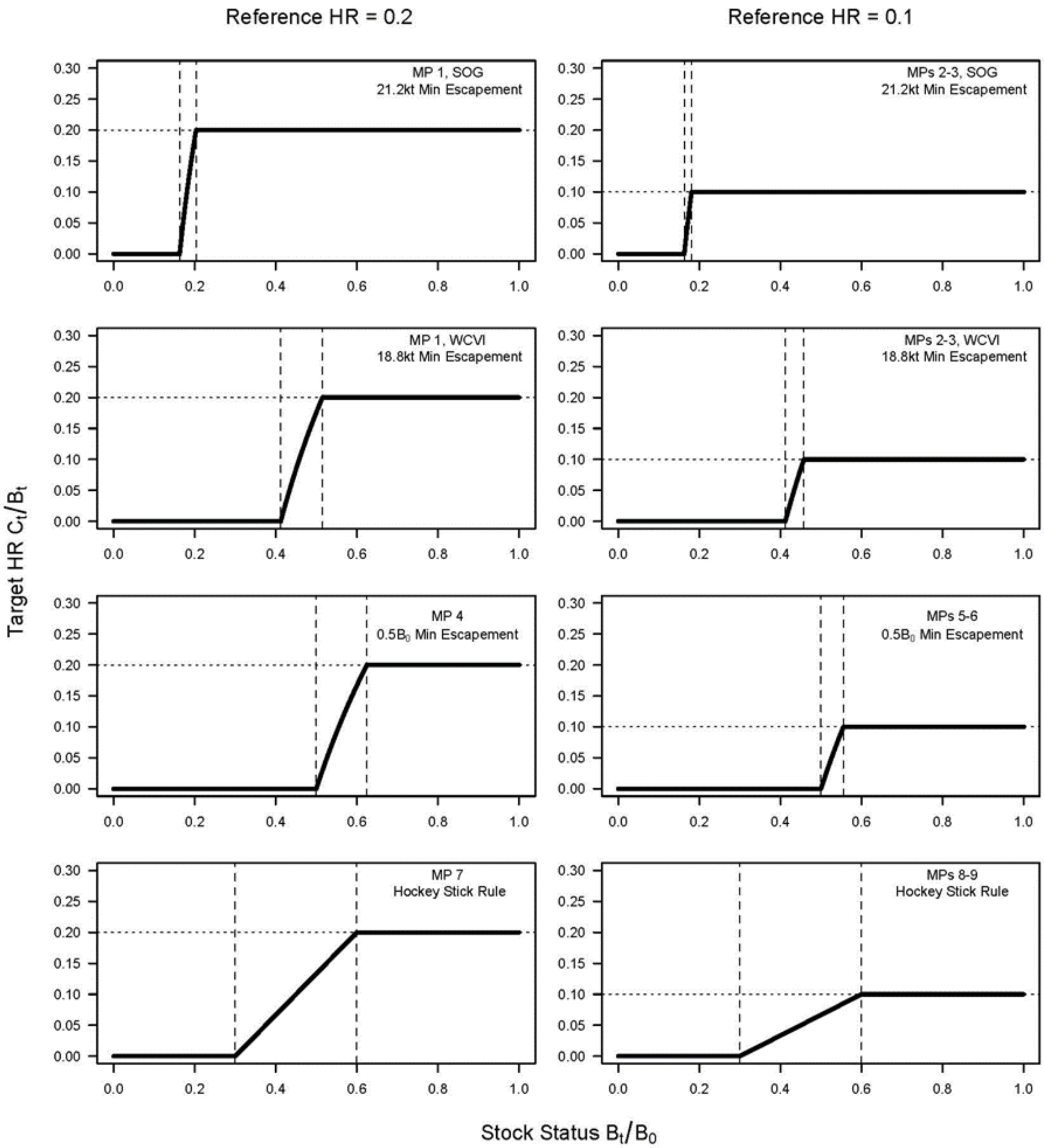


Figure 4. Harvest control rule diagrams showing the functional relationship between harvest rate and stock status for each management procedure. The first row shows the harvest control rule for the minE21.2 procedures for SOG herring MP1 - MP3 (with stock status scaled to operating model B_0), the second row shows the rule minE18.8 procedures for WCVI herring MP1 - MP3 (also scaled to operating model B_0), the third row is the rule for the minE.5B0 procedures MP4 - MP6, and the fourth row shows the rule for the HS30-60 procedures MP7 - MP9.

Table 2. Management procedure performance for the West Coast of Vancouver Island stock. Performance criteria are calculated over three generations (15 years) from the start of the projection period for all Management Objectives except Biomass Objective 4, which is calculated over two generations (10 years, Table 1). Management Procedures are ordered within each scenario by performance achieving the Conservation Objective (Objective 1), 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. Management procedure MP1 (bolded rows) is intended to mimic historical practice for the WCVI management area.

		Conservation	**Biomass**						**Yield**		
		Objective 1	**Objective 2**				**Obj. 3**	**Obj. 4**	**Obj. 5**	**Objective 6**	**Closures**
		>75%	**>50%**	**>50%**	**>50%**	**>50%**	**>75%**	**>75%**	**<25%**	**max**	**min**
Scenario	**MP**	**$P(B_t>.3B_0)$**	**$P(B_t>.4B_0)$**	**$P(B_t>.6B_0)$**	**$P(B_t>B_{ave})$**	**$P(B_t>B_{ave\text{-}prod})$**	**$P(B_t>.75B_0)$**	**$P(B_t>B_{90s})$**	**medAAV**	**medAveCatch**	**$P(C_t<650t)$**
depensatory-*M*	10	88%	81%	61%	61%	40%	46%	42%	6.81	0.13	100%
	6	87%	76%	55%	55%	34%	39%	38%	16.49	1.72	25%
	9	86%	75%	54%	54%	34%	39%	37%	13.14	1.86	14%
	3	86%	76%	54%	54%	34%	38%	37%	8.26	1.85	17%
	5	86%	74%	47%	47%	27%	32%	32%	39.07	3.63	27%
	8	84%	72%	46%	46%	26%	31%	31%	36.33	3.78	14%
	2	84%	72%	46%	46%	27%	31%	31%	34.32	3.79	18%
	4	78%	61%	33%	32%	16%	20%	22%	47.42	6.23	29%
	1	**75%**	**58%**	**30%**	**30%**	**15%**	**19%**	**21%**	**41.28**	**6.66**	**21%**
	7	74%	58%	30%	30%	15%	19%	21%	40.31	6.56	14%
density-independent-*M*	10	78%	66%	39%	40%	23%	27%	32%	10.79	0.13	100%
	6	74%	60%	35%	35%	20%	23%	28%	29.43	1.52	34%
	3	73%	59%	34%	34%	19%	22%	28%	21.35	1.74	26%
	9	73%	59%	34%	34%	19%	23%	28%	18.63	1.73	21%
	5	69%	54%	28%	28%	14%	17%	23%	49.49	2.69	37%
	8	68%	53%	28%	27%	14%	17%	23%	40.85	2.97	22%
	2	68%	53%	27%	27%	14%	17%	23%	41.17	3.08	28%
	4	60%	42%	19%	20%	8%	11%	17%	60.48	4.48	39%
	1	**56%**	**39%**	**18%**	**18%**	**8%**	**10%**	**16%**	**47.74**	**5.06**	**30%**
	7	56%	39%	18%	18%	8%	10%	16%	47.27	5.06	20%
constant-*M*	10	94%	82%	58%	74%	73%	40%	92%	6.67	0.13	100%
	6	91%	80%	53%	70%	68%	36%	88%	7.12	1.98	8%
	3	91%	79%	53%	70%	68%	36%	88%	7.12	1.98	7%
	9	91%	79%	53%	70%	68%	36%	88%	7.10	1.98	7%
	5	87%	70%	38%	59%	57%	25%	83%	29.47	7.68	9%
	8	86%	70%	38%	58%	57%	24%	83%	29.40	7.71	7%
	2	86%	70%	38%	59%	56%	24%	83%	28.89	7.73	7%
	4	73%	50%	23%	41%	39%	13%	70%	31.30	13.09	10%
	7	72%	50%	23%	40%	38%	13%	69%	30.70	13.23	7%
	1	**72%**	**50%**	**23%**	**40%**	**38%**	**13%**	**69%**	**30.46**	**13.30**	**8%**

Under the depM and DIM scenarios, the 10% maximum harvest rate MPs with catch caps maintained annual variability in yield less than 25% (Objective 5), while MP1 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 MP1 never closed SOG herring fisheries under any operating model scenario, which is consistent with historical application since 1986. For most other MPs, closures occurred 0-9% of the time with the highest occurrence being MP4 under the conM scenario.

In contrast to WCVI, MPs met Objective 2 with alternative USRs in almost all cases. The only exception was MP1, which failed to maintain spawning biomass above the USR defined as the average biomass during a productive period ($B_{\text{ave-prod}}$), and also failed to maintain spawning biomass above the USR=0.6B_0, both under the conM scenario.

Sources of Uncertainty

Most elements of fishery management systems are subject to uncertainty. For the Pacific herring management system, key uncertainties relate to the observation process (the spawn survey and test fisheries) as well as uncertainty about ecological dynamics. Both are difficult to quantify and manage. Uncertainties related to the surveys include a shift in sampling strategy between the surface survey (1951-1987) and dive survey (1988-present), a potential reduction in survey coverage over time due to changes in herring spawning behaviour and sampling effort, and differences in the survey procedure between stock areas. At present, survey uncertainty is only represented by different assumptions about catchability (q) for each survey strategy type in the stock assessment model. Fisheries Management quota decisions since 2015 have been based on the AM2 model (q=1) that assumes the dive survey spawn index represents all of the spawn, that no eggs are lost to predation and that these estimates have no associated uncertainty. The OM scenarios presented here implement this AM2 assumption for the dive survey time period in order to inform the short-term risks associated with continued application of this MP. However, future MSE work could include OMs that relax the AM2 assumption, allowing for scenarios where the dive survey q does not equal 1, is estimated with error, and may include bias over time. The MSE approach presented in the working paper provides advice to managers so that they can act in the face of uncertainty. The quality of that advice is dependent on the range and credibility of the uncertainty included in the evaluation.

The three OM scenarios presented in the working paper explore uncertainty in historical and future trends in natural mortality. It is acknowledged that additional scenarios are needed to explore uncertainty in stock-recruitment (the models all include the assumption that SR follows a Beverton-Holt function), SR steepness (h), dive survey catchability (q), and spatial population dynamics. In addition to the natural mortality scenarios, the OMs include uncertainty in the stock-recruitment parameter (via sampling parameter values from a distribution and projecting recruitment deviations from their joint Bayes posterior distribution).

CONCLUSIONS AND ADVICE

The Pacific Herring operating model (DFO 2015) is suitable for simulating realistic data derived from alternative hypotheses about stock and fishery dynamics for WCVI and SOG Pacific Herring. Stock status relative to biological reference points was not included in this MSE but will be provided as part of the upcoming work on the status of Pacific Herring in 2018 and 2019 forecast. The results from this MSE will inform that work.

The simulation evaluations rank performance of management procedures against the Conservation Objective (Objective 1) as the first priority. MP performance against additional biomass and yield objectives is discussed and trade-offs are presented in Figure 5, however there is no ranking of Objectives 2-6 as these decisions are not solely a science-based process. The paper does not include selection of a USR, however candidate USRs are included in Objective 2.

An initial summary of spatially disaggregated abundance date for WCVI and SOG was presented, which could serve to guide development of spatially resolved operating models and management procedures. Implications of spatial structure may include, *inter alia*, spatial population dynamics, sequential fisheries, fishing season timing and duration, and fine-scale spatial objectives of importance to resource users. Abundance and biological data for WCVI and SOG were examined by Herring Statistical Areas and other groupings in an attempt to identify data proxies that could be linked to spatial objectives described by First Nations. No recommendations for such proxies could be provided; to address this, identification of MPs robust to uncertainty in spatial structure will need to be determined via simulation testing following the development of spatial operating models.

Table 3. Management procedure performance for the Strait of Georgia stock. Performance criteria are calculated over three generations (15 years) from the start of the projection period for all Management Objectives. Management Procedures are ordered within each scenario by performance achieving the Conservation Objective (Objective 1), 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. Management procedure MP1 (bolded rows) is intended to mimic historical practice for the SOG management area.

		Conservation Objective 1	Biomass Objective 2					Yield Objective 6	Closures
		>75%	>50%	>50%	>50%	>50%	Obj. 5 <25%	max	min
Scenario	**MP**	**P(B_t>.3B_0)**	**P(B_t>.4B_0)**	**P(B_t>.6B_0)**	**P(B_t>B_{ave})**	**P(B_t>$B_{ave-prod}$)**	**medAAV**	**medAveCatch**	**P(C_t< 650t)**
depensatory-*M*	10	100%	99%	97%	99%	98%		0.14	100%
	3	99%	98%	92%	97%	93%	22.56	21.48	0%
	9	99%	98%	92%	98%	93%	22.98	21.48	0%
	6	99%	98%	92%	98%	93%	23.50	21.48	2%
	8	99%	98%	92%	98%	93%	30.09	23.44	0%
	5	99%	98%	92%	98%	93%	30.32	23.44	2%
	2	99%	98%	91%	97%	93%	29.64	23.44	0%
	4	98%	93%	79%	92%	79%	28.35	39.87	3%
	7	98%	93%	78%	92%	78%	27.83	39.87	0%
	1	**97%**	**92%**	**78%**	**91%**	**78%**	**26.97**	**39.87**	**0%**
density-independent-*M*	10	99%	99%	98%	99%	98%		0.14	100%
	6	99%	98%	93%	98%	94%	22.94	22.63	2%
	3	99%	98%	93%	98%	94%	22.94	22.63	0%
	9	99%	98%	93%	98%	94%	22.94	22.63	0%
	2	99%	98%	93%	98%	94%	29.63	24.88	0%
	8	99%	98%	93%	98%	94%	29.68	24.88	0%
	5	99%	98%	93%	98%	94%	29.95	24.88	2%
	4	98%	95%	85%	95%	86%	28.73	43.92	3%
	7	97%	94%	85%	94%	85%	27.97	43.92	1%
	1	**97%**	**94%**	**84%**	**94%**	**85%**	**27.14**	**43.92**	**0%**
constant-*M*	10	100%	99%	84%	97%	93%		0.14	100%
	3	99%	93%	60%	87%	75%	33.18	13.79	0%
	2	99%	93%	60%	87%	75%	33.54	13.80	0%
	9	99%	93%	60%	88%	75%	35.22	13.56	1%
	8	99%	93%	60%	88%	75%	36.11	13.56	1%
	6	99%	93%	60%	88%	76%	36.19	13.43	6%
	5	99%	93%	60%	88%	76%	37.27	13.43	6%
	4	93%	77%	35%	67%	52%	38.63	23.31	9%
	7	92%	75%	33%	65%	50%	34.28	23.76	1%
	1	**91%**	**73%**	**31%**	**62%**	**48%**	**28.27**	**24.08**	**0%**

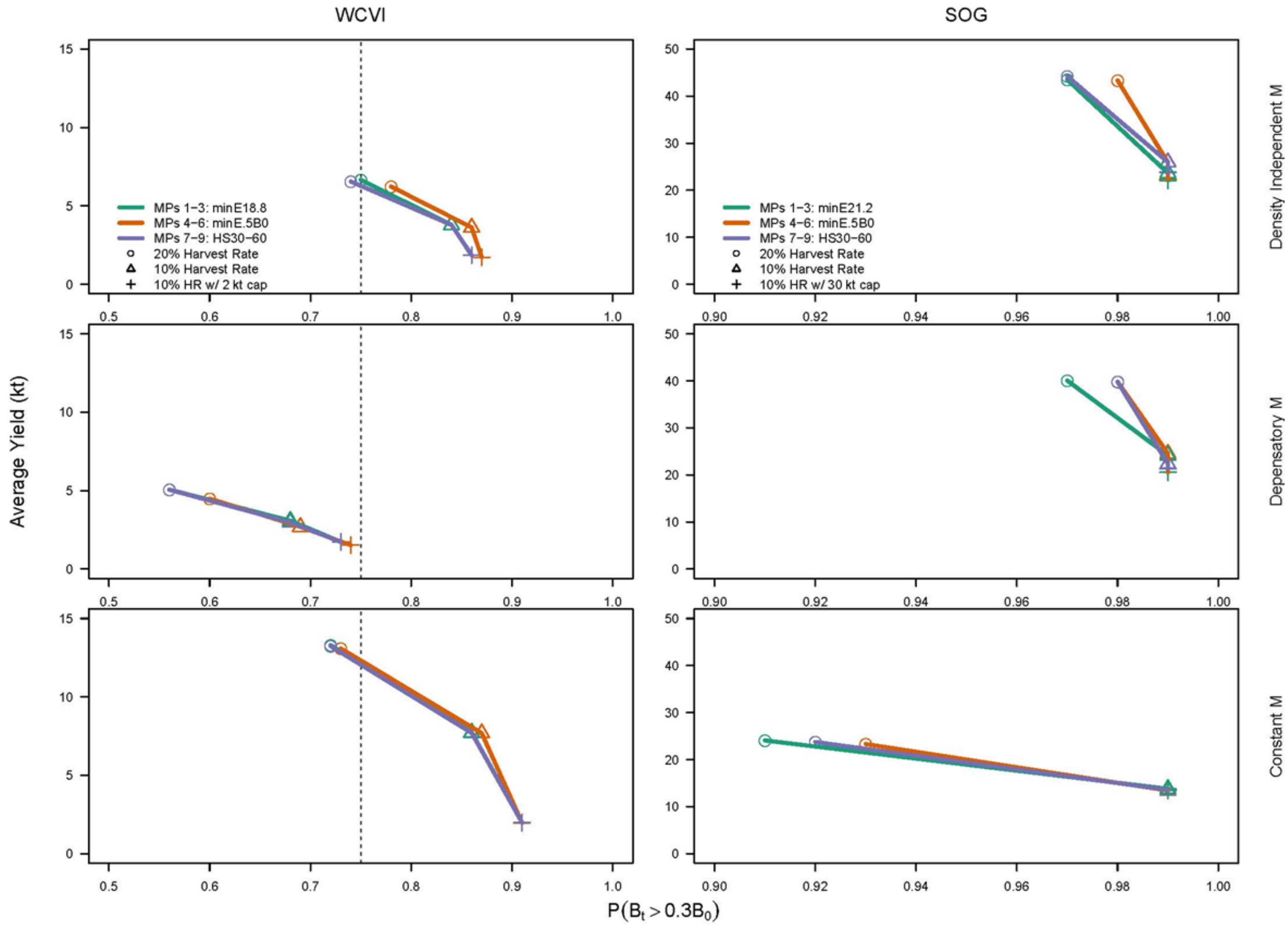

WCVI
SOG
MPs 1–3: minE18.8
MPs 4–6: minE.5B0
MPs 7–9: HS30–60
20% Harvest Rate
10% Harvest Rate
10% HR w/ 2 kt cap
MPs 1–3: minE21.2
MPs 4–6: minE.5B0
MPs 7–9: HS30–60
20% Harvest Rate
10% Harvest Rate
10% HR w/ 30 kt cap
Average Yield (kt)
$P(B_t > 0.3B_0)$
Density Independent M
Depensatory M
Constant M

Figure 5. 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 (depensatory-M, density-independent-M and constant-M 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.

For SOG herring, the original herring harvest control rule, MP1, met the Conservation Objective (Objective 1) under all scenarios. MPs met Objective 2 with candidate USRs in almost all cases. The only exception was MP1, which failed to maintain spawning biomass above the USR defined as the average biomass during a productive period ($B_{\text{ave-prod}}$) under the conM scenario.

For WCVI herring, management procedures with 10% maximum harvest rates and 2,000 t catch caps could meet Objectives 1 and 2 (with candidate USRs a, b, c) as long as future natural mortality rates are lower 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 the defensibility of on-going management advice while safeguarding against heavy depletion in the short-term while further strategic MSE work progresses. However under the DIM scenario, no MP met the Conservation Objective and the sensitivity of WCVI results to future trends in natural mortality implies a need for follow-up work revising the most promising MPs until they can achieve an acceptable result in spite of this sensitivity. Additional MP modifications may be required such as criteria that the spawning stock is increasing above the cut-off prior to resuming harvest, i.e., a slow-up MP

For Pacific Herring, MPs that implement reductions in harvest rates and application of catch caps can mitigate against positive biases in the assessment model, reducing the risk of overharvesting. This finding is applicable to all BC Pacific Herring stocks because the same assessment model included in these simulations is currently applied to all five major stock areas.

Differences in future trends in abundance presented for WCVI and SOG show the importance of undertaking stock-specific selection of objectives and evaluation of MPs via simulation. Although the effects of harvest rate reductions and catch caps are likely to be similar among management areas, future MSE cycles are likely to result in area-specific MP design. This contrasts with the historical practice of applying the same MP design to all areas.

OTHER CONSIDERATIONS

MSE allows for explicit representation of uncertainty in the evaluation of MP performance against objectives. Uncertainty in processes such as natural mortality and predator dynamics, productivity and recruitment, and data quality can be explicitly modelled as alternative operating models. Future iterations of operating models could also allow for the incorporation of climate change scenarios. Modelling the uncertainty of these various processes allows managers and herring users to understand how MPs will perform given these uncertainties.

The MSE process is by nature “iterative” and thus allows for inclusion of new management objectives, MPs, and operating model scenarios. Subsequent MSE cycles are planned to include management objectives, MPs, and operating models for all 5 major herring stocks, and DFO work planning could include operating model development to address key uncertainties.

SOURCES OF INFORMATION

This Science Advisory Report is from the July 25-26, 2018 regional peer review on Evaluation of Management Procedures for Pacific Herring (*Clupea pallasii*) in the Strait of Georgia and the West Coast of Vancouver Island Management Areas of British Columbia. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

DFO 2009. A Fishery Decision-Making Approach Incorporating the Precautionary Approach. Fisheries and Oceans Canada. (Accessed 01 August 2018.)

DFO. 2015. Candidate Limit Reference Points as a Basis for Choosing among Alternative Harvest Control Rules for Pacific Herring (*Clupea pallasii*) in British Columbia. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2015/062.

DFO. 2016. Stock Assessment and Management Advice for BC Pacific Herring: 2016 Status and 2017 Forecast. DFO Can. Sci. Advis. Sec. Sci. Resp. 2016/052.

DFO. 2018. Stock assessment for Pacific Herring (*Clupea pallasii*) in British Columbia in 2017 and forecast for 2018. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2018/002.

Kronlund, A.R., Forrest, R.E., Cleary, J.S., and Grinnell, M.H. 2018. The Selection and Role of Limit Reference Points for Pacific Herring (*Clupea pallasii*) in British Columbia, Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2018/009.

PEER REVIEW PARTICIPANTS

Last Name	First Name	Affiliation
Ashcroft	Chuck	Sport Fishing Advisory Board
Benson	Ashleen	Landmark Fisheries Research
Branch	Trevor	University of Washington
Cass	Al	Herring Industry Advisory Board
Chavez	Lais	Haida Nation
Christensen	Lisa	DFO Science
Cleary	Jaclyn	DFO Science
Cox	Sean	Simon Fraser University,
Davis	Brooke	DFO Science (rapporteur)
Dorner	Brigitte	Heiltsuk Nation
Forrest	Robyn	DFO Science
Ganton	Amy	DFO Fisheries Management
Goruk	Andrea	DFO Fisheries Management
Grinnell	Matthew	DFO Science
Groves	Steven	DFO Fisheries Management
Guo	Chuanbo	DFO Science
Hawkshaw	Sarah	DFO Science
Jones	Russ	Council of the Haida Nation
Kanno	Roger	DFO Fisheries Management
Kenyon	Alexander	Landmark Fisheries Research
Kronlund	Rob	DFO Science
Kulchyski	Tim	Cowichan Tribes
Laliberte	Bernette	Cowichan Tribes
Lane	Jim	Nuu-chah-nulth Tribal Council
MacDougall	Lesley	DFO Science
Marentette	Julie	DFO Science
Marshall	Kristin	National Oceanic and Atmospheric Administration (USA)
McGreer	Madeleine	Central Coast Indigenous Resource Alliance
Miller	Sara	Alaska Government
Morley	Rob	Canadian Fishing Company
Neuman	Amber	DFO Fisheries Management
Obradovich	Shannon	DFO Science
Ormond	Chad	South Island Nations
Patten	Bruce	DFO Science (chair)
Postlethwaite	Victoria	DFO Fisheries Management
Regular	Paul	DFO Science
Rusch	Bryan	DFO Fisheries Management

Last Name	First Name	Affiliation
Rusel	Christa	A'Tlegay Fisheries Society
Schweigert	Jake	DFO emeritus
Spence	Brenda	DFO Fisheries Management
Starr	Paul	Herring Industry Advisory Board
Swain	Doug	DFO Science
Thomas	Greg	Herring Conservation and Research Society

THIS REPORT IS AVAILABLE FROM THE:

Centre for Science Advice
Pacific Region
Fisheries and Oceans Canada
3190 Hammond Bay Road
Nanaimo, BC V9T 6N7

Telephone: (250) 756-7208
E-Mail: csap@dfo-mpo.gc.ca
Internet address: www.dfo-mpo.gc.ca/csas-sccs/

ISSN 1919-5087

Correct Citation for this Publication:

DFO. 2019. Evaluation of Management Procedures for Pacific Herring (*Clupea pallasii*) in the Strait of Georgia and the West Coast of Vancouver Island Management Areas of British Columbia. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2019/001.

Aussi disponible en français :

MPO. 2019. Évaluation des procédures de gestion du hareng du Pacifique (Clupea pallasii) dans le détroit de Georgie et sur la côte ouest de l'île de Vancouver dans les zones de gestion de la Colombie-Britannique. Secr. can. de consult. sci. du MPO, Avis sci. 2019/001