STOCK ASSESSMENT AND MANAGEMENT ADVICE FOR BC PACIFIC HERRING: 2015 STATUS AND 2016 FORECAST

Context

Fisheries and Oceans Canada (DFO) Pacific Fisheries Management Branch requested that DFO Pacific Science Branch assess the status of British Columbia (BC) herring stocks in 2015, and provide projections of potential herring abundance in 2016 and the consequences of a range of potential harvests to inform the development of the 2015/16 Integrated Fisheries Management Plan (IFMP).

Pacific herring abundance is currently assessed using a statistical catch-age-model. The catch-age model is fitted to commercial catch, proportions-at-age and fishery-independent survey index to estimate biomass and recruitment and to generate 1-year forecasts of spawning biomass (Martell et al., 2012; DFO 2014, 2015). A revised catch-at-age model was introduced for BC herring assessment in 2006 (Haist and Schweigert 2006), and the design of the model has since gone through several iterations to fix minor errors, as well as re-design and re-structuring of various model components. One major change introduced in 2011 (Martell et al., 2012) was letting the model estimate the spawn survey scaling parameter q, rather than holding it fixed at q=1, as had been done in previous iterations of the catch-age model. Another major change introduced in 2011 was to make the cut-off dependent on the model's most recent estimate of unfished biomass, whereas it had previously been treated as a fixed quantity estimated from an earlier assessment model. Concerns have been raised regarding the application of these two changes relative to the historical management procedure (q=1 and fixed cut-offs), as well as requests to evaluate the potential consequences of these two management procedures (historical and current) using simulation. The potential consequences of these changes were not evaluated prior to their implementation, which along with lack of rebuilding in some areas has led First Nations and other stakeholders to question the appropriateness of the advice resulting from application of the current management procedure.

In May 2015, a closed loop-simulation tool was developed to evaluate performance of herring management procedures against a suite of conservation and fishery performance metrics. The simulation tool was reviewed in a May 2015 CSAS Regional Peer Review Process and accepted as a "proof of concept" that the methodology was sound. This simulation framework has immediate utility for this year's stock assessment, because it aims to identify tradeoffs between management procedures that assume alternative ecological hypotheses about future conditions (e.g., future patterns of natural mortality and growth for herring) and assessment modeling assumptions (e.g., the proportion of the spawn observed by the survey).

This assessment separately addresses both the request to assess BC herring stock status and to compare approximations of historical and current management procedures using simulation. The status of BC herring stocks in 2015 and forecasts for 2016 are provided in the form of a stock assessment update, using Martell et al. (2012). Current stock status and trends, as well as projected biomass for 2016 are presented in the form of decision tables. Biomass estimates and decision tables reflect both the current management procedure (estimating q, time varying cut-offs) and an approximation of the historical management procedure (q=1, fixed 2014 cut-offs).

The simulation study provides an initial evaluation of the relative performance of the two management procedures using metrics such as mean catch, variability in catch, and the probability of dropping below candidate limit reference points $0.25B_0$, $0.30B_0$ (Pikitch et al. 2012) and $0.40B_0$ (Pikitch et al. 2012) for simulated approximations of the current and historical management procedures under alternate sets of assumptions. The simulation work is intended to guide interpretation of the assessment advice presented in Part 1, and to provide guidance for selection of an interim management procedure for the near term (1-2 years). The stock assessment and simulation analysis are presented in this Science Response.

The objectives of this Science Response are to:

Part 1

1. Assess the current status of Pacific Herring for each of the five major and two minor stocks using both the current (estimate *q*, time varying cut-offs) and historical management procedures (*q*=1, fixed cut-offs).
2. Present trends in herring biomass, depletion, and recruitment for each major and minor stock using both the current and historical management procedures;
3. Present probabilities of spawning biomass levels below cut-offs and harvest rates exceeding targets prescribed by both the current and historical management procedures for a range of 2016 allowable catch levels.

Part 2

4. Present simulation results comparing approximations of the current and historical management procedures against a range of conservation and fishery performance criteria (e.g. candidate limit reference points, yield, variability in yield).

Additional reference points and performance metrics are also included for the Central Coast, arising from discussions within the Heiltsuk-DFO Technical Team.

This Science Response Report results from the Science Response Process of September 2015 on Stock Assessment and Management Advice for BC Pacific Herring: 2015 Status and 2016 Forecast.

Background

Management procedures for BC Pacific Herring fisheries

There are several components to B.C. Pacific Herring (*Clupea pallasii*) management procedures. Herein, management procedure is defined as the suite of inputs and/or activities that lead to harvest decisions in any given year. These components include: which, and how much data are collected; what is assumed about stock structure, the stock assessment model used; and, the herring harvest control rule (HCR) that mathematically converts some estimate of current stock status to a total allowable catch (TAC) and implementation errors (de la Mare 1998). How well a particular management procedure performs depends on what objectives are defined for the management of the stock, including the probability of achieving target biomass level, the probability of avoiding limit biomass levels, the mean catch, the variability in catch and other performance metrics that have not yet been finalized for BC herring. For BC herring, a consultative process with First Nations and industry follows the provision of harvest advice from the management procedure. Fisheries Management considers this information in setting final TAC levels.

Herring is currently managed on the basis of the herring harvest control rule that was first applied in 1986 (Hall et al. 1988). Similar to so-called threshold policies applied in Alaskan herring fisheries (Zheng et al. 1993), the rule consists of a cut-off where if the stock is predicted to be above 25% of the unfished biomass in the next fishing year, then a 20% harvest rate is applied to the biomass predicted by the stock assessment. There were two simulation studies that evaluated the application of this harvest control rule (Zheng et al. 1993, Hall et al. 1988). Both analyses relied on modelling assumptions that are not realistic for BC herring: data collected since these early simulations show that the assumptions that growth (weight at age) and natural mortality would remain constant over time are not valid. BC herring stocks have seen large changes in both natural mortality and weight at age for Haida Gwaii, Central Coast, and West Coast of Vancouver Island areas (DFO 2014, 2015; Cleary and Taylor 2015, in prep.[1]). Because time-varying changes in weight at age and natural mortality were not captured by these initial simulations and yet have since been observed, the original analyses were not adequate to fully evaluate the existing control rule.

The poor performance of harvest control rules for BC herring due to environmental changes has been confirmed by the inability to provide accurate predictions of MP performance. Hall et al. (1988) predicted that by keeping harvest rates below 0.3, the probability of a modelled SOG stock dropping below the 25% cut-off should have been less than 0.05. The HCR has been applied to all five major herring stock areas for BC herring. However, other than PRD and SOG, the data suggest that the herring harvest control rule has not performed according to the original predictions of Hall et al. (1988), most likely due to unforeseen environmental changes (resulting in declining weight at age and changes in natural mortality). Using the assessment models of the day, Haida Gwaii stock was estimated below cut-off in 1988, 1995, 2001, 2003, 2005-2012; Central Coast stock was below cut-off in 2008-2013; and WCVI stock was below cut-off in 2001, 2006-2011, and 2013. In these three areas, stocks were estimated to be below the cut-off much more frequently than 5% of the time. Updated simulation analyses of harvest control rules for all BC herring stocks are needed in order to evaluate how alternative management procedures will perform under potential future conditions.

In addition to environmental changes, no single element of herring management procedures has remained constant. Virtually every element of the herring management procedure has changed over time, including: the inclusion/exclusion of SOK catches; the spawn survey data changed in 1988 from surface to dive surveys; the survey index has been treated both as an absolute and a relative index of herring biomass; the methodology for projecting stock biomass has changed; and, the cut-offs have changed. Largely ignored in the context of herring stock assessments is that the assumptions made in the assessment model are themselves important management procedure choices (Butterworth 2007). Assessment model assumptions have changed on multiple occasions in herring (Haist and Stocker 1984, Haist and Schweigert 2006, Christensen et al. 2010, Cleary and Schweigert 2011). All these changes were made without first evaluating the implications of such changes using simulation (as this was not common practice at the time). In general, simulation (NRC 1998) and retrospective analyses (e.g. Walters and MacGuire 1996) have shown that in any given year, assessment models can be considerably in error. The tendency for assessment models to produce unreliable estimates of stock size has important consequences for annual decision making; notably that the uncertainty represented in decision tables may only represent the uncertainty given a model whose estimates are biased.

A new statistical catch at age model was introduced in 2011 (Martell et al., 2012), and subsequently used for stock assessment in 2012, 2013, and 2014. Martell et al. (2012) includes two significant changes to the management procedure: changing the assessment model from one with fixed cut-offs and the spawn survey scaling parameter q fixed to one (for the dive survey), to a procedure that estimates the surface and dive survey qs (using a prior) and

[1] Cleary, J.S. and Taylor, N.G. 2015. Status of B.C. Pacific Herring (*Clupea pallasii*) in 2014 and forecasts for 2015. DFO Can. Sci. Advis. Sec. Res. Doc. In prep.

estimates the cut-offs annually. Except for the Prince Rupert District, the changes implemented in 2011 resulted in allowing fishing at lower biomass levels because the estimated cut-offs were lower than the fixed ones established in 1996. Plus, estimated values of q were less than one for all stock areas: this change alone had very large effects on the catches given by the harvest control rule relative to the pre-2011 practice. In some areas, catches predicted by the current management procedure were approximately double to what would have been considered using the historical procedure (Cleary and Taylor 2015, in prep[1]).

Since 2011, there has been considerable disagreement within the herring community on the application of the current management procedure over the historically used approach. Concerns amongst First Nations, Resource Managers, Science, and industry, stemming from, among other things, inconsistencies between on-grounds observations of stock abundances and predictions from the current and historical assessment models, motivated the formation of a Pilot Technical Working Group, consisting of DFO Science and Fisheries Management and technical representatives nominated by several First Nations and the herring industry. The pilot technical working group provided technical support for the development of this Science Response.

Broadly this Science Response provides a stock assessment for Pacific Herring using the current and historical management procedures and a simulation analysis to illustrate the long-term consequences of applying approximations of these management procedures. The simulation analysis of current vs. historical management procedures will aid in understanding performance trade-offs between these procedures to help guide fisheries management decision-making for 2016, i.e., in the absence of a full evaluation of management procedures against objectives for BC herring stocks. The simulation analysis will use the closed-loop simulation framework reviewed by CSAS in May 2015 to evaluate the long term performance of each management procedure against operating models (described below) that characterize each set of underlying assumptions.

It is important to note that the ‘historical management procedure’ being presented as part of the stock assessment and simulation evaluations that follow, is not identical to what previously occurred. There are several reasons why this is so. One reason is that past herring management was based on recruitment forecasting approaches that are now deemed to be invalid (DFO 2014a). Also, as discussed below, there have been several changes to the assessment model. Another reason is that implementation of the harvest control rule in terms of allowable and realized catches has not been consistent from year to year, in that TAC levels were often set lower than levels prescribed by the MP. It is, therefore, not possible to replicate what was done historically exactly. The term ‘historical management procedure’, referrs to two key elements of past practice: fixing the dive survey q and fixing the cut-offs at the levels determined in 1996. In this SR, the terms Management Procedure 1 (MP1) and Management Procedure 2 (MP2) refer to the estimated q/estimated cut-off and the fixed q/fixed cut-off procedures for the simulation analysis. A similar approach is adopted for describing the stock assessment with stock assessment model 1 (AM1) referring to the estimate q/estimate cut-off model, and stock assessment model 2 (AM2) where the dive survey q is fixed at one and the cut-offs are fixed at 1996 levels.

Analysis and Response

PART 1: Stock Assessment Modelling for 2015

The integrated statistical catch-at-age model (Martell et al., 2012) was the statistical platform used for the estimation of herring spawning stock biomass for both AM1 and AM2. This approach has since been used for the provision of science advice from 2011 to 2015. This combined-sex, catch-at-age model was applied independently to each stock area and fitted to fishery-independent spawn index data, annual estimates of commercial catch since 1951, and age composition data from the commercial fisheries and the test fishery charter program. The key results from stock assessments of Pacific Herring in five major and two minor stock areas are summarized as stock reconstructions, status of spawning stock in 2015, and projected spawning biomass in 2016.

Parameters estimated in AM1 and AM2 include stock-recruitment parameters (recruitment is modelled as age-2 fish), natural mortality rates for each year (1951-2015), spawn survey scaling parameters for the surface (q_1, 1951-1987) and dive (q_2, 1988-2015) survey time series, and age-based selectivity parameters for the commercial and test fisheries, where available. Model results and advice are presented using assumptions of the current and historical management procedures, where, as discussed above, AM1 includes a stock assessment model that estimates the spawn survey scaling parameters q using a prior (Martell et al. 2012) and implements time-varying cut-offs (based on the model's most recent estimate of 25% unfished biomass), whereas AM2 includes an assumption of q=1 (for the dive survey) and implements fixed cut-offs (HG: 10,700 t, PRD: 12,100 t, CC: 17,600 t, SOG: 21,200 t, WCVI: 18,800 t).

Uncertainty for each assessment model is represented in parameter estimates and projections via Bayes posterior distributions that integrate prior knowledge and assumptions (e.g., natural mortality and spawn survey q's) with likelihood functions computed from the assessment data. Posterior distributions from the model exist in the form of 5,000 random samples from a Markov Chain Monte Carlo (MCMC) sample. These samples are used to develop graphical presentations, probability calculations, and 5-95% credibility intervals for parameters and projections. For the projections, each MCMC sample is combined with a constant catch level to forecast spawning biomass to 2016 and then uses the resulting spawning biomass and harvest rate distributions to compute probabilities that spawning biomass is below cut-off and harvest rates are above targets specified in the herring harvest control rules.

Part 1 describes coast-wide trends in catch, weight at age, spawning biomass, and natural mortality for the 5 major BC herring stocks. This is followed by stock-specific summaries of estimated (current) spawning biomass, SB_{2015}, estimated unfished equilibrium spawning biomass (SB_0), estimated ratios of SB_{2015}/SB_0, trends in age-2 recruitment and rates of instantaneous natural mortality. All results are presented for both management procedures. Updates are also provided for the two minor stocks: Area 2W and Area 27. Additional outputs are also included for the Central Coast, arising from discussions within the Heiltsuk-DFO Technical Team.

Input data

At present, the BC Pacific Herring fisheries consist of commercial fishing opportunities for food and bait herring, special use fisheries, spawn-on-kelp products, and roe herring; First Nations food, social, and ceremonial fisheries (FSC); and, recreational opportunities. Combined commercial removals for 2008 to 2015 from the roe, food and bait, and special use fisheries operating in the five major and two minor BC Herring stock assessment areas are shown in Table 1.

Biological samples collected from the roe seine fishery and the test charter program are combined to calculate mean weight at age for each stock area. In all major stock areas, mean weight at age trended downward for ages 3 and older from the late 1980s, reaching the lowest values for the time series between 2009 and 2011 (Figure 1). This trend held for all fish age 3 to age 8. For age 9 and age 10 (not shown), the pattern of recent increases in mean weight at age has not held across all ages and areas, but it should be noted that the sample sizes for calculating mean weight at age for these older age classes have been small. Since 2011, mean weight at age for all the major stock areas for ages 3-8 has generally been increasing, although there are a few year-to-year exceptions (e.g., a decline in mean weight at age 3 of SOG herring from 2014 to 2015). Biological samples are also used to calculate proportions at age for each stock, used in the estimation of fishery selectivity, and to inform the estimation of natural mortality rates and recruitment. Age proportions observed in 2015 are reported in the stock-specific sections below.

Table 1. Combined commercial removals (tonnes) from roe, and food and bait and special use fisheries operating in the BC herring stock assessment areas from 2008 to 2015. FSC, spawn-on-kelp and recreational fishery removals are not included in this table.

Stock Area	2008	2009	2010	2011	2012	2013	2014	2015
Haida Gwaii	0	0	0	0	0	0	0	0
Prince Rupert District	1,662	2,000	1,484	2,147	1,383	2,027	2,003	2,163
Central Coast	0	0	0	0	0	0	687	626
Strait of Georgia	9,934	10,170	8,324	5,128	11,339	16,566	20,307	19,969
West Coast Vancouver Island	0	0	0	0	0	0	0	0
Area 2W	0	0	0	0	0	0	0	0
Area 27	0	0	0	0	0	0	0	0

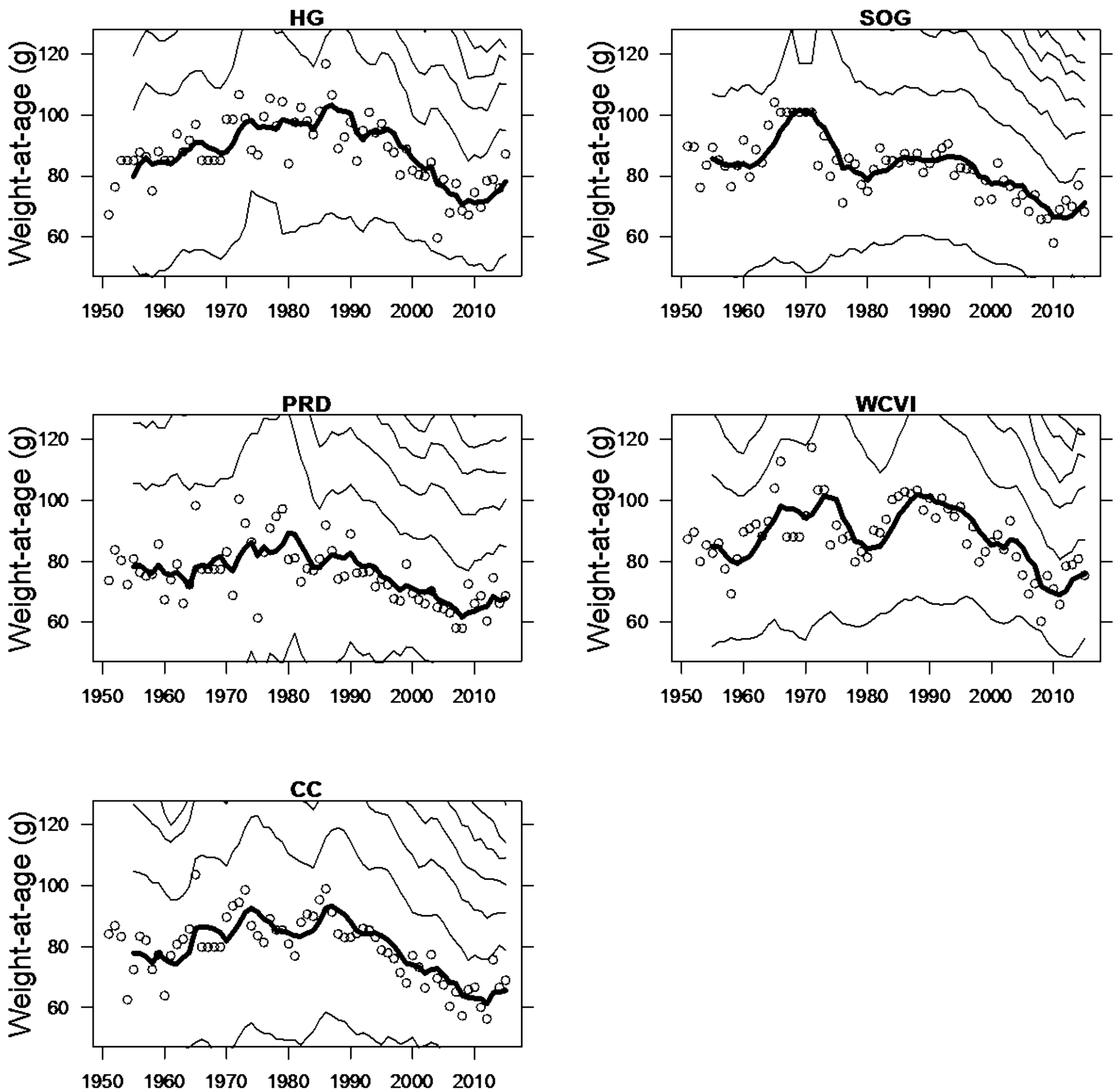

Figure 1. Time series of observed mean weight at age of age3 fish (circles) and five-year running mean weight at age 3 (thick black lines) for the major stock areas. Thinner black lines represent five-year mean weight at age 2 (lowest) and ages 4-7 (incrementing upwards from age 3).

Coast-wide Trends in Catch, Spawning Biomass, and Natural Mortality

Relative to the reduction period (1951-1965), catches have been much smaller. On several occasions between 1951 and 1965 coast-wide catch exceeded 150 kt, with a maximum of 220 kt in 1956 (Figure 2). Following a closure in the late 1960s, coast-wide catch in the 1970s went from 8.9 kt to 82 kt in 1976. In the 1980s, catches ranges between 16 and 41 kt and between 22 and 40 kt in the 1990. Coast-wide catches generally declined between 2005 and 2011 from 31 kt to 7.3 kt, respectively.

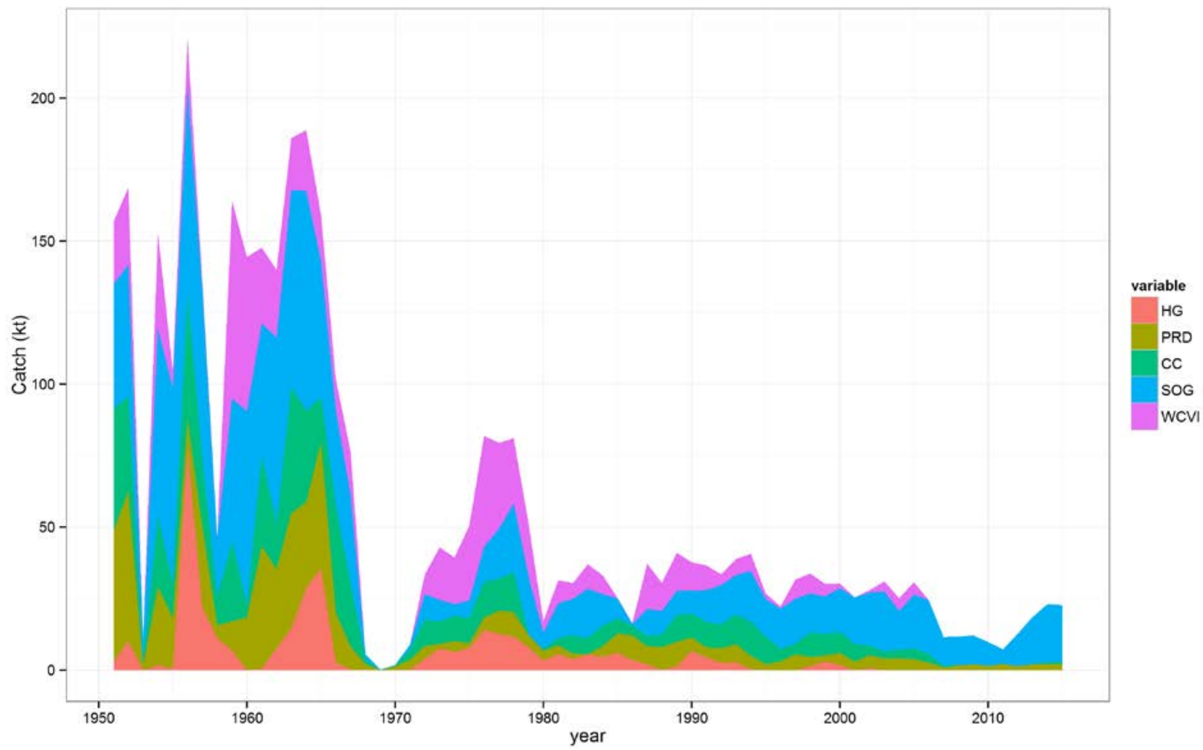

Figure 2. Stacked plots of coast-wide catch by area, in kilo-tonnes (kt).

Like the catches, the coast-wide spawning biomass has varied considerably since 1950. Following the reduction period, the coast-wide biomass was lowest in the mid-1960s. The highest coast-wide biomass occurred in the late 1970s. The second period of lowest biomass occurred between 2000 and 2010. While patterns of coast-wide biomass are similar between AM1 and AM2, each assessment model produces very different absolute coast-wide biomass estimates (Figure 3). Important to note is that reduction fishery catches include a high proportion of immature fish, fish which are not reflected in the spawning biomass presented in Figure 3.

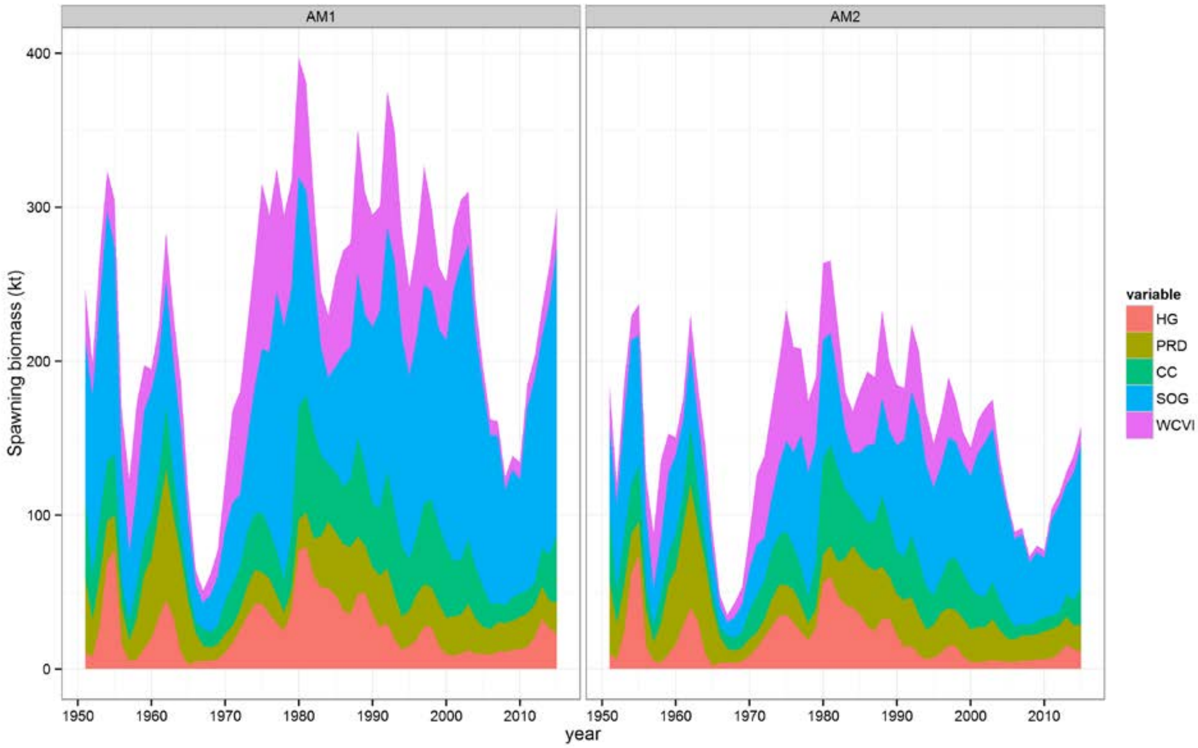

Figure 3. Stacked plots of coast-wide biomass estimates by area for AM1 (estimate q/estimate cut-off model) and AM2 (dive survey q is fixed at one/ fixed cut-offs).

Concurrent with variable total coast-wide biomass, the distribution of spawning biomass and catch between the major stock areas varied too. There are some differences between the estimates of each assessment model, but estimates of both show that before 1990 the coast-wide herring biomass was distributed more evenly between the major stock areas (Figure 3). During some periods, large proportions of the coast-wide spawning biomass occurred in both the WCVI and PRD areas (Figure 4). Since 1990, the proportion of the coast-wide spawning biomass in the Strait of Georgia has been progressively increasing, and both assessment models estimate that greater than 50% of the coast-wide spawning biomass occurs there (Figure 4). Associated with both fisheries closures and apparent changes in the relative distribution of the coast-wide spawning biomass, the proportion of coast-wide catch that comes out of the SOG stock has progressively increased from 25% in 1990 to greater than 75% in 2015 (Figure 4, top).

While there are some differences between estimates from AM1 and AM2, the trends are similar with the estimated median natural mortality having differed between the major stock areas in the last 15 years. In general, AM2 estimates natural mortality values that are less than current assessment model (AM1) with the mean biomass estimates from 2001-2015 being on average 3.9%, 1.4%, 6.1%, 17% and 5.5% less for AM2 than AM1 in each of the major stock areas, respectively.

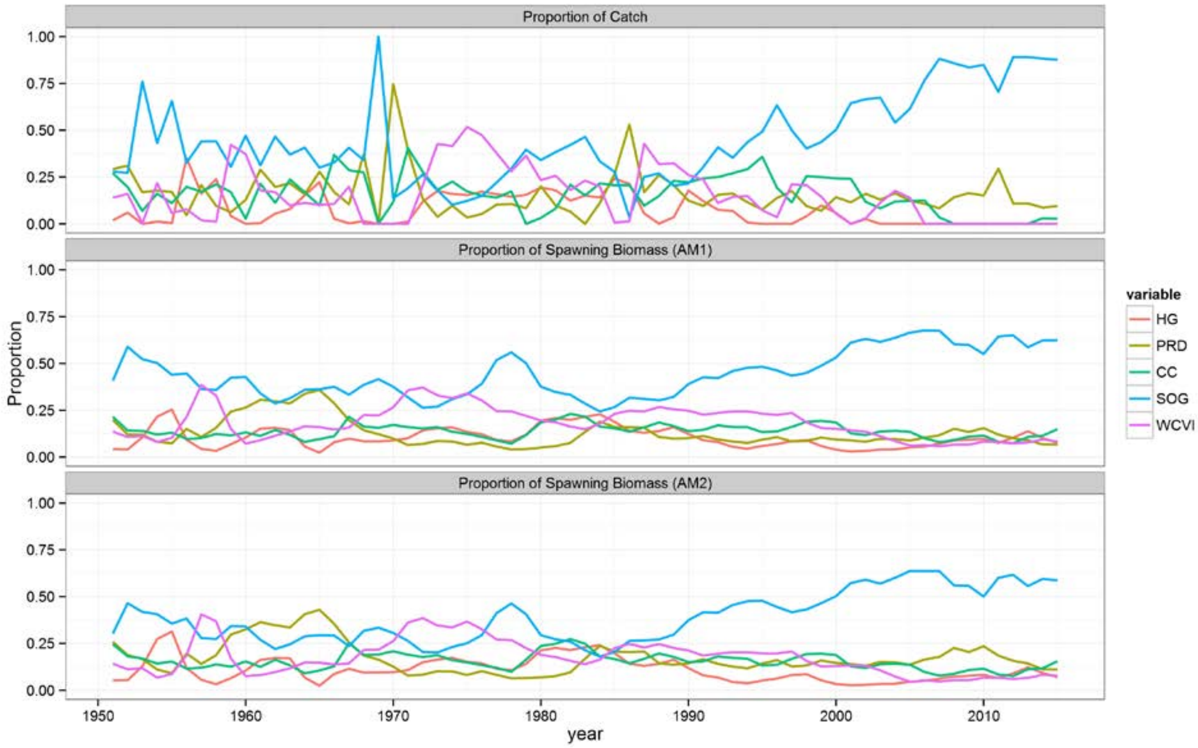

Figure 4. Proportion of spawning stock biomass between area estimated using AM1 (estimate q/estimate cut-off model) and AM2 (dive survey q is fixed at one/ fixed cut-offs) assessment models (bottom two panels) and proportion of total catches by area (top panel).

In all areas, estimated natural mortality increased for several years following the reduction period (Figure 5). Median natural mortality has been steadily declining in HG since 2004, and in 2015 was 0.63 and 0.62 for both assessment models (Figure 6 c). While there has been some oscillation up and down in the PRD, natural mortality has increased from a low of 0.27 (AM1) or 0.24 (AM2) in 1980, to maxima of 0.55 and 0.51 in 2015 for AM1 and AM2, respectively (Figure 7 c). Estimated CC natural mortality increased between 2001 and 2008 (from 0.46 to 0.92 with AM1 and from 0.38 to 0.88 using AM2) but is estimated to have declined steadily since then to 0.36 (AM1) and 0.35 (AM2) in 2015 (Figure 9 c). The SOG followed a similar pattern to the CC with natural mortality peaking in 2007 at 0.85 (AM1) and 0.71 (AM2), and a steadily declining since then (Figure 10 c). In the last 15 years, the estimated WCVI natural mortality has oscillated up and down, with the highest median natural mortality at 1.18 (AM1) or 1.10 (AM2) in 2006, and current estimates of 0.82 and 0.76, for AM1 and AM2, respectively (Figure 11 c). For all stocks, the uncertainty around the natural mortality estimates is very high in recent years, as evident in the 90% credible intervals (Figures 6 c, 7 c, 9 c – 11 c).

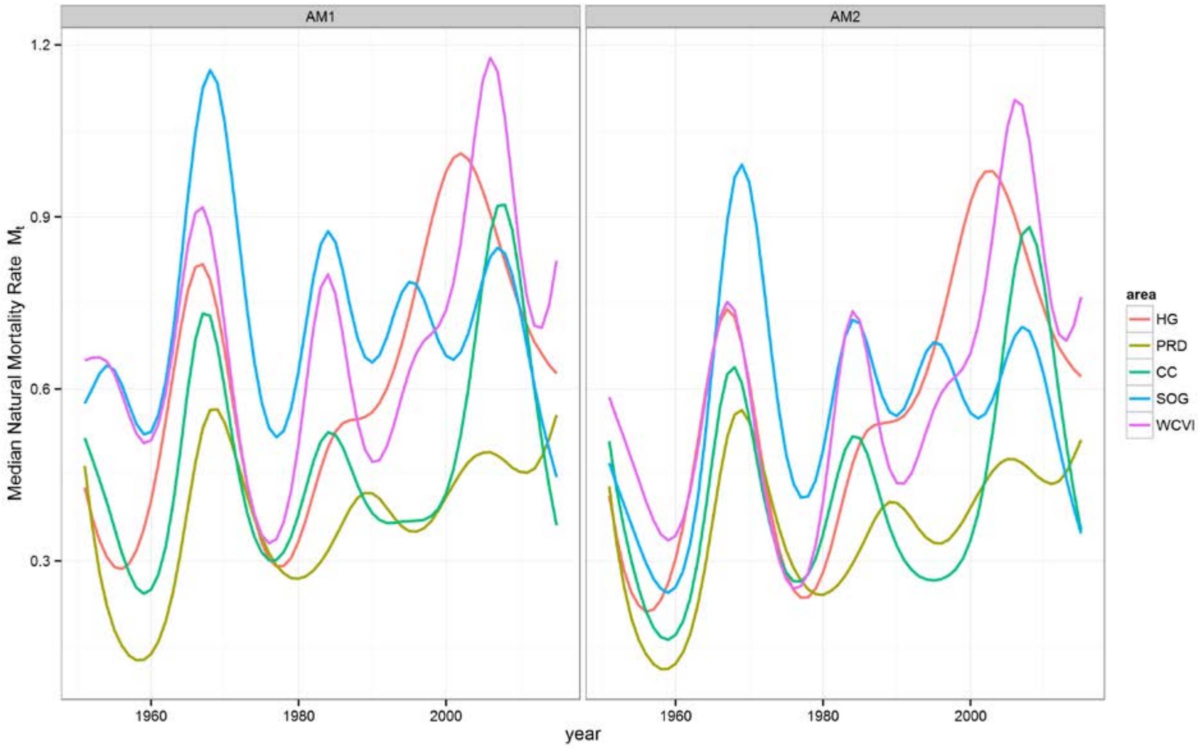

Figure 5. Time series of median posterior estimates of natural mortality rate for the major stock areas for AM1 (estimate q/estimate cut-off model) and AM2 (dive survey q is fixed at one/ fixed cut-offs) assessment models.

Table 2. Median estimates (with 5-95% credible interval) of spawning biomass (SB_t) for BC herring stocks, 2011-2015.

Stock	AM	2011	2012	2013	2014	2015
HG	AM1	13,265 (8,622-19,958)	20,150 (13,075-30,151)	31,518 (20,230-48,379)	26,536 (16,572-42,413)	23,354 (12,359-44,129)
	AM2	6,674 (4,997-8,888)	10,067 (7,556-13,430)	15,761 (11,524-21,621)	13,322 (9,388-19,719)	11,892 (6,574-21,320)
PRD	AM1	20,419 (13,798-30,470)	19,133 (12,975-28,558)	20,099 (13,635-30,122)	17,543 (11,641-27,338)	20,759 (11,291-38,357)
	AM2	18,550 (14,472-23,413)	17,418 (13,768-22,012)	18,658 (14,483-23,669)	16,521 (11,886-22,770)	19,728 (11,374-34,148)
CC	AM1	14,774 (10,494-20,930)	14,776 (10,429-20,616)	25,257 (17,583-35,730)	29,841 (19,717-43,846)	44,900 (26,913-71,461)
	AM2	8,687 (6,986-10,789)	8,550 (6,958-10,583)	14,383 (11,445-17,940)	16,482 (12,319-21,535)	24,823 (16,201-36,214)
CC Area 06,07	AM1	13,358 (9,346-19,152)	13,323 (9,369-19,187)	22,352 (15,346-32,682)	26,405 (17,235-40,272)	40,981 (24,598-67,309)
	AM2	7,924 (6,294-9,979)	7,859 (6,315-9,949)	13,039 (10,213-16,737)	14,818 (10,824-19,927)	23,126 (15,119-33,762)
SOG	AM1	108,829 (77,933-153,659)	120,670 (86,571-170,326)	126,136 (89,782-179,002)	150,746 (103,787-218,480)	174,687 (108,471-274,797)
	AM2	62,753 (53,135-73,187)	69,981 (59,220-81,735)	71,593 (59,660-84,642)	83,077 (65,502-103,617)	92,511 (63,421-130,815)
WCVI	AM1	14,130 (9,572-20,828)	14,273 (9,564-21,172)	17,742 (11,949-26,274)	24,102 (16,172-36,373)	25,338 (14,423-43,356)
	AM2	6,739 (5,179-8,657)	6,825 (5,196-8,756)	8,467 (6,502-10,825)	11,688 (8,654-15,619)	12,708 (7,667-20,725)
Area 2W	AM1	3,901 (2,263-6,564)	4,004 (2,309-6,948)	3,935 (2,100-7,407)	3,410 (1,471-7,577)	3,260 (856-8,929)
	AM2	1,671 (1,127-2,501)	1,715 (1,124-2,661)	1,693 (997-2,959)	1,485 (650-3,228)	1,428 (350-3,957)
Area 27	AM1	1,305 (845-2,085)	1,218 (775-1,978)	1,399 (871-2,323)	1,567 (965-2,637)	2,176 (1,206-3,875)
	AM2	1,080 (810-1,478)	1,017 (753-1,422)	1,180 (840-1,686)	1,305 (895-1,871)	1,738 (1,068-2,780)

Table 3. Median estimates (with 5-95% credible interval) of 2015 spawning biomass (SB_{2015}), unfished spawning biomass (SB_0), 0.25 SB_0, and the ratio SB_{2015}/ SB_0 for all BC herring stocks.

		Spawning biomass (SB_{2015})			Unfished biomass (SB_0)			0.25*SB_0			Median ratio of spawning biomass to unfished equilibrium spawning biomass (SB_{2015}/SB_0)		
Stock	AM	5th %ile	Median	95th %ile	5th %ile	Median	95th %ile	5th %ile	Median	95th %ile	5th %ile	Median	95th %ile
HG	AM1	12,359	23,354	44,129	25,908	34,176	46,779	6,477	8,544	11,695	0.37	0.68	1.24
	AM2	6,574	11,892	21,320	20,480	26,305	35,806	5,120	6,576	8,952	0.25	0.44	0.81
PRD	AM1	11,291	20,759	38,357	47,085	60,487	89,739	11,771	15,122	22,435	0.18	0.33	0.63
	AM2	11,374	19,728	34,148	46,217	60,571	94,201	11,554	15,143	23,550	0.17	0.32	0.55
CC	AM1	26,913	44,900	71,461	48,163	60,348	78,987	12,041	15,087	19,747	0.45	0.74	1.16
	AM2	16,201	24,823	36,214	43,177	53,523	70,172	10,794	13,381	17,543	0.29	0.46	0.69
CC Area 06,07	AM1	24,598	40,981	67,309	43,420	54,436	70,412	10,855	13,609	17,603	0.46	0.75	1.20
	AM2	15,119	23,126	33,762	39,933	49,826	66,371	9,983	12,456	16,593	0.29	0.46	0.70
SOG	AM1	108,471	174,687	274,797	116,426	143,013	185,613	29,107	35,753	46,403	0.79	1.22	1.79
	AM2	63,421	92,511	130,815	99,844	117,655	151,556	24,961	29,414	37,889	0.51	0.78	1.13
WCVI	AM1	14,423	25,338	43,356	45,780	57,143	72,721	11,445	14,286	18,180	0.26	0.44	0.72
	AM2	7,667	12,708	20,725	36,790	44,440	55,484	9,198	11,110	13,871	0.17	0.28	0.47
Area 2W	AM1	856	3,260	8,929	1,940	3,219	5,893	484	805	1,473	0.31	1.01	2.36
	AM2	350	1,428	3,957	1,187	1,924	3,477	297	481	869	0.20	0.72	1.86
Area 27	AM1	1,206	2,176	3,875	1,526	2,185	3,292	382	546	823	0.58	0.99	1.68
	AM2	1,068	1,738	2,780	1,410	1,830	2,362	352	458	591	0.56	0.95	1.60

Table 4. Estimates of projected pre-harvest spawning biomass in 2016 given zero catch, and predicted proportions of fish of age-3 and of ages 4-10 for all BC herring stocks.

		Projected proportion age-3 fish in 2016			Projected proportion ages 4-10 fish in 2016			Projected pre-harvest spawning biomass (SB_{2016}) given zero catch		
Stock	MP	5^{th} %ile	Median	95^{th} %ile	5^{th} %ile	Median	95^{th} %ile	5^{th} %ile	Median	95^{th} %ile
HG	AM1	0.12	0.21	0.32	0.46	0.66	0.78	9,732	19,795	40,732
	AM2	0.11	0.20	0.30	0.41	0.65	0.78	5,266	10,450	20,870
PRD	AM1	0.29	0.47	0.66	0.28	0.44	0.63	13,530	26,580	52,452
	AM2	0.28	0.47	0.65	0.28	0.45	0.64	13,439	25,530	48,531
CC	AM1	0.08	0.24	0.53	0.39	0.67	0.85	24,780	44,210	76,944
	AM2	0.09	0.27	0.56	0.37	0.63	0.83	15,310	25,570	42,401
	AM3	-	-	-	-	-	-	-	*32,772*	-
CC Area06,07	AM1	0.08	0.23	0.53	0.40	0.68	0.86	22,900	40,945	72,782
	AM2	0.09	0.26	0.56	0.36	0.64	0.84	14,470	24,170	40,412
	AM3	-	-	-	-	-	-	-	*30,473*	-
SOG	AM1	0.37	0.46	0.54	0.38	0.46	0.54	129,100	217,800	355,405
	AM2	0.35	0.43	0.52	0.41	0.49	0.56	80,270	123,000	183,405
WCVI	AM1	0.42	0.57	0.68	0.19	0.28	0.37	18,560	34,450	62,873
	AM2	0.40	0.55	0.67	0.19	0.28	0.37	10,040	17,830	32,043
Area 2W	AM1	0.03	0.06	0.12	0.74	0.90	0.95	626	2,834	9,019
	AM2	0.03	0.06	0.12	0.72	0.90	0.95	253	1,255	4,124
Area 27	AM1	0.08	0.24	0.54	0.40	0.68	0.68	1,217	2,348	4,538
	AM2	0.08	0.24	0.55	0.38	0.68	0.87	1,094	1,885	3,288

Projection Results and Decision Tables

Projected pre-harvest spawning biomasses, assuming zero catch in 2016, and the relative contribution of fish of age-3 and ages 4-10 are presented in Table 4. Advice to managers for 2016 for each stock area is presented in the stock-specific sections as a two sets of decision tables, one for each assessment model (AM1 and AM2). Tables for AM1 provide probabilities of the projected pre-harvest spawning biomass in 2016 (SB_{2016}) falling below the 0.25 SB_0 level (estimated annually), and of the harvest rate exceeding the 20% and 10% target rates for a range of constant catch levels. Tables representing AM2 provide probabilities of the projected pre-harvest spawning biomass in 2016 (SB_{2016}) falling below the historically used stock-specific fixed cut-off levels (calculated as 0.25 SB_0 in 1996), and of the harvest rate exceeding the 20% and 10% target rates for a range of constant catch levels.

As an example of how to read the tables for the five major stock areas (HG, PRD, CC, SOG, WCVI), using AM1 (Table 5, Left): Given a catch of 1,700 t from HG, the estimated probability that the harvest rate (U') exceeds the 20% target rate is 0.02 (2.0%), the ratio of SB_{2016}/0.25 SB_0 value is 2.17, and the probability that SB_{2016} < 0.25 SB_0 is estimated to be 0.04 (4%). Under the assumptions of AM2 (Table 5, Right), given the same catch of 1,700 t from HG, the estimated probability that the harvest rate (U') exceeds the 20% target rate is 0.25 (25%), and the probability that SB_{2016} < fixed cut-off (10,700 t) is estimated to be 0.62 (62%).

Decision tables for the minor stocks (Area 2W, Area 27) provide probabilities of the harvest rate exceeding the 10% target rate for a range of constant catch levels and do not include biomass performance metrics because they are not used in the control rule for minor herring stocks.

Haida Gwaii

In 2015, biological samples were collected by a seine test charter vessel funded by the DFO. The primary purpose of the test charter vessel was to collect biological samples from main aggregations of herring from Haida Gwaii major (priority) and the Area 2W minor stock, identified from soundings. The vessel operated from March 9th to April 2nd, collecting samples from HG and Area 2W. The spawn reconnaissance vessel operated from March 30th to April 17th, and the dive charter vessel from March 29th to April 21st. A total of 11 biological samples were collected in the HG major stock area.

Haida Fisheries Program conducted the herring spawn dive surveys in Haida Gwaii from March 29 to April 21 aboard the Lasqueti Explorer. In addition to the test charter and spawn data collections programs, there were several general observations made during the data collection operations and locally. The herring spawn in Haida Gwaii was unusual this year compared to last in terms of both spawn duration and location. The spawn occurred over a very short time period from the 27th to the 31st of March, with no new spawn discovered after. This was a very unusual pattern for Haida Gwaii, which typically sees an extended spawning period across different areas. Compared to last year, the duration of spawning activity over Area 02E was considerably shorter and less intense. The spawn located and surveyed covered a total of 41.75 km of substrate. Far less wildlife was attracted by the spawn: the largest group of sea lions only numbered 5, by Alder Island whereas in 2014 groups of over 50 in Harriet Harbour were observed. Herring survey operations also observed a high amount of what resembled fungus on the spawn. It had a white, ‘gloopy’ texture, which when agitated caused the top layer of eggs to detach from the rest. This was mostly noted in shallower depths. The fungus was not limited to patches of dead eggs, but appeared to be in the middle of live eggs, spreading and consequently causing mortality of eggs underneath it. Spawn coverage was lighter in layers. In general, Haida traditional harvest of spawn on kelp in the major stock area was tiny, if at all, especially compared to 2014. Throughout the area, warmer water temperatures than usual were observed. This is consistent with NOAA observations that showed a large warm water anomaly over much of the west coast of British Columbia in early 2015.

The time series of spawn survey data for the HG major stock appears to be increasing overall from 2005-2015 (Figure 6 a, Table A.1). This trend is also tracked by the trend in spawn length (not shown). Both assessment models estimate the stock to have declined from 2013 to 2015 (Figure 6 d, Table 2). While the model fits the most recent observation, it does not fit the 2014 observation, and instead estimates a downward trajectory since 2013. AM1 estimates the median spawning biomass in 2015 (SB_{2015}) at 23,354 t and SB_{2015} is estimated to be 68% (median) of the unfished level, SB_0 (Table 2 and 3). AM2 estimates the median spawning biomass in 2015 (SB_{2015}) at 11,892 t and 44% of SB_0. The pattern of biomass estimates for AM2 is similar to that of AM1, however AM2 estimates of spawning biomass in 2015 (SB_{2015}) and stock status relative to SB_0 are lower than the AM1 estimates (Tables 2 and 3).

Both AM1 and AM2 project a decline in median spawning biomass in 2016. AM1 projects the median pre-harvest spawning stock biomass in 2016 at 19,795 t, consisting of 21% (median) age-3 fish and 66% (median) age-4 and older fish (Table 4). AM2 projects the median pre-harvest spawning stock biomass at 10,450 t (Table 4). Projected proportions of age-3 and age-4 and older fish are near-identical using AM2. At the root of the declines in projected spawning stock biomass, using both stock assessment models, is that recruitment in 2013 and 2015 is estimated to be below average (Figure 6 b), so that recruitment is not replacing losses to the biomass from natural mortality. In the absence of fishing, AM1 estimates that there is a 2% probability the stock will be below the cut-off of 25% SB_0 in 2016 and AM2 estimates a 52% probability of being below the fixed cut-off level of 10,700 t in 2016 (Table 5).

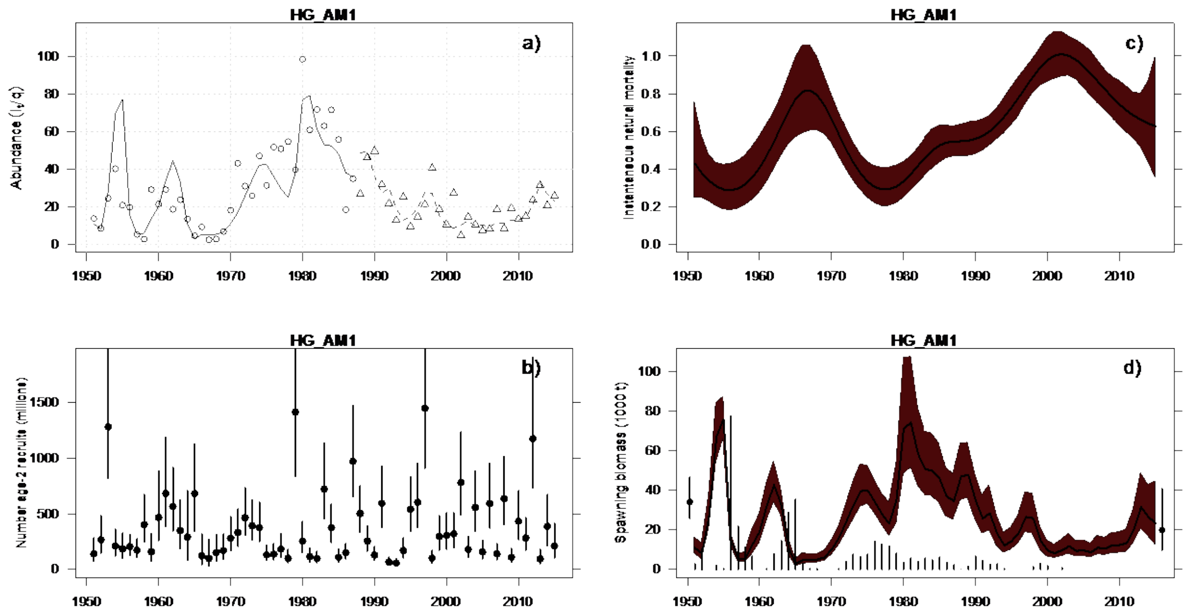

Figure 6. Model outputs for Haida Gwaii, AM1. Model fits to the spawn index, scaled by q (a), estimated recruitment (b), estimated natural mortality (c), and estimated spawning biomass (d) for the HG stock (AM1) from 1951 to 2015. Open circles and open triangles reflect time series of surface (1951-1987) and dive (1988-2015) survey data. Index values reported in Appendix, Table A-1. Solid circles with vertical lines, and solid lines with surrounding pink envelopes, represent medians and 5-95% credible intervals. Upper left panel (a) shows model fit to time series of spawn survey data; Lower left panel (b) shows the reconstruction of number of age-2 recruits (millions); Upper right panel (c) shows the reconstruction of instantaneous natural mortality; Lower right panel (d) shows the reconstruction of spawning biomass (SB_t) for each year t, with unfished values (SB_0) shown at far left (solid circle and vertical lines) and the projected pre-harvest spawning biomass given zero catch (SB_{2016}) using AM1 shown at the far right (solid circle and vertical lines). Time series of thin vertical lines denote commercial catch (excluding commercial SOK). Model outputs from AM2/ AM2 show similar trends with lower numeric values (Tables 2-4). Figures not included.

*Table 5. Decision tables concerning the harvest and biomass metrics drawn from **AM1** (left) and **AM2** (right) for projected spawning biomass in 2016, given a range of total allowable catch (TAC) (in tonnes) for **Haida Gwaii**. Probabilities are estimated using the proportion of the MCMC samples for which the given criteria hold. One-year projections for HG use catch allocation ratios for each of the three fisheries (F&B/ SU, seine roe and gillnet roe) based on 20-year historical average catches.*

*Left (**AM1**): Values are probabilities, under each TAC level, of the post-harvest spawning biomass in 2016 (SB_{2016}) falling below 0.25 SB_0, and of the harvest rate (HR) being greater than 20% or 10%.*

*Right (**AM2**): Values are probabilities, under each TAC level, of the post-harvest spawning biomass in 2016 (SB_{2016}) falling below fixed cut-off of 10,700 t, and of the harvest rate (HR) being greater than 20% or 10%.*

Haida Gwaii (HG)						Haida Gwaii (HG)					
	Biomass metrics – AM1		**Harvest metrics – AM1**				**Biomass metrics – AM2**		**Harvest metrics – AM2**		
TAC (metric tonnes)	Prob (biomass after harvest is below 0.25 SB_0 in 2016) P(SB_{2016} < 0.25 SB_0)	Median ratio of projected post-harvest biomass to 0.25 SB_0 Med (SB_{2016} / 0.25 SB_0)	Prob (removal rate > target HR) P(U'2016 > 20%)	Prob (removal rate > target HR) P(U'2016 > 10%)	Median removal rate Med (U'2016)	TAC (metric tonnes)	Prob (biomass after harvest is below cut-off in 2016 P(SB_{2016} < 10,700 t)	Median ratio of projected post-harvest biomass to cut-off Med (SB_{2016} / 10,700 t)	Prob (removal rate > target HR) P(U'2016 > 20%)	Prob (removal rate > target HR) P(U'2016 > 10%)	Median removal rate Med (U'2016)
0	0.02	2.30	0.00	0.00	0.00	0	0.52	0.98	0.00	0.00	0.00
500	0.03	2.26	0.00	0.00	0.03	500	0.55	0.94	0.00	0.03	0.05
820	0.03	2.24	0.00	0.02	0.04	820	0.57	0.92	0.01	0.25	0.08
1,000	0.03	2.22	0.00	0.05	0.05	1,000	0.58	0.91	0.02	0.42	0.09
1,080	0.03	2.22	0.00	0.07	0.05	1,080	0.58	0.91	0.04	0.50	0.10
1,540	0.04	2.18	0.01	0.25	0.08	1,540	0.61	0.88	0.18	0.80	0.14
1,700	0.04	2.17	0.02	0.34	0.08	1,700	0.62	0.87	0.25	0.87	0.15
2,000	0.04	2.14	0.04	0.48	0.10	2,000	0.64	0.85	0.39	0.93	0.18
2,040	0.05	2.14	0.04	0.50	0.10	2,040	0.64	0.85	0.41	0.94	0.18
2,230	0.05	2.13	0.07	0.58	0.11	2,230	0.65	0.84	0.50	0.96	0.20
3,000	0.06	2.07	0.21	0.81	0.14	3,000	0.69	0.79	0.76	0.99	0.26
3,170	0.06	2.05	0.25	0.84	0.15	3,170	0.69	0.78	0.80	0.99	0.27
4,000	0.08	1.99	0.45	0.94	0.19	4,000	0.73	0.73	0.92	1.00	0.34
4,230	0.08	1.97	0.50	0.95	0.20	4,230	0.74	0.72	0.94	1.00	0.35
6,000	0.12	1.84	0.79	0.99	0.27	6,000	0.79	0.62	0.99	1.00	0.48

Prince Rupert District

Because there were commercial fisheries in the PRD (2,163 t), there are more biological samples relative to the adjacent closed areas. There were a total of 51 samples processed for PRD; 11 test samples and 40 commercial fishery samples. Test charter vessels collected samples in both Big Bay and Kitkatla, through the latter two weeks of March. Following patterns seen on the rest of the coast, the mean weight at age observed in these samples supports an increasing trend in mean weight at age for herring (Figure 1).

A 20-day dive survey measured a total of 59.8 linear kilometers of spawn from late-March through mid-April. There was a modest increase in the dive survey index in 2015, to 17,408 t, up from 17,125 t in 2014 (Table A.1). While the total spawn length and number of egg layers were comparable to 2014, the average spawn width declined from 123 to 105 m, and the average number of eggs layers increased from 0.46 to 0.49. The trend in the biomass estimates from 2014 to 2015 is comparable to the recent dive survey index values (Table A.1). Both AM1 and AM2 estimate a relatively large recruitment of age 2 fish to the population in 2015 (Figure 7 b) owing in large part to the age composition information showing a high proportion of samples consisting of this age class. The median AM1 estimate of the 2015 spawning biomass is 20,759 tonnes, relative to 17,541 in 2014 (Table 2). AM2 shows a similar pattern of increase going from 16,521 in 2014 to 19,728 tonnes in 2015. Stock status in 2015 is estimated at 33% (AM1) and 32% (AM2) of the unfished level (Table 3). Both AM1 and AM2 project an increase in spawning stock biomass from 2014 to 2015. AM1 and AM2's median estimates of spawning stock biomass were 20,759 and 19,728 tonnes in 2015, and both models project an increase in the stock's pre-harvest spawning biomass, with median SB_{2016} values of 26,580 and 25,530 tonnes, respectively (Table 4). The probabilities of being below cut-off, and of achieving selected harvest rates for a range of catch levels for the PRD major stock area for both AM1 and AM2 are reported in Table 6. When comparing predictions from AM1 and AM2, unlike the other stock areas, AM1 predicts a higher probability of being below the $0.25SB_0$ level (when estimating q), and AM2 predicts a lower probability of being below the fixed cut-off of 12,100 t (with q=1) for the same proposed catch. In the absence of fishing, AM1 predicts a 10% probability the PRD stock will be below the $0.25SB_0$ level, and AM2 predicts a 3% probability of being below the fixed cut-off level of 12,100 t.

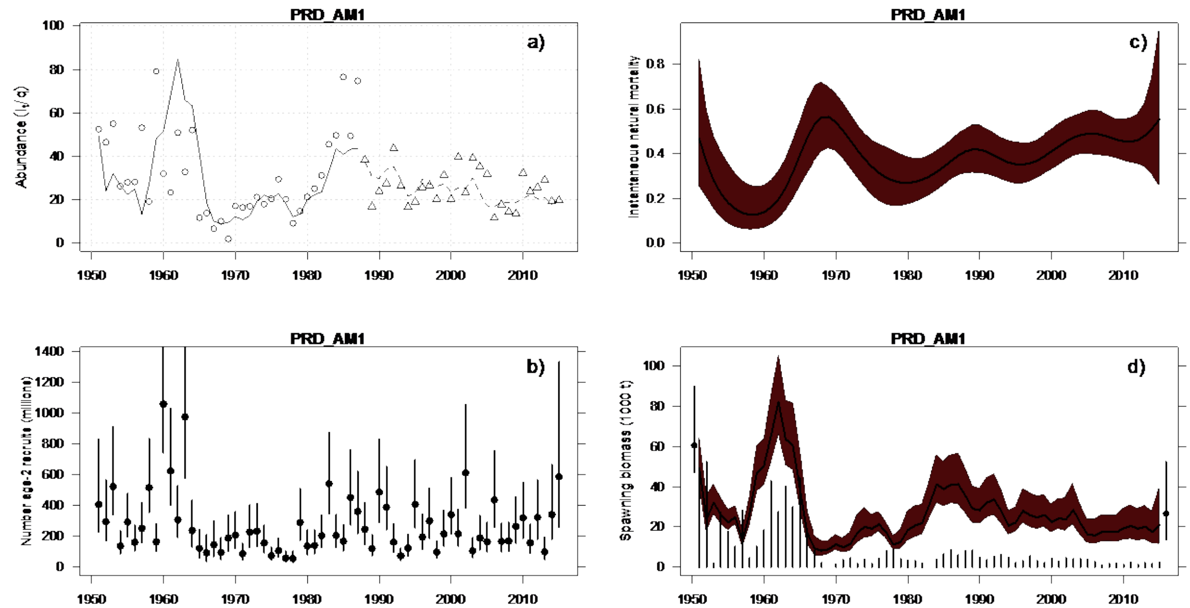

Figure 7. Model outputs for Prince Rupert District, AM1. See detailed description in Figure 6.

*Table 6. Decision tables concerning the harvest and biomass metrics drawn from **AM1** (left) and **AM2** (right) for projected spawning biomass in 2016, given a range of total allowable catch (TAC) (in tonnes) for **Prince Rupert District**. Probabilities are estimated using the proportion of the MCMC samples for which the given criteria hold. One-year projections for PRD use catch allocation ratios for each of the three fisheries (F&B/ SU, seine roe and gillnet roe) based on 20-year historical average catches.*

*Left (**AM1**): Values are probabilities, under each TAC level, of the post-harvest spawning biomass in 2016 (SB_{2016}) falling below 0.25 SB_0, and of the harvest rate (HR) being greater than 20% or 10%.*

*Right (**AM2**): Values are probabilities, under each TAC level, of the post-harvest spawning biomass in 2016 (SB_{2016}) falling below fixed cut-off of 12,100 t, and of the harvest rate (HR) being greater than 20% or 10%.*

Prince Rupert District (PRD)						Prince Rupert District (PRD)					
Biomass metrics – AM1			Harvest metrics – AM1			Biomass metrics – AM2			Harvest metrics – AM2		
TAC (metric tonnes)	Prob (biomass after harvest is below 0.25 SB_0 in 2016) P(SB_{2016} < 0.25 SB_0)	Median ratio of projected post-harvest biomass to 0.25 SB_0 Med (SB_{2016} / 0.25 SB_0)	Prob (removal rate > target HR) P(U'2016 > 20%)	Prob (removal rate > target HR) P(U'2016 > 10%)	Median removal rate Med (U'2016)	TAC (metric tonnes)	Prob (biomass after harvest is below cut-off in 2016 P(SB_{2016} < 12,100 t)	Median ratio of projected post-harvest biomass to cut-off Med (SB_{2016} / 12,100 t)	Prob (removal rate > target HR) P(U'2016 > 20%)	Prob (removal rate > target HR) P(U'2016 > 10%)	Median removal rate Med (U'2016)
0	0.10	1.72	0.00	0.00	0.00	0	0.03	2.11	0.00	0.00	0.00
2,010	0.14	1.62	0.01	0.22	0.07	2,010	0.05	1.98	0.01	0.25	0.08
2,090	0.14	1.62	0.01	0.25	0.08	2,090	0.05	1.98	0.01	0.29	0.08
2,500	0.15	1.60	0.02	0.41	0.09	2,500	0.06	1.95	0.02	0.45	0.10
2,610	0.15	1.59	0.03	0.45	0.10	2,610	0.06	1.95	0.03	0.50	0.10
2,700	0.15	1.59	0.03	0.49	0.10	2,700	0.06	1.94	0.04	0.53	0.10
2,725	0.15	1.59	0.04	0.50	0.10	2,725	0.06	1.94	0.04	0.54	0.10
3,000	0.16	1.57	0.06	0.59	0.11	3,000	0.06	1.92	0.06	0.63	0.11
4,125	0.19	1.52	0.22	0.84	0.15	4,125	0.08	1.85	0.25	0.87	0.16
4,300	0.19	1.51	0.25	0.86	0.16	4,300	0.09	1.84	0.28	0.89	0.16
5,000	0.21	1.48	0.38	0.93	0.18	5,000	0.10	1.80	0.43	0.95	0.19
5,400	0.22	1.46	0.46	0.95	0.19	5,400	0.11	1.77	0.50	0.97	0.20
5,600	0.23	1.45	0.50	0.96	0.20	5,600	0.12	1.76	0.54	0.98	0.21
6,000	0.24	1.43	0.56	0.97	0.21	6,000	0.12	1.74	0.61	0.99	0.22
8,000	0.29	1.34	0.80	1.00	0.28	8,000	0.17	1.62	0.83	1.00	0.29

Central Coast

The Central Coast (CC) stock assessment region was historically delineated based on the combination of the distribution of spawning areas, and results of tagging studies and genetic analyses. Areas 06, 07, and 08 were grouped together into a management area following the reduction fishery period, because a significant portion of CC catch originated from each of these areas during that time. However, Area 08 has typically had fish that were smaller at age and, although a small SOK fishery currently occurs in this area, Area 08 has been of limited interest to the commercial roe or special use sectors over the past several decades. The CC has been open for commercial fishing for 30 of the 36 years from 1980-2015. During that period, commercial fishing (non-SOK) occurred in Area 08 in 3 years, with annual catches all less than 100 tonnes.

Area 08 has historically made up around 10% of Central Coast assessed biomass, with 91% of spawn on average occurring in Areas 06 and 07 (average from 1980-2015). The inclusion of Area 08 in the Central Coast assessment area was identified by the HTC-DFO Technical Team as an area of concern for First Nations. Specifically, concern was raised as to whether the process of including spawn from Area 08 in the aggregate CC spawning biomass has resulted in Areas 06 and 07 being fished more heavily than would be expected based on their relative contribution to the aggregate CC spawning biomass. A full study on stock structure, including review/re-evaluation of historical tagging and genetics data, and life history differences in the Central Coast assessment area is beyond the scope of this document. However, as a starting point investigate to what degree the available size at age data support the continued inclusion of Area 08 in the Central Coast assessment is investigated. Size data (fish weight) from Area 08 are consistently smaller on average than fish of the same age found in Areas 06 or 07. While this distinction in weight at age was clearly apparent for 1996 – 2005 (left panel in Figure 8), it has become more pronounced in the recent decade (right panel in Figure 8). The hypothesis that the fish in Area 08 are part of a single, well-mixed ‘Central Coast’ stock predicts that weight at age distributions within all three statistical areas should be similar. The weight at age data provides evidence to suggest that the stocks in Area 08 may be distinct from those in Area 06 and 07, an observation that merits further investigation. In light of this information and past patterns of removals occurring in Areas 06 and 07 only, and because these analyses were specifically requested, estimates of spawning stock biomass and pre-harvest projections, and decision tables for 2016 for Central Coast herring appear under two scenarios: inclusion and exclusion of Area 08 data. These appear as CC and CC_Area06,07 in Tables 2-4 and 7-10.

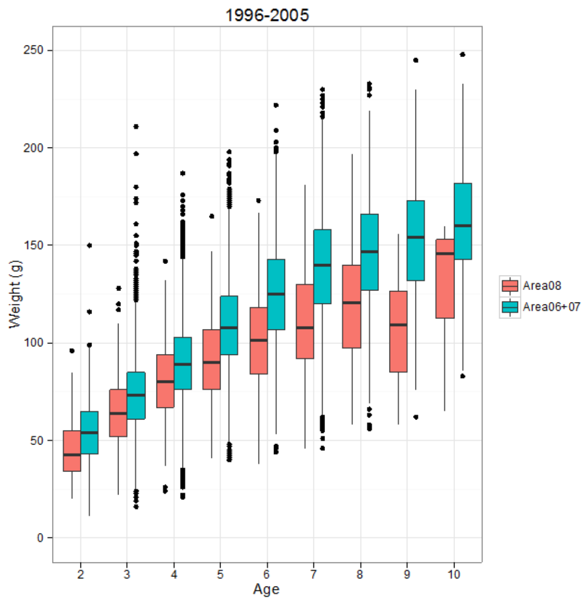

Figure 8. Distribution of weight at age for Central Coast herring by area, 1996-2005 (left) and 2006-2015 (right).

In 2015, the Heiltsuk operated 3 gillnet sounding vessels for 14 days each, and the FV *Kwiaahwah* as an in-season sounding/ biological sampling vessel for 21 days, identifying areas of high and low herring biomass, and collecting biological samples in Areas 06, 07 and 08 from pre-spawning aggregations. The Heiltsuk herring stock assessment projects have been funded by DFO though Aboriginal Fisheries Strategy (AFS) agreements.

In 2014 and 2015, the *Kwiaahwah* collected biological samples for the DFO stock assessment program, and to support new research initiatives occurring at SFU and UBC. Area 08 is a small section of the CC stock area and, in the recent most 2 years, a high number of samples were collected in Area 08. In order to ensure consistency in the calculation of average weight at age and numbers at age for the CC stock across years, the Area 08 samples were weighted by the average proportion of samples from this area over the past 10-years. The vessel operated from March 15th to April 3rd and collected 14 samples from the CC stock area. An additional 6 samples were collected from commercial fisheries.

Yields from FSC and commercial SOK fisheries were poor overall for the 2015 season. Fishers generally found average spawn thickness to be very low, and egg size to be on the small side. SOK fishers spend a large amount of time and effort setting kelp at various depths and in various locations in attempts to match spawning patterns, but with limited success. While some good product was landed, overall yield and product quality was mostly poor. There was also very little FSC harvest, in spite of considerable effort, with locals having to rely on trimmings from the SOK fishery to compensate for failed FSC harvests. While local observations confirm that abundance of spawners has been gradually rebuilding in areas such Stryker and Waskisu, Heiltsuk fishers report spawn to be still completely absent or well below normal in many areas that historically have been important harvesting sites and are, therefore, of key interest to the Heiltsuk, including Stryker, Houghton islands, Cape Mark, and St Johns.

The 2015 spawning season was unusual in several respects. Heiltsuk fishers report that spawn occurred in unexpected locations and was much deeper than in previous years. Additional observations include a general increase in predator sightings, in 2015 reflecting a continuing trend in increased predator sighting in recent years , as well as the presence of a fungal or bacterial mat on the eggs with a white, ‘gloopy’ texture similar to what was reported in Haida Gwaii.

Two dive survey charters operated in the CC stock area, surveying a total of 163.4 linear kilometers of herring spawn between March 8 and April 23. The time series of spawn survey data for the CC aggregate stock (Area 06,07,08) increased from 7,592 t in 2012 to 20,359 t in 2013, declined to 13,309 t in 2014, and increased to 32,146 t in 2015 (Table A.1).

Although the recent estimates of biomass do not match spawn index data precisely, both assessment models estimate the aggregate stock to have been increasing since 2012 (Figure 9 d, Table 2). The model does not exactly fit the most recent spawn index, however, it does fit 2013 and 2014 (Figure 9 a). These observations are consistent across scenarios of including/ excluding Area 08 data. Under the scenario of aggregating all CC data, the median estimates of spawning biomass in 2015 (SB_{2015}) for AM1 and AM2 are 44,900 t and 24,832 t, and SB_{2015} is estimated to be 74% and 46% of the unfished level, SB_0 (Table 2 and 3). Under the scenario of excluding the Area 08 data from the CC assessment, the median estimates of spawning biomass in 2015 (SB_{2015}) for AM1 and AM2 40,981 t and 23,126 t and SB_{2015} is estimated to be 75% and 46% of SB_0 (Table 2 and 3). The pattern of biomass estimates for AM2 is similar to that of AM1, however AM2 estimates of spawning biomass in 2015 (SB_{2015}) and stock status relative to SB_0 are lower than the AM1 estimates (Tables 2 and 3).

Projected biomass for 2016 is almost identical to the biomass estimates for 2015. This holds for both AM1 and AM2, and is true irrespective of whether Area 08 is included or excluded from the assessment area. Under the scenario of aggregating all CC data, AM1 projects the median pre-harvest spawning stock biomass in 2016 at 44,210 t, consisting of 24% (median) age-3 fish and 67% (median) age-4 and older fish (Table 4). AM2 projects the median pre-harvest spawning stock biomass as 25,570 t (Table 4). Projected proportions of age-3 and age-4 and older fish are near-identical using AM2. Under the scenario of excluding the Area 08 data from the CC assessment, AM1 projects a median pre-harvest spawning stock biomass in 2016 of 40,945 t, consisting of 23% (median) age-3 fish and 68% (median) age-4 and older fish (Table 4). AM2 projects a median pre-harvest spawning stock biomass of 24,170 t (Table 4). Again, projected proportions of age-3 and age-4 and older fish are near-identical using AM1 and AM2.

To calculate the fixed cut-off for the excluded Area 08 data scenario, the area-specific proportions of spawning observed by the dive survey since 1980 was examined. An average of 91% of herring spawn was observed in Area 06 and 07 since 1980, thus the fixed cut-off by this proportion was adjusted. Accordingly, for AM2, a fixed cut-off of 16,016 t; reflecting 91% of the CC fixed cut-off level used from 1996-2011 was used. In the absence of fishing, AM1 estimates that there is a 0% probability the stock will be below the cut-off of 25% SB_0 in 2016 (under both data scenarios, Tables 7 and 8). AM2 estimates a 12% and 16% probability of being below fixed cut-off levels of 17,600 t and 16,016 t in 2016 (include and exclude Area 08, respectively, Tables 7 and 8).

Decision tables for CC herring include an alternate cut-off of 0.60 SB_0 and harvest rates of 5%, 10% and 20%, as was requested through the HTC-DFO Technical Team. This alternate cut-off reflects Heiltsuk concerns about continuing poor FSC harvests, as well as continuing absence of spawners from many of the traditional spawning areas of importance to the Heiltsuk. An extended period of relatively high abundance may be required to prompt re-colonization of these areas. Also, following from the May 2015 CSAS meeting, there was a request to use an empirical biomass forecasting methodology, calculated as:

$$\text{forecast biomass } (SB_{2016}) = \text{spawn index } (I_{2015}) + \text{catch } (C_{2015})$$

Using this method, the pre-harvest spawning biomass for 2016 is estimated as 32,772 t (Area 06,07,08) or 30,473 t (Area 06,07 only; Table 4). A 10% harvest rate was also requested, and application of this harvest rate would prescribe a TAC of 3,277 t and 3,047 t (include and exclude Area 08, respectively). The long-term performance of this alternate forecasting method and harvest decision rule is explored in Part 2.

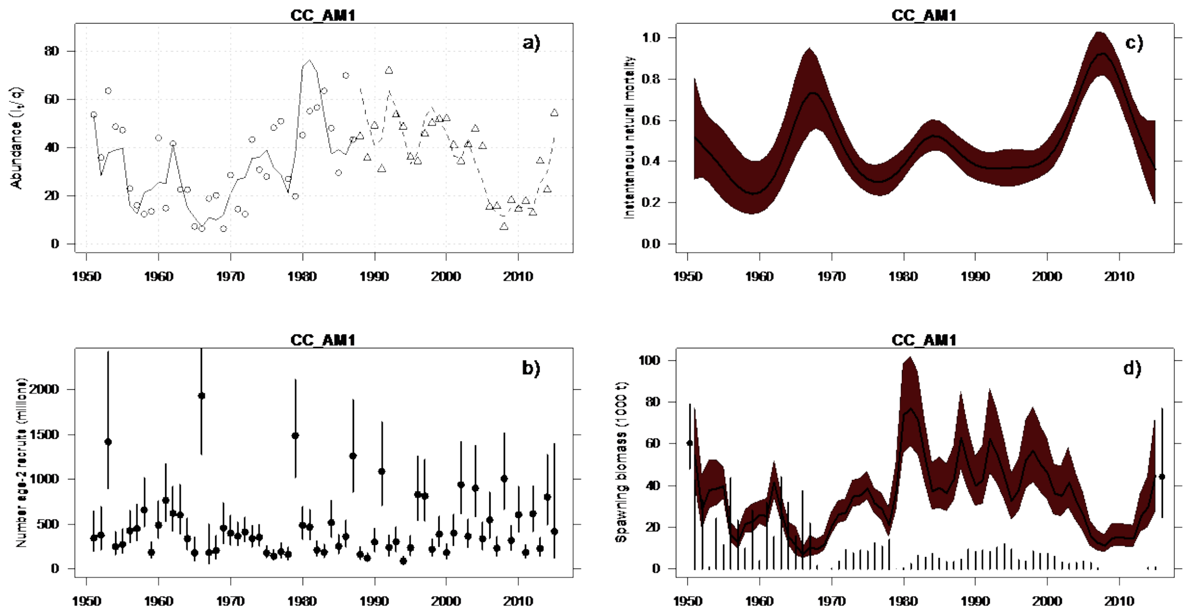

Figure 9. Model outputs for the Central Coast aggregate stock (Areas 06,07,08), AM1. See detailed description in Figure 6. Model outputs from Central Coast (Area 06,07 only) produce similar results to the aggregate stock (under both AM1 and AM2). Figures not included.

*Table 7. Decision tables concerning the harvest and biomass metrics drawn from **AM1** (top) and **AM2** (bottom) for projected spawning biomass in 2016, given a range of total allowable catch (TAC) (in tonnes) for **Central Coast (aggregate stock- Area 06,07,08)**. Probabilities are estimated using the proportion of the MCMC samples for which the given criteria hold. One-year projections for CC use catch allocation ratios for each of the three fisheries (F&B/ SU, seine roe and gillnet roe) based on 20-year historical average catches. Top (**AM1**): Values are probabilities, under each TAC level, of the post-harvest spawning biomass in 2016 (SB_{2016}) falling below 0.25 SB_0, and of the harvest rate (HR) being greater than 20% or 10%. Bottom (**AM2**): Values are probabilities, under each TAC level, of the post-harvest spawning biomass in 2016 (SB_{2016}) falling below fixed cut-off of 17,600 t, and of the harvest rate (HR) being greater than 20% or 10%.*

Central Coast (CC-Area 06,07,08)								
	Biomass metrics - AM1				Harvest metrics - AM1			
TAC (metric tonnes)	Prob (biomass after harvest is below 0.25 SB_0 in 2016) P(SB_{2016} < 0.25 SB_0)	Median ratio of projected post-harvest biomass to 0.25 SB_0 Med (SB_{2016} / 0.25 SB_0)	Prob (biomass after harvest is below 0.60 SB_0 in 2016) P(SB_{2016} < 0.60 SB_0)	Median ratio of projected post-harvest biomass to 0.60 SB_0 Med (SB_{2016} / 0.60 SB_0)	Prob (removal rate > target HR) P(U'2016 > 20%)	Prob (removal rate > target HR) P(U'2016 > 10%)	Prob (removal rate > target HR) P(U'2016 > 5%)	Median removal rate Med (U'2016)
0	0.00	2.89	0.29	1.20	0.00	0.00	0.00	0.00
1,050	0.00	2.84	0.31	1.18	0.00	0.00	0.01	0.02
1,300	0.00	2.83	0.32	1.18	0.00	0.00	0.06	0.03
1,760	0.00	2.81	0.33	1.17	0.00	0.00	0.25	0.04
2,120	0.00	2.79	0.34	1.16	0.00	0.01	0.44	0.05
2,230	0.00	2.79	0.34	1.16	0.00	0.02	0.50	0.05
2,620	0.00	2.77	0.35	1.15	0.00	0.06	0.68	0.06
3,570	0.00	2.72	0.36	1.13	0.00	0.25	0.92	0.08
4,000	0.00	2.70	0.38	1.12	0.01	0.36	0.96	0.09
4,370	0.01	2.68	0.38	1.12	0.01	0.45	0.98	0.10
4,550	0.01	2.67	0.39	1.11	0.02	0.50	0.98	0.10
5,400	0.01	2.63	0.41	1.09	0.06	0.70	1.00	0.12
7,000	0.01	2.55	0.44	1.06	0.20	0.90	1.00	0.15
7,350	0.01	2.53	0.44	1.05	0.25	0.93	1.00	0.16
8,000	0.01	2.50	0.46	1.04	0.33	0.95	1.00	0.17
9,300	0.02	2.43	0.48	1.01	0.50	0.99	1.00	0.20
10,000	0.02	2.40	0.50	1.00	0.58	0.99	1.00	0.21
11,000	0.02	2.35	0.52	0.98	0.69	1.00	1.00	0.23

Table 7 continued

Central Coast (CC-Area 06,07,08)								
	Biomass metrics – AM2				Harvest metrics – AM2			
TAC (metric tonnes)	Prob (biomass after harvest is below cut-off in 2016) P(SB_{2016} < 17,600 t)	Median ratio of projected post-harvest biomass to cut-off Med (SB_{2016} / 17,600 t)	Prob (biomass after harvest is below 0.60 SB_0 in 2016) P(SB_{2016} < 0.60 SB_0)	Median ratio of projected post-harvest biomass to 0.60 SB_0 Med (SB_{2016} / 0.60 SB_0)	Prob (removal rate > target HR) P(U'2016 > 20%)	Prob (removal rate > target HR) P(U'2016 > 10%)	Prob (removal rate > target HR) P(U'2016 > 5%)	Median removal rate Med (U'2016)
0	0.12	1.45	0.77	0.79	0.00	0.00	0.00	0.00
1,050	0.15	1.41	0.79	0.77	0.00	0.00	0.25	0.04
1,300	0.15	1.40	0.80	0.76	0.00	0.01	0.50	0.05
1,760	0.16	1.38	0.81	0.75	0.00	0.10	0.84	0.07
2,120	0.18	1.36	0.81	0.74	0.00	0.25	0.95	0.08
2,230	0.18	1.36	0.82	0.74	0.00	0.30	0.96	0.09
2,620	0.19	1.34	0.82	0.73	0.01	0.50	0.99	0.10
3,570	0.23	1.30	0.84	0.71	0.09	0.84	1.00	0.13
4,000	0.24	1.29	0.85	0.70	0.16	0.92	1.00	0.15
4,370	0.26	1.27	0.85	0.69	0.25	0.95	1.00	0.16
4,550	0.26	1.26	0.86	0.69	0.29	0.96	1.00	0.17
5,400	0.29	1.23	0.87	0.67	0.50	0.99	1.00	0.20
7,000	0.35	1.16	0.89	0.63	0.80	1.00	1.00	0.26
7,350	0.36	1.15	0.90	0.63	0.84	1.00	1.00	0.27
8,000	0.39	1.12	0.90	0.61	0.90	1.00	1.00	0.29
9300	0.43	1.07	0.92	0.58	0.96	1.00	1.00	0.33
10,000	0.46	1.04	0.92	0.57	0.98	1.00	1.00	0.35
11,000	0.50	1.00	0.93	0.54	0.99	1.00	1.00	0.38

*Table 8. Decision tables concerning the harvest and biomass metrics drawn from **AM1** (top) and **AM2** (bottom) for projected spawning biomass in 2016, given a range of total allowable catch (TAC) (in tonnes) for **Central Coast (Area 06,07 only)**. Probabilities are estimated using the proportion of the MCMC samples for which the given criteria hold. One-year projections for CC use catch allocation ratios for each of the three fisheries (F&B/ SU, seine roe and gillnet roe) based on 20-year historical average catches. Top (**AM1**): Values are probabilities, under each TAC level, of the post-harvest spawning biomass in 2016 (SB_{2016}) falling below 0.25 SB_0, and of the harvest rate (HR) being greater than 20% or 10%. Bottom (**AM2**): Values are probabilities, under each TAC level, of the post-harvest spawning biomass in 2016 (SB_{2016}) falling below fixed cut-off of 16,016 t, and of the harvest rate (HR) being greater than 20% or 10%.*

Central Coast (CC-Area 06,07 only)								
	Biomass metrics - AM1				**Harvest metrics - AM1**			
TAC (metric tonnes)	Prob (biomass after harvest is below 0.25 SB_0 in 2016) P(SB_{2016} < 0.25 SB_0)	Median ratio of projected post-harvest biomass to 0.25 SB_0 Med (SB_{2016} / 0.25 SB_0)	Prob (biomass after harvest is below 0.60 SB_0 in 2016) P(SB_{2016} < 0.60 SB_0)	Median ratio of projected post-harvest biomass to 0.60 SB_0 Med (SB_{2016} / 0.60 SB_0)	Prob (removal rate > target HR) P(U'2016 > 20%)	Prob (removal rate > target HR) P(U'2016 > 10%)	Prob (removal rate > target HR) P(U'2016 > 5%)	Median removal rate Med (U'2016)
0	0.00	3.01	0.26	1.25	0.00	0.00	0.00	0.00
990	0.00	2.95	0.28	1.23	0.00	0.00	0.02	0.02
1,220	0.00	2.94	0.28	1.23	0.00	0.00	0.07	0.03
1,650	0.00	2.92	0.29	1.22	0.00	0.00	0.25	0.04
2,000	0.00	2.90	0.30	1.21	0.00	0.02	0.46	0.05
2,070	0.00	2.89	0.30	1.21	0.00	0.02	0.50	0.05
2,480	0.00	2.87	0.30	1.20	0.00	0.07	0.70	0.06
3,350	0.00	2.82	0.33	1.18	0.00	0.25	0.91	0.08
4,150	0.00	2.78	0.34	1.16	0.02	0.49	0.98	0.10
4,200	0.00	2.77	0.34	1.16	0.02	0.50	0.98	0.10
5,100	0.01	2.72	0.36	1.14	0.07	0.71	0.99	0.12
6,000	0.01	2.68	0.38	1.11	0.14	0.85	1.00	0.14
6,900	0.01	2.63	0.41	1.09	0.25	0.92	1.00	0.16
7,000	0.01	2.62	0.41	1.09	0.27	0.93	1.00	0.16
8,000	0.02	2.56	0.43	1.07	0.41	0.97	1.00	0.19
8,650	0.02	2.53	0.45	1.05	0.50	0.98	1.00	0.20
9,000	0.02	2.51	0.45	1.05	0.55	0.99	1.00	0.21
10,000	0.02	2.45	0.48	1.02	0.67	0.99	1.00	0.23

Table 8 continued

Central Coast (CC-Area 06,07 only)								
Biomass metrics – AM2					Harvest metrics – AM2			
TAC (metric tonnes)	Prob (biomass after harvest is below cut-off in 2016) P(SB_{2016} < 16,016 t)	Median ratio of projected post-harvest biomass to cut-off Med (SB_{2016} / 16,016 t)	Prob (biomass after harvest is below 0.60 SB_0 in 2016) P(SB_{2016} < 0.60 SB_0)	Median ratio of projected post-harvest biomass to 0.60 SB_0 Med (SB_{2016} / 0.60 SB_0)	Prob (removal rate > target HR) P(U'2016 > 20%)	Prob (removal rate > target HR) P(U'2016 > 10%)	Prob (removal rate > target HR) P(U'2016 > 5%)	Median removal rate Med (U'2016)
0	0.16	1.37	0.76	0.80	0.00	0.00	0.00	0.00
990	0.19	1.33	0.78	0.78	0.00	0.00	0.25	0.04
1,220	0.20	1.32	0.79	0.77	0.00	0.01	0.50	0.05
1,650	0.21	1.30	0.80	0.76	0.00	0.09	0.83	0.07
2,000	0.23	1.29	0.81	0.75	0.00	0.25	0.94	0.08
2,070	0.23	1.28	0.81	0.75	0.00	0.28	0.96	0.08
2,480	0.24	1.27	0.82	0.74	0.01	0.50	0.99	0.10
3,350	0.27	1.23	0.84	0.72	0.08	0.84	1.00	0.13
4,150	0.31	1.20	0.85	0.70	0.25	0.95	1.00	0.16
4,200	0.31	1.19	0.85	0.70	0.27	0.96	1.00	0.17
5,100	0.35	1.16	0.87	0.67	0.50	0.99	1.00	0.20
6,000	0.39	1.12	0.88	0.65	0.71	1.00	1.00	0.23
6,900	0.42	1.08	0.89	0.63	0.84	1.00	1.00	0.27
7,000	0.43	1.08	0.89	0.63	0.85	1.00	1.00	0.27
8,000	0.46	1.03	0.90	0.60	0.93	1.00	1.00	0.31
8,650	0.49	1.01	0.91	0.59	0.96	1.00	1.00	0.33
9,000	0.50	0.99	0.91	0.58	0.97	1.00	1.00	0.34
10,000	0.54	0.95	0.92	0.55	0.98	1.00	1.00	0.37

Strait of Georgia

A total of 158 samples were processed in 2015, collected from herring commercial fisheries (2014/15 season) and through the test charter program (March-April 2015). This includes commercial samples from the roe seine (37), roe gillnet (36), food and bait (37) and special use (10) fisheries, and the test charter (27) and industry-funded testing programs (11). Duplicate samples were not processed. The dive survey teams measured a total of 166.8 linear kilometers of herring spawn, commencing on Feb 24 and continuing through mid-April.

Both assessments estimate the stock to have increased from 2014 to 2015 (Figure 10 d). The spawn index decreased from 120,468 t in 2014 to 104,481 t in 2015 (Table A.1). The models fit the most recent observation, but do not fit the 2014 and the 2002-2005 observations (Figure 10 a). Both models estimate an upward trajectory since 2010. AM1 and AM2 estimate the median spawning biomass in 2015 (SB_{2015}) at 174,687 t and 92,511 t (Table 2 and 3). Stock status in 2015 is estimated at 122% (AM1) and 78% (AM2) of the unfished level (Table 3). The pattern of biomass estimates for AM2 is similar to that of AM1 but AM2 estimates of spawning biomass in 2015 (SB_{2015}) and stock status relative to SB_0 are lower than the AM1 estimates (Table 2 and Table 3).

Both AM1 and AM2 project an increase in median projected spawning biomass in 2016. AM1 projects a median pre-harvest spawning stock biomass in 2016 of 217,800 t, consisting 46% (median) age-3 fish and 46% (median) age-4 and older fish (Table 4). AM2 projects a median pre-harvest spawning stock biomass of 123,000 t (Table 4). Projected proportions of age-3 and age-4 and older fish is near-identical using AM2 (assuming q=1). The upward trajectory in spawning biomass and projections for 2016 are the result of the upward trajectory in model fits to the spawn index since 2010 (Figure 10 a) and both models estimating above average recruitment of age-2 fish in 2013-2015 (Figure 10 b).

In the absence of fishing, AM1 estimates that there is a 0% probability the stock will be below the cut-off of 25% SB_0 in 2016 and AM2 estimates a 0% probability of being below the fixed cut-off level of 21,200 t in 2016 (Table 9).

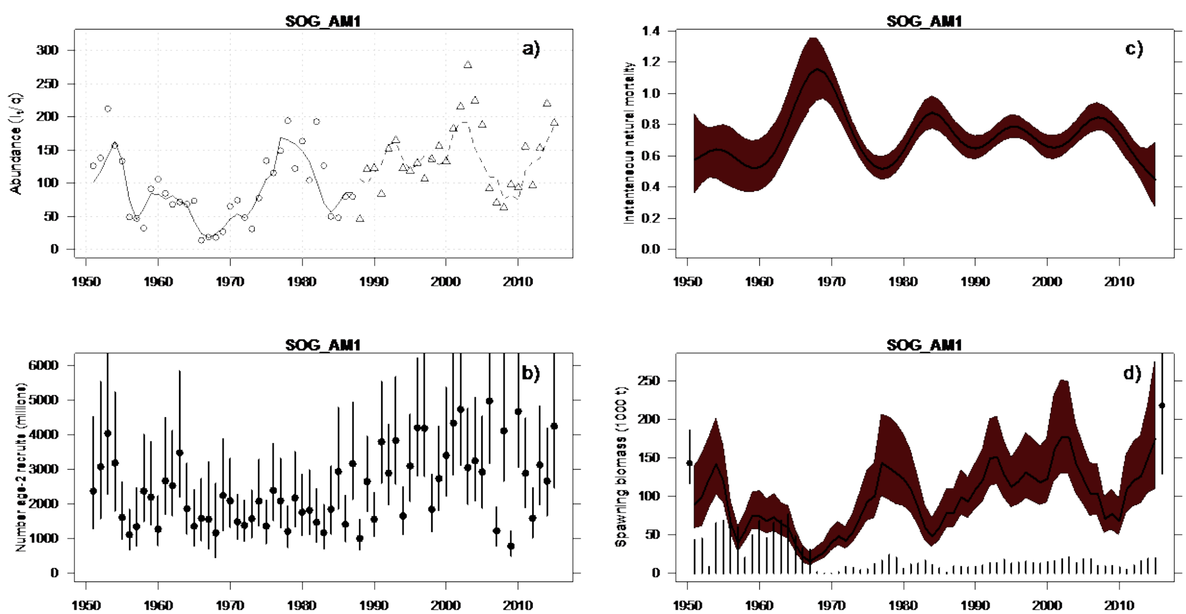

Figure 10. Model outputs for Strait of Georgia, AM1. See detailed description in Figure 6.

*Table 9. Decision tables concerning the harvest and biomass metrics drawn from **AM1** (left) and **AM2** (right) for projected spawning biomass in 2016, given a range of total allowable catch (TAC) (in tonnes) for **Strait of Georgia**. Probabilities are estimated using the proportion of the MCMC samples for which the given criteria hold. One-year projections for SOG assumes a 50% allocation of TAC to the food and bait/ special use fisheries, 30% to seine roe, and 20% to gillnet roe.*

*Left (**AM1**): Values are probabilities, under each TAC level, of the post-harvest spawning biomass in 2016 (SB_{2016}) falling below 0.25 SB_0, and of the harvest rate (HR) being greater than 20% or 10%.*

Strait of Georgia (SOG)					
	Biomass metrics – AM1		Harvest metrics – AM1		
TAC	Prob (biomass after harvest is below 0.25 SB_0 in 2016)	Median ratio of projected post-harvest biomass to 0.25 SB_0	Prob (removal rate > target HR)	Prob (removal rate > target HR)	Median removal rate
(metric tonnes)	P(SB_{2016} < 0.25 SB_0)	Med (SB_{2016} / 0.25 SB_0)	P(U'2016 > 20%)	P(U'2016 > 10%)	Med (U'2016)
0	0.00	6.06	0.00	0.00	0.00
10,000	0.00	5.86	0.00	0.01	0.05
10,600	0.00	5.85	0.00	0.01	0.05
12,600	0.00	5.81	0.00	0.04	0.06
17,000	0.00	5.73	0.00	0.18	0.08
18,250	0.00	5.70	0.00	0.25	0.08
21,800	0.00	5.64	0.01	0.46	0.10
22,500	0.00	5.63	0.01	0.50	0.10
25,000	0.00	5.58	0.03	0.64	0.11
25,900	0.00	5.56	0.03	0.68	0.11
30,000	0.00	5.47	0.08	0.84	0.13
38,000	0.00	5.32	0.25	0.96	0.17
40,000	0.00	5.28	0.32	0.97	0.17
46,500	0.00	5.15	0.50	0.99	0.20
50,000	0.00	5.09	0.60	1.00	0.21

*Right (**AM2**): Values are probabilities, under each TAC level, of the post-harvest spawning biomass in 2016 (SB_{2016}) falling below fixed cut-off of 21,200 t, and of the harvest rate (HR) being greater than 20% or 10%.*

Strait of Georgia (SOG)					
	Biomass metrics – AM2		Harvest metrics – AM2		
TAC	Prob (biomass after harvest is below cut-off in 2016	Median ratio of projected post-harvest biomass to cut-off	Prob (removal rate > target HR)	Prob (removal rate > target HR)	Median removal rate
(metric tonnes)	P(SB_{2016} < 21,200 t)	Med (SB_{2016} / 21,200 t)	P(U'2016 > 20%)	P(U'2016 > 10%)	Med (U'2016)
0	0.00	5.80	0.00	0.00	0.00
10,000	0.00	5.45	0.00	0.18	0.08
10,600	0.00	5.43	0.00	0.25	0.08
12,600	0.00	5.36	0.00	0.50	0.10
17,000	0.00	5.21	0.05	0.89	0.13
18,250	0.00	5.16	0.09	0.94	0.14
21,800	0.00	5.04	0.25	0.99	0.17
22,500	0.00	5.01	0.28	1.00	0.17
25,000	0.00	4.92	0.44	1.00	0.19
25,900	0.00	4.89	0.50	1.00	0.20
30,000	0.00	4.75	0.72	1.00	0.23
38,000	0.00	4.48	0.94	1.00	0.29
40,000	0.00	4.41	0.97	1.00	0.30
46,500	0.00	4.19	1.00	1.00	0.34
50,000	0.00	4.07	1.00	1.00	0.37

West Coast Vancouver Island

In 2015 biological samples were collected through the seine test charter program, funded by DFO. The primary purpose of the test charter vessel was to collect biological samples from main aggregations of herring from Areas 23, 24 and 25, identified from soundings (late Feb-April 2015). A total of 17 biological samples were collected and processed from the test sample program. An additional 3 biological samples were collected though a pilot sampling program with the Nuu-chah-nulth Tribal Council fisheries program.

In addition, there were several observations from Nuu-chah-nulth harvesters and other local observations regarding WCVI herring in 2015. Early, warm spring with good weather led to some earlier than usual WCVI herring spawning activity (late February, early March). Nuu-chah-nulth harvesters set whole trees and lines of tree branches to harvest herring spawn on bough. Trees and boughs were set in both usual herring spawning locations and in active spawning locations in Barkley Sound (Area 23), Clayoquot Sound (Area 24), Nootka Sound, Esperanza Inlet, Nuchatlitz (Area 25), and Kyuquot Sound (Area 26, which is outside of DFO assessment area for WCVI herring). With the exception of one small spawn on the south end of Flores Island and an intense but small spawn in Kyuquot Sound (Area 26), Nuu-chah-nulth harvesters did not acquire any harvestable herring spawn on bough in 2015. Trees and boughs set in all other locations were either barren or had so little spawn the herring eggs on the trees or boughs were left to hatch. (A minimum of four to six layers of eggs are necessary to provide enough eggs to peel off branches for harvesting.) Nuu-chah-nulth fishers, marine transportation workers (water taxis, barge operators, etc.), and others on the water during the 2015 spring herring season reported few observations of active herring spawn or marine life associated with active herring spawn throughout Areas 23, 24, 25. Small spawns of short duration were observed. Observations of DFO “spawn reconnaissance” contractors in Area 23, 24, and 25 were consistent with the observations of Nuu-chah-nulth harvesters. Generally, WCVI herring spawns in 2015 were short duration, limited area and few egg layers. Seven commercial seine licence holders and vessels, working with information from DFO test vessels, attempted to harvest commercially acceptable roe herring in 2015, but were unsuccessful in finding herring of sufficient quality and/or quantity to harvest at the time of their arrival to the WCVI. Nuu-chah-nulth fishers reported ocean sea surface temperatures that were noticeably warmer than usual during the 2015 herring season.

The Maa-nulth, Hesquiat and Nuchatlaht First Nations operated spawn reconnaissance (charter patrol) vessels in Areas 23, 24, and 25. Vessels were responsible for identifying pre-spawning schools of herring in their territories, and relaying this information daily to the WCVI resource manager. In some cases, reconnaissance vessels also conduct surface surveys in areas unreachable by the contract dive team. First Nations operated spawn reconnaissance vessels have been a regular part of the WCVI assessment program since 2007. Spawning events reported by the spawn reconnaissance vessels and from spawn flights (~2 flights per week) were used to direct dive survey teams. Dive surveys measured a total of 20.25 linear kilometers of herring spawn.

The time series of spawn survey data declined from 13,937 t in 2014 to 11,323 t in 2015 (Table A.1). There was a decline in total length of spawn and an increase in average spawn width, and the average number of egg layers declined in 2014 and 2015 (not shown).

AM1 estimates the median spawning biomass (SB_{2015}) at 25,338 tonnes and SB_{2015} is estimated to be 44% (median) of the unfished level, SB_0. AM2 estimates the median spawning biomass in 2015 (SB_{2015}) at 12,708 t and 28% of SB_0 (Table 3). While there were some small increases in the median spawning stock estimates from 2014 to 2015, the absolute magnitude of the increases was small and the uncertainty in the estimates large (Table 2). AM1 and AM2 fit the

2015 spawn survey index value, while under-fitting the 2013 and 2014 values, thus explaining how the model can estimate a stock that is apparently increasing, even though the most recent spawn index data indicate it has decline in the last year (Figure 11 a, d). Both AM1 and AM2 estimate above average recruitment of age 2 fish in 2015, relative to the years before and also the apparent median estimate of natural mortality increasing from 0.71 in 2013 to 0.82 in 2015 (AM1, Figure 11 b, c) or 0.68 to 0.76 (AM2, not shown).

In association with differences between AM1 and AM2, projected 2016 spawning biomass estimates, there are pronounced differences in the probabilities of being below estimated and fixed cut-offs. AM1 projects a median pre-harvest spawning stock biomass in 2016 of 34,450 t, consisting 57% (median) age-3 fish and 28% (median) age-4 and older fish (Table 4). AM2 projects a median pre-harvest spawning stock biomass of 17,830 t (Table 4) with projected proportions of age-3 and age-4 and older fish nearly identical to results from AM2 (assuming *q*=1). Once the effect of the projected biomass estimates for each of the stock assessment models is propagated through to the probability of being below estimated or fixed cut-offs, AM1 results suggest there is a 1% chance of the stock being below the estimated 0.25 SB_0, whereas AM2 results suggest there is a 56% chance of being below the fixed cut-off of 18,800 tonnes (Table 10). The probabilities of being below cut-off, and of achieving selected harvest rates for a range of catch levels for the WCVI major stock areas are reported in Table 10.

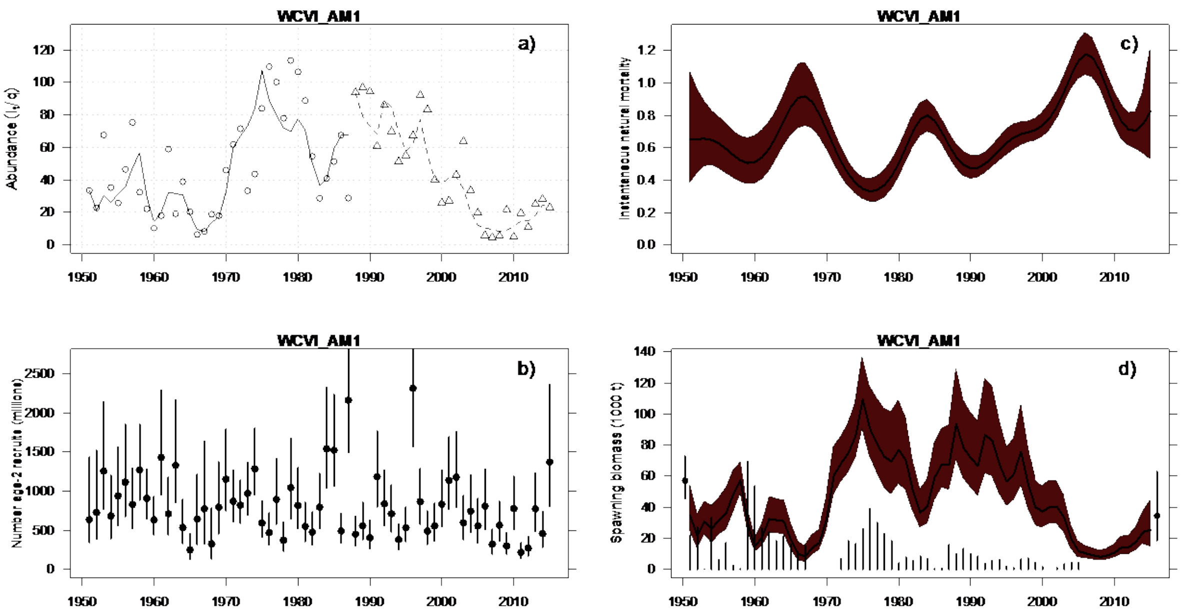

Figure 11. Model outputs for West Coast Vancouver Island, AM1. See detailed description in Figure 6.

*Table 10. Decision tables concerning the harvest and biomass metrics drawn from **AM1** (left) and **AM2** (right) for projected spawning biomass in 2016, given a range of total allowable catch (TAC) (in tonnes) for **West Coast Vancouver Island**. Probabilities are estimated using the proportion of the MCMC samples for which the given criteria hold. One-year projections for WCVI use catch allocation ratios for each of the three fisheries (F&B/ SU, seine roe and gillnet roe) based on 20-year historical average catches.*

*Left (**AM1**): Values are probabilities, under each TAC level, of the post-harvest spawning biomass in 2016 (SB_{2016}) falling below 0.25 SB_0, and of the harvest rate (HR) being greater than 20% or 10%.*

*Right (**AM2**): Values are probabilities, under each TAC level, of the post-harvest spawning biomass in 2016 (SB_{2016}) falling below fixed cut-off of 18,800 t, and of the harvest rate (HR) being greater than 20% or 10%.*

West Coast Vancouver Island (WCVI)						**West Coast Vancouver Island (WCVI)**					
	Biomass metrics – AM1		**Harvest metrics – AM1**				**Biomass metrics – AM2**		**Harvest metrics – AM2**		
TAC	Prob (biomass after harvest is below 0.25 SB_0 in 2016)	Median ratio of projected post-harvest biomass to 0.25 SB_0	Prob (removal rate > target HR)	Prob (removal rate > target HR)	Median removal rate	TAC	Prob (biomass after harvest is below cut-off in 2016	Median ratio of projected post-harvest biomass to cut-off	Prob (removal rate > target HR)	Prob (removal rate > target HR)	Median removal rate
(metric tonnes)	P(SB_{2016} < 0.25 SB_0)	Med (SB_{2016} / 0.25 SB_0)	P(U'2016 > 20%)	P(U'2016 > 10%)	Med (U'2016)	(metric tonnes)	P(SB_{2016} < 18,800 t)	Med (SB_{2016} / 18,800 t)	P(U'2016 > 20%)	P(U'2016 > 10%)	Med (U'2016)
0	0.01	2.40	0.00	0.00	0.00	0	0.56	0.95	0.00	0.00	0.00
1,000	0.01	2.36	0.00	0.00	0.03	1,000	0.60	0.92	0.00	0.04	0.05
1,480	0.01	2.34	0.00	0.01	0.04	1,480	0.61	0.90	0.00	0.25	0.08
1,850	0.01	2.32	0.00	0.04	0.05	1,850	0.62	0.89	0.02	0.50	0.10
2,800	0.02	2.28	0.01	0.25	0.08	2,800	0.66	0.86	0.16	0.88	0.15
3,100	0.02	2.27	0.01	0.35	0.09	3,100	0.66	0.85	0.25	0.93	0.16
3,600	0.02	2.25	0.02	0.50	0.10	3,600	0.68	0.83	0.42	0.97	0.19
3,850	0.02	2.24	0.04	0.58	0.11	3,850	0.69	0.82	0.50	0.98	0.20
4,000	0.02	2.23	0.05	0.62	0.11	4,000	0.69	0.82	0.54	0.99	0.21
5,000	0.02	2.19	0.14	0.82	0.14	5,000	0.72	0.79	0.77	1.00	0.25
5,850	0.03	2.15	0.25	0.91	0.16	5,850	0.75	0.76	0.88	1.00	0.29
6,000	0.03	2.15	0.28	0.92	0.16	6,000	0.75	0.75	0.90	1.00	0.30
7,500	0.04	2.08	0.50	0.98	0.20	7,500	0.79	0.71	0.97	1.00	0.36
8,000	0.04	2.06	0.58	0.98	0.21	8,000	0.80	0.69	0.98	1.00	0.38
8,500	0.05	2.04	0.64	0.99	0.23	8,500	0.81	0.68	0.99	1.00	0.40

Area 2W

Spawn survey information has been collected in Area 2W since 1978, however, there are no spawn survey observations in 1995-1997 and 1999 due to lack of available resources, and in 2015 due to weather. The majority of survey observations in Area 2W are conducted by surface survey, thus the survey data are treated as a single time series (with one *q* value). The spawn index has been decreasing, from 2,871 t in 2009 to 1,386 t in 2014 (Table A.1). Biological samples in Area 2W are collected from commercial SOK operations and through the test charter program. There were 4 charter samples collected in 2015.

Both assessment models estimate the stock biomass as stable, with median biomass levels fluctuating from 3,260 – 4,004 t (AM1) and 1,428 – 1,715 t (AM2) from 2011 to 2015 (Table 2). Both models fit the 2014 observation and under-fit observations from 2006-2013 (Figure 12 a), and estimate a downward trajectory with a high degree of uncertainty (Figure 12 d). AM1 and AM1 estimate the median spawning biomass in 2015 (SB_{2015}) to be 3,260 t and 1,428 t, and status of the stock (SB_{2015}) relative to the unfished level (SB_0) is estimated to be 101% and 72% (median values, Table 2 and Table 3). The pattern of biomass estimates for AM2 is similar to that of AM1, but AM2 estimates of spawning biomass in 2015 (SB_{2015}) and stock status relative to SB_0 are lower than the AM1 estimates (Table 2 and Table 3). Both models project a decline in median spawning biomass in 2016, with AM1 and AM2 predicting SB_{2016} of 2,834 t and 1,255 t, respectively (Table 4).

Decision tables for Area 2W report the probability of catch levels exceeding the 10% harvest rate (Table 11). Cut-offs are not implemented in the management procedure for this minor stock area.

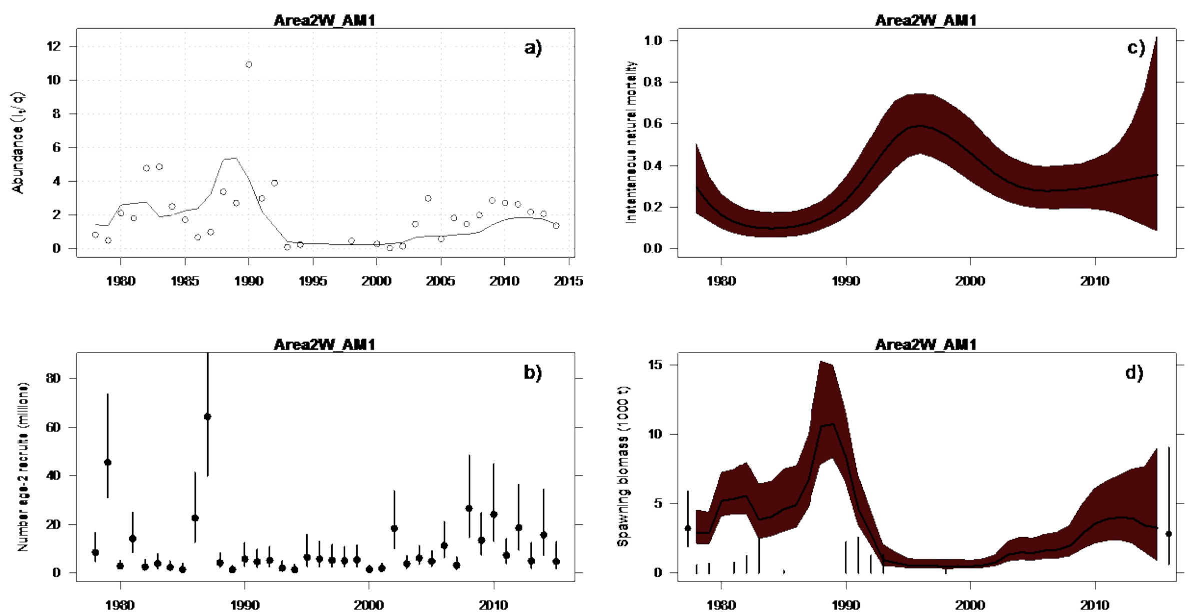

Figure 12. Model outputs for Area 2W, AM1. See detailed description in Figure 6.

*Table 11. Decision tables concerning the harvest metrics drawn from **AM1** (left) and **AM2** (right) for projected spawning biomass in 2016, given a range of total allowable catch (TAC) (in tonnes) for Haida Gwaii minor stock **Area 2W**. Probabilities are estimated using the proportion of the MCMC samples for which the given criteria hold. One-year projections for Area 2W use catch allocation ratios for each of the three fisheries (F&B/ SU, seine roe and gillnet roe) based on 20-year historical average catches.*

Area 2W – AM1			**Area 2W – AM2**		
TAC (metric tonnes)	Prob (removal rate > target HR) P(U'2016 > 10%)	Median removal rate Med (U'2016)	TAC (metric tonnes)	Prob (removal rate > target HR) P(U'2016 > 10%)	Median removal rate Med (U'2016)
0	0.00	0.00	0	0.00	0.00
50	0.03	0.02	50	0.16	0.04
70	0.06	0.02	70	0.25	0.06
100	0.11	0.04	100	0.38	0.08
127	0.17	0.04	127	0.50	0.10
164	0.25	0.06	164	0.62	0.13
200	0.33	0.07	200	0.71	0.15
290	0.50	0.10	290	0.86	0.22
300	0.52	0.10	300	0.87	0.23
400	0.65	0.14	400	0.94	0.30
500	0.76	0.17	500	0.98	0.37
600	0.83	0.20	600	0.99	0.44

Area 27

Spawn survey information has been consistently collected in Area 27 since 1978. In 2015, herring spawn was surveyed using the shore-based dive team. The spawn index has been increasing since 2011 (547 t), and in 2015 the index increased to 2,169 t from 1,307 in 2014 (Table A.1). In recent years, biological samples have been collected in Area 27 from commercial SOK operations only (no test charter samples), and in 2014 and 2015 SOK opportunities were not pursued in Area 27.

Both assessments estimate the stock as increasing from 2012 to 2015 (Table 2). There is little contrast in the spawn index from 2000-2015, and both models fit the majority of these survey observations (Figure 13 a). Both models estimate an upward trajectory since 2012 (Figure 13 d). AM1 and AM2 estimate median spawning biomass in 2015 (SB_{2015}) of 2,176 t and 1,738 t, and SB_{2015} is estimated at 99% and 95% of SB_0 (Table 2 and Table 3). The pattern of biomass estimate for AM2 is similar to that of AM1, but AM2 estimates of spawning biomass in 2015 (SB_{2015}) and stock status relative to SB_0 are lower than the AM1 estimates (Table 2 and Table 3). Both models project an increase in median spawning biomass in 2016, with AM1 and AM2 predicting median biomass levels of 2,348 t and 1,885 t, respectively (Table 4).

Decision tables for Area 27 report the probability of catch levels exceeding the 10% harvest rate (Table 12). Cut-offs are not implemented in the management procedure for this minor stock area.

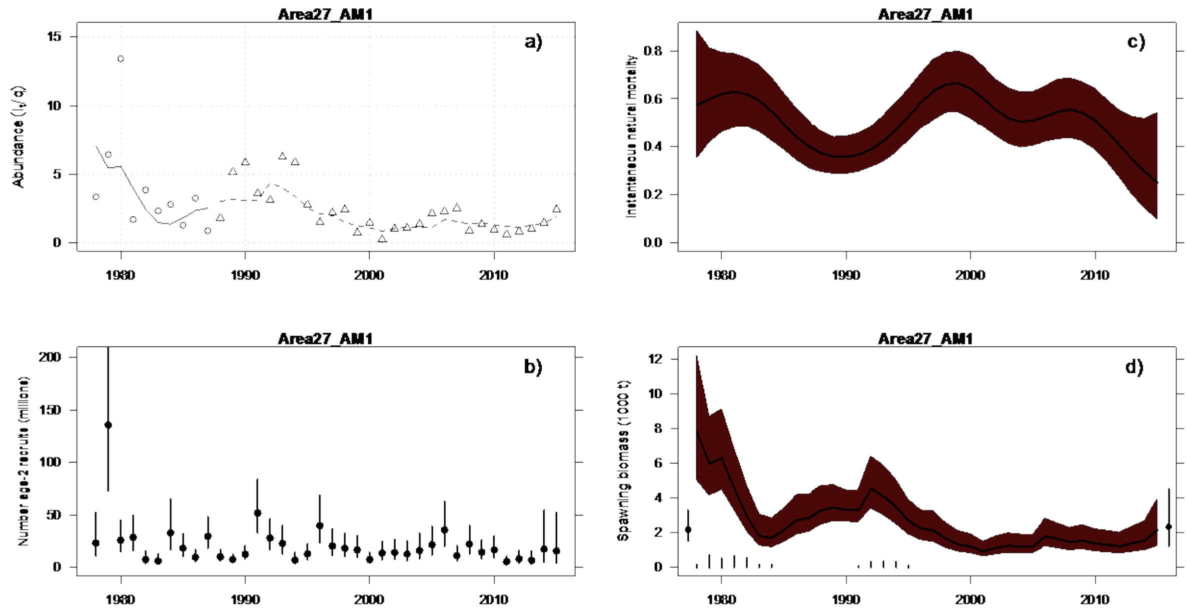

Figure 13. Model outputs for Area 27, AM1. See detailed description in Figure 6.

*Table 12. Decision tables concerning the harvest metrics drawn from **AM1** (left) and **AM2** (right) for projected spawning biomass in 2016, given a range of total allowable catch (TAC) (in tonnes) for West Coast Vancouver Island minor stock **Area 27**. Probabilities are estimated using the proportion of the MCMC samples for which the given criteria hold. One-year projections for Area 27 use catch allocation ratios for each of the three fisheries (F&B/ SU, seine roe and gillnet roe) based on 20-year historical average catches.*

Area 27 – AM1			**Area 27 – AM2**		
TAC (metric tonnes)	Prob (removal rate > target HR) P(U'2016 > 10%)	Median removal rate Med (U'2016)	TAC (metric tonnes)	Prob (removal rate > target HR) P(U'2016 > 10%)	Median removal rate Med (U'2016)
0	0.00	0.00	0	0.00	0.00
100	0.01	0.04	100	0.03	0.05
150	0.12	0.06	150	0.22	0.08
155	0.13	0.07	155	0.25	0.08
160	0.15	0.07	160	0.28	0.08
170	0.19	0.07	170	0.35	0.09
180	0.24	0.08	180	0.41	0.09
192	0.29	0.08	192	0.50	0.10
200	0.33	0.08	200	0.55	0.10
210	0.37	0.09	210	0.61	0.11
220	0.41	0.09	220	0.66	0.11
230	0.46	0.10	230	0.70	0.12
240	0.50	0.10	240	0.75	0.12
250	0.54	0.10	250	0.78	0.13

PART 2: Simulation testing of alternative management procedures for Pacific Herring (*Clupea pallasii*) fisheries in British Columbia

Methods

Part 1 of this Science Response provided herring fishery catch advice in the form of two decision tables for each of the 5 major herring fisheries. These tables – one made using the current assessment model (AM1) and one for approximating the historical approach (AM2) – mainly differ in:

(1) the dive survey scaling parameter (*q*) assumption underlying the statistical catch-at-age model component of each procedure; and,

(2) the choice of cut-off.

For some herring stocks, the alternative decision tables differ somewhat drastically in their yield-risk trade-offs, leading to concerns among fishery managers, First Nations, and other stakeholders. Since 2012, there has been little scientific information to illustrate the consequences of choosing AM1 or AM2 for the decision making purposes.

This part of the Science Response uses a closed-loop simulation approach (Cox et al. 2015, in prep[2]) to evaluate the potential future consequences of adopting either the current management procedure (estimated cut-off and estimated *q*s, MP1), or the historical management procedure (fixed cut-off and q=1, MP2). In particular, this analysis demonstrates two outcomes:

(1) how future yield and conservation risk could be affected when MP1 or MP2 is applied; and,

(2) the expected yield and conservation performance of each MP averaged over the uncertainty about which spawn survey scaling parameter (*q*) assumption is actually appropriate.

When examined over a 20-year period, results indicate that MP1 generally maintains lower biomass relative to the unfished level and higher catch than the approximation of the MP2. MP1 also has a higher probability of breaching any of the limit reference points (LRP) considered. The relative differences are maintained when calculated over a short-term (5-year) period, although the performance of both MPs with respect to LRPs improves at this shorter time scale.

The closed-loop simulations are intended to provide a reasonable facsimile of the system's population dynamics, stock assessment, and harvest control rules. The parameter values estimated for the simulations will not be identical to those estimated in previous stock assessments. With respect to fixed vs. estimated cut-offs specifically, the simulations mimic the process of setting a fixed cut-off based on the estimate of $0.25B_0$ in some year. 2014 was chosen because it was easier to implement in simulation. With respect to the fixed vs. estimated cut-off, the simulation results can only provide information about the performance of a management procedure, like the historical practice of using fixed a cut-off, they cannot provide information about the performance of employing the actual cut-offs used from 1996-2011. Fixed vs. estimated cut-offs are but only one example where the simulated system is not identical what occurred historically. For a variety of reasons, including implementation, alternative stock assessment models, etc., the simulations will not reflect historical practice or parameter values exactly.

[2] Cox, S.P., Benson, A.J., Cleary, J.S., and Taylor, N.G. 2015. Candidate limit reference points as a basis for choosing among alternate harvest control rules for Pacific Herring (*Clupea pallasii*) in British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. In prep.

The Cox et al. (2015, in prep.[2]) simulation framework includes an operating model (OM), representing the "true", i.e. known (but unobserved) population dynamics defined by the operating model for each herring stock and fishery, and management procedures (MPs), representing the scientific assessment and harvest decision-making processes leading to annual fishery catches. MPs include an observation sub-model that generates observed spawn index and age-composition data subject to error, a stock assessment sub-model (AM) that uses observed (i.e., simulated) data to generate estimates of current stock status, biomass, and cut-offs, and harvest control rules (HCRs) that use AM outputs to set annual catch limits. Inputs and methods within the Cox et al. (2015, in prep.[2]) simulation framework are modified to better reflect the specific management context for BC Pacific Herring fisheries. These inputs and changes include:

(1) Two operating model scenarios (OM1 and OM2) are derived for each major stock to reflect the different assumptions about the dive survey scaling parameter (*q*).

(2) Projecting natural mortality rates (*M)* 20 years into the future via a time-series bootstrap of the historical *M* time series estimated by the current (AM1) and historical (AM2) assessment models from Part 1. The bootstrap method avoids arbitrary assumptions about future conditions and trends, and instead uses past variability and trends as a reference. On the other hand, bootstrapping historical estimates assumes that the future will be like the past, so, in general, natural mortality rates trend toward their long-term averages, which may lead to increasing or decreasing trends in the projections.

(3) Model-based management procedures representing the current (MP1) and historical (MP2) MPs applied to each stock. These procedures involve a statistical catch-at-age model, configured to mimic the behaviour of the Martell et al. (2012) model. Specifically, when used in simulations of the current MP, the assessment model estimates the dive survey scaling parameter (*q*) using a Bayesian prior and annually updates estimates of unfished biomass, which leads to inter-annual variation in the cut-off. When simulating the historical MP, the dive survey scaling parameter is set equal to 1, and the cut-off is fixed as 25% of the unfished biomass estimate for 2014. For the Central Coast, a third MP that uses only the survey and catch data to set annual catch limits is evaluated. This MP does not involve a catch-at-age stock assessment model, but does vary the cut-off annually (see below).

Operating model scenarios

Operating models for each of the 5 major stocks are parameterized using stock assessment estimates of biomass, natural mortality, fishing mortality, and recruitment given data up to 2014 (Table 13). Cox et al. (2015, in prep.[2]) showed that the effect of growth changes on management procedure performance was relatively small. To constrain the total number of scenarios considered here, only operating models that consider the two alternative *q*s were used. Different assumptions about the spawn survey scaling parameter (*q*) in the stock assessment model result in different estimates of these parameters; therefore, two operating models for each stock that capture these differences were developed. OM1 is based on the dynamics and stock history, defined by fitting the current stock assessment model (AM1, Part 1; DFO 2014, Cleary and Taylor 2015, in prep.[1]). This assessment model separately estimates *q* for the surface and dive surveys. OM2 is defined by estimates obtained using the historical stock assessment model (AM2) that fixes *q*=1 for the dive survey and estimates *q* for the surface survey. Natural mortality, shown in column 4 of Table 13, is the average over the assessment period 1951-2014. This value was used to compute the biomass limit reference points (LRPs). The symbols used to describe the models used in the simulation analysis are included in Table A2.

Implementing the two operating model scenarios involved modifying equation OM2.21 from Cox et al. (2015, in prep.[2]) to separate *q's* for the surface and dive survey periods, i.e.,

OM2.21 $$I_t = q_t B_t^{Ex} \exp[\tau_{I,t}\varepsilon_t - 0.5\tau_{I,t}^2]$$

where

$$q_t = \begin{cases} q_1 & 1951 \leq t < 1988 \\ q_2 & t \geq 1988 \end{cases}$$

Operating model values for the dive (q_2) survey scaling parameter are set to their 2014 posterior mean values from either the current (AM1; q_2=estimated with prior mean 0.56), or historical stock assessment models (AM2; q_2=1) (Table 13; Cleary and Taylor 2015, in prep.[1]). The surface survey scaling parameters (q_1) were set to the 2014 estimate using either AM1 or AM2, depending on the operating model scenario. The observation error values τ used for the simulation, reported in Table 13, came from the estimated values in Cleary and Taylor (2015, in prep.[1]).

Projecting natural mortality (M)

A time-series bootstrap (Kunsch, 1989) is used to simulate possible future natural mortality patterns for each herring stock. This method simulates natural mortality time-series (each 20 years in length) by drawing (with replacement) random temporal blocks from the stock-specific natural mortality rate time-series (1951-2014). Sampling in blocks preserves temporal dependence (i.e., temporal auto-correlation) between consecutive observations present in the original series, although temporal dependence may be an artifact of the way in which *M* time-series were estimated in the first place. The bootstrapping approach ensures that future natural mortality rates will always lie within the range of historical estimates.

Table 13. Parameter values, taken from the 2014 assessment (Cleary and Taylor 2015, in prep.[1]) define operating model scenarios OM1 and OM2 for each B.C. herring stock. Natural mortality is the average over the 1951-2014 period.

Stock	Name	Unfished biomass ($\bar{B}_0$)	Natural mortality ($\bar{M}$)	SR steepness ($\bar{h}$)	Recruitment variability (σ_R)	Surface scaling parameter (q_1)	Dive scaling parameter (q_2)	Survey observation error (τ)
HG	OM1	34.76	0.63	0.79	0.79	0.33	0.55	0.50
	OM2	26.81	0.58	0.79	0.80	0.39	1.0	0.40
PRD	OM1	64.14	0.40	0.70	0.70	0.53	0.88	0.50
	OM2	65.15	0.35	0.69	0.70	0.57	1.0	0.50
CC	OM1	61.39	0.49	0.80	0.70	0.30	0.61	0.40
	OM2	54.56	0.42	0.81	0.70	0.34	1.0	0.40
SOG	OM1	144.53	0.74	0.73	0.50	0.64	0.60	0.70
	OM2	118.51	0.57	0.77	0.50	1.01	1.0	0.70
WCVI	OM1	58.50	0.67	0.73	0.50	0.61	0.52	0.80
	OM2	47.60	0.57	0.72	0.60	0.84	1.0	0.60

Management procedures

The main goals of this simulation study are to evaluate the potential yield and conservation consequences of:

(1) alternative assumptions about the dive survey scaling parameter q_2 used in the stock assessment model;

(2) using a fixed or variable cut-off biomass level in the herring harvest control rule; and,

(3) applying a purely data-based approach to setting TACs for the Central Coast herring fisheries.

Options (1) and (2) represent elements of existing herring management procedures, while (3) represents a completely different management procedure from the existing options. In the following sections, first described are modifications to the stock assessment and harvest control rule elements described in the Cox et al. (2015, in prep.[2]) simulation framework. Then, a proposed data-based approach ("ccRule") for the Central Coast fishery that only uses observed survey biomass estimates and catch to set annual TACs, is presented.

Simulating model-based herring management procedures requires three main components:

(1) a fishery data set involving time-series of total catch, relative (current MP) or absolute (historical MP) estimates of spawning biomass, and proportions-at-age in the fishery catch;

(2) a stock assessment model (AM) that estimates historical biomass, recruitment, natural mortality, selectivity, stock-recruitment parameters, the spawning biomass cut-off (i.e., $0.25B_0$), and a 1-year ahead forecast of exploitable biomass required by the harvest control rule (Cox et al. 2013); and

(3) a harvest control rule for adjusting the target fishing mortality rate and TAC in response to changes in the stock status and exploitable biomass forecast.

Implementation details for each component can be found in Cox et al. (2015, in prep.[2]). Here only provided are the modifications to these elements needed to address goals (1)-(3). A summary of assessment model and harvest control rule specifications are given in Table 14.

Scaling parameter assumptions for model-based MPs

Most surveys of fish populations provide an index that is (by design) proportional to the abundance or biomass, setting up a simple linear relationship of the form,

$$I_t = qB_t$$

where I_t (tonnes) is the index value in year t, B_t (tonnes) is the true stock biomass, and q (unitless in this particular case) is the so-called catchability coefficient that scales the biomass to the index. For herring, this coefficient is referred to as the spawn survey scaling parameter. Index values I_t (tonnes) from the herring survey are derived from a suite of estimates for egg densities from egg layer estimates, total length and average width of spawning bed and an estimate of the number of eggs produced by a tonne of herring. Persistent over- or under-estimation in any one of these components would result in a true scaling parameter value different from one. For instance, if total area of spawn was under-estimated by 50%, then q=0.5 and an index value I_t = 1,000 t would convert to B_t = 2,000 t of actual biomass, since only half of the true spawn had been observed. The opposite, i.e., B_t = 500 t, would occur if the total area of spawn was over-estimated by a factor of two (q=2). It is almost impossible to measure the scaling parameter directly for large-scale fisheries, since there are so many possible sources of bias in the component estimates, as well as in simply defining what is meant by the "stock" at any particular time. Therefore, most stock assessments treat q as a "nuisance parameter"; that is, a scalar that needs to be estimated by the model, but is not directly relevant in any other way to harvest advice. Problems arise, however, when the scaling parameter cannot be estimated reliably from the data input to the stock assessment model. It can be demonstrated via simulation that the scaling parameter is not reliably estimated when, among other things, noisy survey estimates combine with fishery catches that are small relative to the true stock size (i.e., high observation error and a low, steady harvest rate; Schnute and Richards 1995), and parameter confounding more generally. Thus, it is not immediately clear whether to estimate q or set it equal to 1 by definition because: most B.C. herring survey data are noisy; the more recent harvest rates are low or zero; and, definitions of "stock" are fluid given the potential for movement among stock areas (Hay et al., 2001; Flostrand et al., 2009).

What can be done is to create a simulation in which the true scaling parameter is known and then seeing how alternative assumptions in the stock assessment and harvest control rules affect expected yield and conservation risk (i.e., the performance measures of interest) under situations that mimic realities (i)-(iii) for Pacific Herring.

In the current MP (MP1), q is estimated annually in the stock assessment model, but it requires an informative Bayes prior distribution (as expected from the above discussion because it is not reliably determined from the data). Following from Martell et al. 2012's derivation the 2014 assessment (Part 1), the current MP stock assessment model (AM1) uses a prior of $q_2 \sim Normal(0.56, 0.27^2)$ where q_2 is the dive survey scaling parameter and "*Normal*" is a symmetric probability density function that treats values above and below the expected value (0.56) as equally probable.

The historical MP (MP2) is also based on an informative prior on the dive survey q, i.e.$q^2 = 1$, although it is not really a prior distribution, since it assumes the value is known exactly. In fact, the above definition means that q is not estimated at all; it simply treats the I_t values as absolute, unbiased estimates; therefore, catch levels will generally be consistent with survey biomass observations.

The catch-at-age stock assessment model component in the Cox et al. (2015, in prep.[2]) simulation framework is modified to allow for separate treatment of the surface and dive surveys. The surface survey scaling parameter (q_1) assumption did not change between current and historical MPs and is, therefore, estimated in both MP1 and MP2 (described below). The assessment model component was changed in three places to implement differences between MPs in how q is treated:

(1) Modifying the conditional estimator of the survey scaling parameter coefficient (Cox et al.[2] Equation L.2) to use a surface survey scaling parameter from 1951-1987 and a dive survey scaling parameter from 1988-2014.

(2) Modifying the residual function (Cox et al.[2] Equation L.3) to account for two separate q's.

(3) Adding Bayes prior distributions (Cox et al.[2] Equations L.10) on the survey scaling parameters where they are being estimated.

For the current MP, where both surface and dive q's are estimated, the revised likelihood terms and log-posterior are,

L.2.Curr
$$\widehat{\log q_i} = \begin{cases} \frac{1}{37}\sum_{t=1}^{37} z_t & i = 1 \\ \frac{1}{27}\sum_{t=38}^{64} z_t & i = 2 \end{cases}$$

L.3.Curr $$Z_I = \sum_{t=1}^{37}\left(z_t - \widehat{\log q_1}\right)^2 + \sum_{t=38}^{64}\left(z_t - \widehat{\log q_2}\right)^2$$

L.10.Curr $$G = \ell_{IR} + \ell_P^F + \ell_P^S + \ell_h + \ell_M + \sum_i \frac{1}{2(0.27^2)}\left(\widehat{\log q_i} - \log(0.56)\right)^2$$

The log-posterior function (G, L.10.Curr) includes identical Bayes priors for both surface and dive survey catchabilities. For the historical MP, where the dive survey q_2=1 by the definition above, revised Equations L.2, L.3, and L.10 are,

L.2.Hist $$\widehat{\log q_i} = \begin{cases} \frac{1}{37}\sum_{t=1}^{37} z_t & i=1 \\ 0 & i=2 \end{cases}$$

L.3.Hist $$Z_I = \sum_{t=1}^{37}\left(z_t - \widehat{\log q_1}\right)^2 + \sum_{t=38}^{64}\left(z_t - \widehat{\log q_2}\right)^2$$

L.10.Hist $$G = \ell_{IR} + \ell_P^F + \ell_P^S + \ell_h + \ell_M + \frac{1}{2(0.27^2)}\left(\widehat{\log q_1} - \log(0.56)\right)^2$$

where the log-q_2 parameter in L.3.Hist is retained for clarity, even though it's value is 0 by definition in L.2.Hist (i.e., log(1) = 0).

Harvest control rule: fixed and variable cut-offs for model-based MPs

The Cox et al. (2015, in prep.[2]) HCR function was modified to mimic the way in which the cut-off contributes to TAC decisions in the current and historical MPs for each herring stock (Table 14). Historically (i.e., management period 1996-2011), cut-off values were set at constant (“fixed”) stock-specific biomass levels derived from unfished biomass estimated using data up to 1996.

Reconstructing fixed cut-offs in the simulations (specific to 1996) was beyond the scope of this paper. In addition, it was not possible to simply use the cut-offs that were established in 1996, because they would not have been representative of the operating model(s). Instead, an approximation of the historical approach is used in MP2 by estimating unfished biomass given simulated data up to 2014, and then setting the cut-off to this value for the remainder of the 20-year projection period. For MP1, the cut-off was changed annually based on B_0 estimates obtained each year as new data were available to the stock assessment. Both current and historical MPs use a 20% target harvest rate to set annual TACs. The specific formulas for computing annual TACs are given in Cox et al. (2015, in prep.[2]) Section 2.2.3.

Data-based MP: ccRule

Also simulated is the performance of a purely data-based management procedure that was proposed for the Central Coast fishery. This "ccRule" MP (Table 14) generates annual biomass forecasts B_{T+1} by adding the (unscaled) spawn survey index and catch from the previous year, while the cut-off is given by the lowest biomass forecast value from which the stock recovered during the previous 10 years (i.e. the minimum biomass over the previous 10 years). In some cases, a herring stock might decline for at least 10 consecutive years, so the most recent cut-off value is used in that case. Using a cut-off based on a 10-year window attempts to track time-varying productivity of herring. Note that the ccRule implicitly assumes that q_2=1, similar to the historical MP. A 10% target harvest rate is the other key difference between ccRule and the model-based MPs.

Table 14 Specifications for the current (MP1), historical (MP2), and ccRule management procedures. Model-based procedures MP1 and MP2 forecast biomass in the next year by projecting the age-structured population forward one year given fishing, natural mortality, and age-1 recruitment obtained from the stock-recruitment relationship. The ccRule MP biomass forecast (i.e., year T+1) method adds the spawn survey index (I_T) and catch (C_T).

		Assessment model			Harvest control rule	
MP symbol	MP Description	Scaling parameter assumption	Prior	Forecast biomass	Cut-off	Target harvest rate
MP1	Current model-based MP with variable CUT-OFF	Estimated	Normal Mean=0.56 S.D.=0.27	1-year ahead model-based forecast	**Updated annually**: 25% of unfished biomass estimate	20%
MP2	Historical model-based MP with constant CUT-OFF	Constant q_2=1	NA	1-year ahead model-based forecast	**Constant at 2014 level**: 25% of estimated unfished biomass given data up to 2014 only	20%
ccRule	Data-based MP with variable CUT-OFF	NA	NA	Spawn index plus catch in the previous year	**Updated annually**: Lowest biomass from which stock has recovered in the past 10 years, or most recent CUT-OFF value if stock has declined continuously for 10 years or longer	10%

Performance indicators

Performance indicators are quantitative measures that are used to evaluate MP performance against specific objectives. Because objectives have yet to be defined for herring fisheries, three commonly accepted fishery performance metrics were used as indications of the yield and conservation risks associated with each simulated management procedure. Conservation risk was measured using the probability (P_{cons}) of spawning stock biomass falling below conservation thresholds defined by three candidate LRPs described in Cox et al. (2015, in prep.[2]) - $0.25B_0, 0.30B_0, 0.40B_0$, with an additional LRP of $\overline{B}_{1985\text{-}1994}$ (i.e., average biomass between 1985 and 1994) considered for the Central Coast. The equilibrium-based LRPs are derived separately for each operating model based on historical growth conditions in 1951 and the estimated average natural mortality rate from 1951-2014. P_{cons} was computed as the mean across simulation trials of the proportion of all projection years that the operating model spawning biomass is at or below each LRP.

The additional LPR of $\overline{B}_{1985\text{-}1994}$ considered for Central Coast represents the average biomass during the most recent period of "good" FSC fishing opportunities as identified by the Heiltsuk First Nation. It is meant as a proxy for conditions likely to sustain FSC harvests of the desired and traditionally available quantity and quality. As above, P_{cons} is computed as the mean across simulation trials of the proportion of all projection years.

Simulation outcomes (as opposed to performance relative to an objective) are summarized using median average depletion ($\overline{D}$; the amount of biomass remaining relative to the average unfished level, B_0), median average annual yield over the short (5-years) and long term (20-years), and average annual variability of yield (AAV) for each MP. The AAV statistic is the average proportional change in catch from year-to-year, regardless of direction, i.e.,

$$AAV = \sum_{t=t_1}^{T} \left| Q_t - Q_{t-1} \right| \Bigg/ \sum_{t=t_1}^{T} Q_t$$

where Q_t is the simulated quota (catch is always assumed equal to the quota) obtained by applying a given MP in year t.

Results

Simulated productivity scenarios

The time series bootstrap constrains future natural mortality trajectories within the range of historical estimates with long-term trends toward the mean of the historical time series (Figure 14). The future trends realized in simulated trajectories of M are highly influential in MP performance against the LRPs as discussed below.

Performance against candidate LRPs

Simulated management procedures caused spawning biomasses to fall below equilibrium-based LRPs relatively frequently over the long-term for some stocks and infrequently for others (Table 15). The CC-LRP ($\overline{B}_{1985\text{-}1994}$), which represented the typical biomass during a period of "good" fishing opportunities and stock productivity as identified by the Heiltsuk First Nation, was breached over 50% of the time for all MPs, including the ccRule. The CC-LRP represented the highest biomass and was, therefore, the most challenging LRP to avoid of the 4 candidates considered.

Although the absolute value of MP performance indicators varies by stock and OM scenario, the rank order of conservation performance was relatively similar. MP1 (current) generally resulted in higher median average catch than MP2, though catch was also more variable for MP1 than for MP2 (AAV was higher in MP1 than in MP2). Stocks were more heavily depleted under MP1, i.e., stock biomass relative to unfished equilibrium was lower for MP1 than for MP2. MP1 also had the highest probability of breaching each of the candidate LRPs, regardless of stock or OM scenario.

The ccRule maintained higher stock biomass (and correspondingly higher biomass relative to the unfished state), but at the cost of much reduced catch and higher catch variability from year-to-year (AAV increasing by ~ 68-91% depending on OM scenario) (Table 15). Lower yield from the ccRule resulted in slightly more than half as frequent violation of LRPs compared to the model-based procedures. Nevertheless, the ccRule resulted in spawning biomass less than LRPs 3%-54% of the time depending on the OM scenario (Table 15).

Cox et al. (2015, in prep.[2]) found that MP performance against candidate LRPs was strongly related to future natural mortality rate (*M*) scenarios. This study supports that finding, as stocks with decreasing or stable future trends in *M* (e.g. HG, PRD, Figure 14) appear more resilient to fishing than stocks with increasing future trends in *M* (e.g. SOG and WCVI Figure 14). It is important to note, however, that these trends are strongly dependent on the recent levels of *M* relative to the longer historical period. For example, stocks that had high natural mortality peaks in the past decade or so (HG, CC, WCVI) tend to show decreasing future trends in *M* because the bootstrap is sampling from the whole historical series of *M*'s, which were mostly lower than the recent peak. For the SOG in particular, the effects of sampling the whole historical series of *M*'s has particularly pronounced effects in that the *M* estimates from the mid-1960s to the late 1990 were higher there than for the other stock areas (Figure 5), so that for the projection period the *M* experienced by the stock is higher than recent years. On the other hand, natural mortality rates for PRD were consistent historically so are projected to be stable in the future (Figure 14). MPs are, therefore, able to maintain a less than 5% chance of SSB dropping below the $0.25B_0$ and $0.30B_0$ LRPs for HG and PRD, in large part due to their relatively optimistic simulated future productivity.

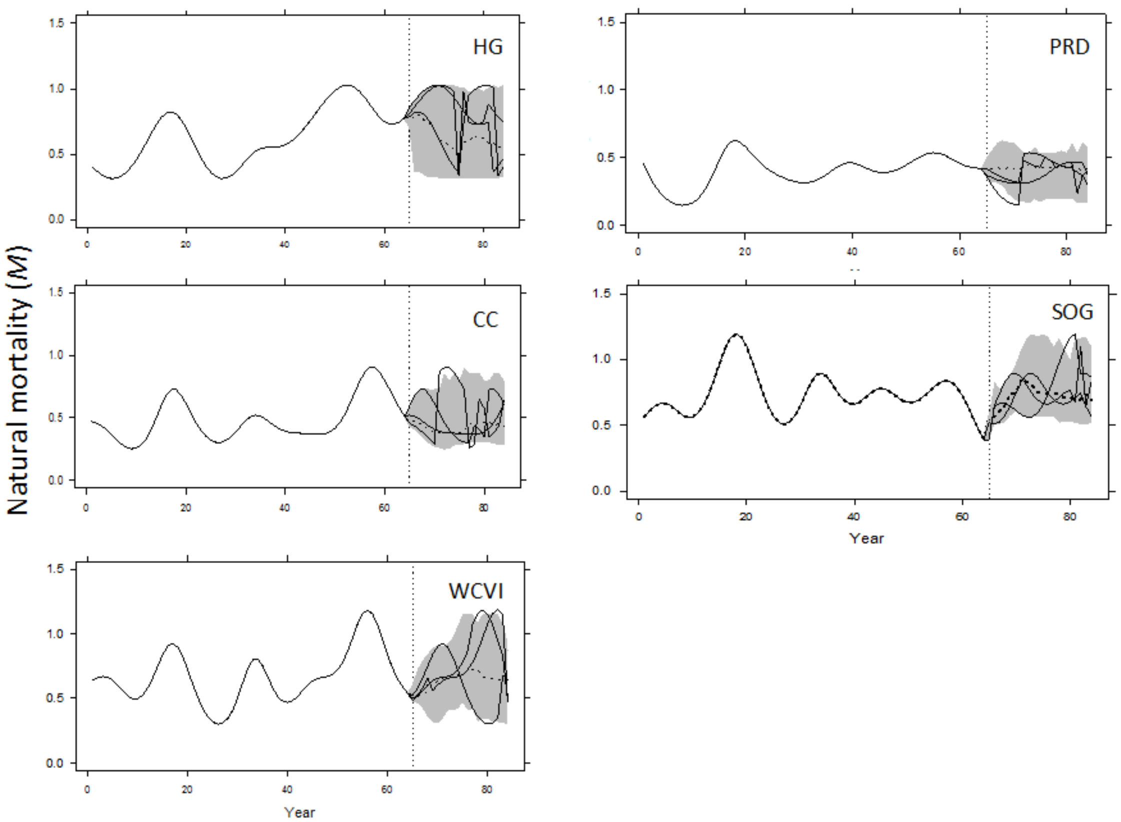

Figure 14. Historical natural mortality rate estimates (left of vertical dotted line) and simulated values (right of vertical dotted line) for each herring stock. Vertical line represents the first year of the projection period. Simulation envelopes include the median (thick dashed black line), central 90% of 100 trajectories (grey shaded region), and three individual simulation replicates (thin lines)

Management procedure evaluation

Approximation of the current MP (MP1) generally achieves higher catch than approximation of the historical MP (MP2), but at the cost of lower biomass relative to the unfished level, higher conservation risk, and increased variability in catch. A formal decision-theoretic approach would integrate, or average, performance over OM scenarios, with weights assigned to the output statistics (e.g. Table 15) from each operating model to account for the plausibility of each hypothesis about *q*. Integrating over the OM scenarios allows the MPs to be ranked and compared directly (Table 16), providing a unified picture of the yield-risk trade-offs. The plausibility weights assigned to each OM scenario are important for MP selection, but are not simple to develop. For example, there is no agreement within the Pilot Technical Working Group on the relative plausibility of OM1 and OM2. In the absence of consensus, a 50:50 weighting to calculate the mean statistics was used for the purpose of summarizing the results, but this does not mean these hypotheses are equally likely, nor does it mean that it would be appropriate to average across the assessment model results in Part 1.

MP performance averaged across (weighted) operating models, and over the long-term (20 years), is consistent with the general result that MP1 achieves higher catch, but at the cost of drawing down stocks more heavily, producing higher inter-annual variability in catch than MP2, and violating LRPs more often (Table 16). This result is maintained across all 5 major stock areas. In addition, both MP1 and MP2 appear to meet conservation criteria $0.25B_0$, $0.30B_0$ in HG and PRD. Performance for the ccRule relative to MP1 and MP2 was insensitive to the integration, in the sense that ccRule maintains higher biomass relative to the unfished level and violates LRPs less frequently than the model-based MPs, but at the cost of lower catch, and higher variability in catch (Table 16).

MP performance summaries over the short-term (first five years of the projection period) more closely reflect MP performance for current stock status, growth, and natural mortality conditions. In general, short-term statistics revealed a more optimistic picture for all performance indicators than the longer-term statistics, regardless of the stock area (Table 16; Short-term). The only exception occurred for CC, where the short-term probability of being below LRPs was higher in the short term than over the long-term for all MPs.

Table 15 Long-term (all projection years) simulation performance summaries for herring management procedures applied to each operating model scenario. OM1 and OM2 are operating models derived from stock assessment models that apply current (OM1) and historical (OM2) assumptions about fishery scaling parameter. MP1 and MP2 approximate the current and historical MPs, respectively, which differ in scaling parameter assumptions and whether to update the cut-off (MP1) or keep it fixed at the 2014 estimate (MP2). Performance statistics include median average depletion ($\bar{D}$), median average catch ($\bar{C}$; thousands mt), average annual catch variability (AAV), and P_{cons} values for four possible biomass limit reference points. P_{cons} is the mean across simulation trials of the proportion of years that the operating model spawning biomass is at or below each LRP. Bold values indicate P_{cons} less than 5%.

						Candidate Limit Reference Points			
Stock	Operating model scenario	MP	$\bar{D}$	$\bar{C}$	*AAV*	$0.25B_0$	$0.30B_0$	$0.40B_0$	$\bar{B}_{1985\text{-}1994}$
HG	OM1	MP1	1.30	4.85	65.90	**0.02**	**0.03**	0.09	--
		MP2	1.37	3.61	73.95	**0.01**	**0.02**	0.05	--
	OM2	MP1	1.23	4.14	75.61	**0.03**	**0.05**	0.11	--
		MP2	1.36	2.80	56.21	**0.01**	**0.03**	0.08	--
PRD	OM1	MP1	0.79	5.62	30.49	**0.02**	**0.04**	0.10	--
		MP2	0.84	4.78	28.81	**0.01**	**0.02**	0.07	--
	OM2	MP1	0.69	5.58	29.80	**0.03**	0.06	0.15	--

						Candidate Limit Reference Points			
Stock	Operating model scenario	MP	$\bar{D}$	$\bar{C}$	*AAV*	0.25B_0	0.30B_0	0.40B_0	$\bar{B}_{1985\text{-}1994}$
		MP2	0.75	4.85	27.66	**0.02**	**0.03**	0.11	--
CC	OM1	MP1	0.62	8.52	24.42	0.14	0.18	0.26	0.73
		MP2	0.63	8.54	23.29	0.13	0.17	0.25	0.72
		ccRule	0.91	3.98	44.43	**0.03**	0.06	0.11	0.50
	OM2	MP1	0.46	6.89	25.63	0.25	0.38	0.52	0.72
		MP2	0.49	6.69	24.87	0.23	0.37	0.50	0.70
		ccRule	0.71	4.47	43.05	0.09	0.20	0.32	0.54
SOG	OM1	MP1	1.06	23.10	25.45	0.09	0.12	0.18	--
		MP2	1.08	20.04	24.87	0.09	0.11	0.17	--
	OM2	MP1	0.97	21.68	29.87	0.17	0.22	0.30	--
		MP2	1.02	20.00	29.49	0.15	0.19	0.27	--
WCVI	OM1	MP1	1.06	8.08	37.72	0.05	0.07	0.12	--
		MP2	1.15	4.85	35.63	**0.03**	**0.04**	0.08	--
	OM2	MP1	0.97	6.31	59.43	0.07	0.09	0.14	--
		MP2	1.12	3.14	53.60	**0.03**	0.05	0.09	--

Identifying an Interim Management Procedure

The choice of an Interim MP for BC Herring fishery management is challenging because there are no clearly articulated management objectives for these fisheries. If objectives did exist, scientific advice would be much more precise and could essentially eliminate MPs that failed to meet the stated objectives. MPs that appear to be consistent with management goals would be retained for further evaluation, perhaps against more challenging operating models and scenarios.

In the absence of specific management objectives and criteria for meeting those objectives, Candidate Limit Reference Points (Cox et al. 2015, in prep.[2]) are used as biological criteria, and a default 5% probability as the criterion for judging MP performance. Thus, an MP would "fail" if it caused biomass to fall below an LRP more often than 5% of the time (Shelton and Sinclair, 2008). When performance is evaluated over a 20-year time frame based on these criteria and averaged over operating model scenarios, the following are observed:

- across all stocks, all MPs failed to meet the high-biomass LRP objectives (0.40B_0, CC-LRP of $\bar{B}_{1985\text{-}1994}$);
- both model-based MPs failed to meet the 0.25B_0 and 0.30B_0 LRP criteria for SOG and CC;
- no MP met any LRP criteria for CC;
- both model-based MPs met the 0.25B_0 and 0.30B_0 LRP criteria for HG, PRD; and,
- only MP2 met the 0.25B_0 and 0.30B_0 LRP criteria for WCVI;

The set of objectives and probability criteria used above do not consider other conservation or yield objectives. Lacking clear objectives (i.e. an agreed-upon set of LRP), no MP's were eliminated from consideration. Therefore, the relative performance of each MP, in terms of simulation outcomes (depletion and catch), along with the probability of exceeding the LRPs to explore the trade-offs inherent in MP choice, is provided.

A simple average of MP statistics across the two operating model scenarios to summarize expected performance was used. This analysis showed that for all stock areas, MP1 achieves lower biomass relative to the unfished level and higher catch than MP2. MP1 also consistently has a higher probability of breaching any LRP considered. The relative differences are maintained when calculated over a short-term (5 year) period, although the performance of both MPs with respect to the LRP improves at this shorter time scale.

The two model-based MPs use identical harvest control rules (i.e., a 20% harvest rate and a $0.25B_0$ cut-off value) for setting the total allowable catch each year, but the main difference between the two is in the assumption about *q*. The source of the cut-off value (fixed vs. annual) differs between the MPs, but the estimates change relatively little from year to year (maximum relative change of 30%). The key difference between the MPs lies in the assumptions about the spawn survey scaling parameter *q*: the current MP (MP1) estimates *q* based on an informative *q*~0.56 prior distribution, while the more conservative MP2 fixes *q*=1. The reason that *q* has a larger effect on management procedure performance is that estimating *q* can as much as double the biomass levels in any given year, with a corresponding increase in TAC (when applying a fixed harvest rate).

Based on the average performance of the two model-based management procedures, MP2 leads to higher biomass relative to unfished levels, lower AAV, and lower probability of breaching limit reference points, but at the expense of lower catches than MP1 across all areas. The results differ according to the time frame considered. In the long term, across all areas the mean (minimum, maximum) difference in depletion was 0.07(0.02, 0.12) for MP2 relative to MP1 (i.e. higher biomass), whereas, in the short term, the difference was 0.04(0.02, 0.06). Across all areas, the mean difference between MP2 and MP2 in AAV was -2.59(-5.67, -0.48) in the long term and -7.58(-42.58, 6.49) in the short term. The mean differences in long and short term catches for MP1, relative to MP2 were -1.55(-3.2, -0.09) and -2.07(-4.41, -0.43), respectively.

Table 16 Management procedure performance averaged (50:50 weighting) across operating models OM1 and OM2. The last four rows give the probability of biomass dropping below each of the Candidate Reference points indicated. Performance statistics include median average depletion ($\bar{D}$), median average catch ($\bar{C}$; thousands mt), average annual catch variability (AAV), and P_{cons} values for four possible biomass limit reference points. P_{cons} is the mean across simulation trials of the proportion of years that the operating model spawning biomass is at or below each LRP. Bold values indicate P_{cons} less than or equal to 5%. Results presented for the long term (all projection years) and short term (first five years of projection period).

	HG		PRD		CC			SOG		WCVI	
	MP1	MP2	MP1	MP2	MP1	MP2	ccRule	MP1	MP2	MP1	MP2
Long-term											
$\bar{D}$	1.26	1.37	0.74	0.80	0.54	0.56	0.81	1.01	1.05	1.01	1.13
$\bar{C}$	4.50	3.20	5.60	4.81	7.70	7.61	4.22	22.39	20.02	7.20	4.00
AAV	70.75	65.08	30.15	28.24	25.03	24.08	43.74	27.66	27.18	48.58	44.62
$0.25B_0$	**0.02**	**0.01**	**0.02**	**0.01**	0.19	0.18	0.06	0.13	0.12	0.06	**0.03**
$0.30B_0$	**0.04**	**0.02**	0.05	**0.03**	0.28	0.27	0.13	0.17	0.15	0.08	**0.05**
$0.40B_0$	0.10	0.07	0.12	0.09	0.39	0.38	0.21	0.24	0.22	0.13	0.09
$\bar{B}_{1985-1994}$	--	--	--	--	0.72	0.71	0.52	--	--	--	--
Short-term											
$\bar{D}$	0.92	0.97	0.69	0.71	0.41	0.43	0.50	2.00	2.03	1.01	1.07
$\bar{C}$	3.17	1.89	6.16	4.77	5.93	5.50	2.38	31.03	26.62	4.07	1.23
AAV	105.92	112.41	30.85	26.33	24.90	23.55	33.55	26.36	30.44	59.32	16.74

	HG		PRD		CC			SOG		WCVI	
	MP1	MP2	MP1	MP2	MP1	MP2	ccRule	MP1	MP2	MP1	MP2
$0.25B_0$	**0.01**	**0.00**	**0.01**	**0.01**	0.19	0.17	0.06	**0.00**	**0.00**	**0.00**	**0.00**
$0.30B_0$	**0.02**	**0.00**	**0.03**	**0.02**	0.38	0.34	0.22	**0.00**	**0.00**	**0.01**	**0.00**
$0.40B_0$	0.07	0.03	0.09	0.07	0.51	0.48	0.39	**0.01**	**0.01**	**0.02**	**0.01**
$\overline{B}_{1985\text{-}1994}$	--	--	--	--	0.95	0.95	0.87	--	--	--	--

The catch implications of selecting MP2 might not be as severe in practice compared to simulations, because the actual catch from most major BC herring stocks tends to be lower than quota recommendations. For instance, in several areas, the realized catch is often less than the TAC (i.e. the harvest rate is less than 20%). Low harvest rates on the order of 10% are not uncommon for forage fish fisheries managed under simulation-tested management procedures. For example, TACs for South African anchovy are set to 9% of the estimated biomass, mainly because simulations revealed high risks in relying on model-based recruitment estimated from noisy acoustic survey data (Butterworth and Bergh 1993). Other simulation studies show that surprisingly low target harvest rates are needed to offset risks of stock assessment model errors (NRC 1998).

Special consideration: The ccRule

The ccRule (MP3) considered for CC maintained the highest spawning biomass (relative to unfished levels) and lowest probabilities of breaching LRPs, but catches averaged 54% and 55% of those achieved under MP1 and MP2, respectively. More precautionary outcomes for the ccRule are probably driven more by the lower 10% target harvest rate than by the "data-based" approach to forecasting biomass. The most obvious performance difference between ccRule and the other MPs was in the AAV, which measures the average proportional change in TAC from year-to-year. For the ccRule, AAV was approximately 44 and 34 in the long and short term, respectively, whereas it ranged from 24-25 for the model-based procedures, in both short and long term. Many of the ccRule's annual TAC changes are arbitrary responses to noise in the survey, because the "data-based" approach uses unfiltered survey data directly in forecasting biomass (i.e., no model or averaging to smooth out noise in the survey). Therefore, the ccRule is expected to cause frequent fishery closures and large year-to-year fluctuations in the catch when fisheries are open.

Sources of Uncertainty

Modelling results in Part I reflect only the structural assumptions specified in the model and weights assigned to the various data components, representing a minimum estimate of uncertainty. While uncertainty in the estimated parameters and derived quantities is explicitly addressed using a Bayesian approach, the uncertainty presented depends on the structural assumptions of the models. Operating models that use alternative parameterizations of natural mortality, or that have different structural assumptions about stock structure will produce different ranges of uncertainty.

The Part 2 scenarios in this analysis are based on historical patterns of productivity and may not reflect the future conditions in any stock area. As stated previously, MP performance was strongly related to the simulated future productivity scenarios. For instance, MPs meet the LRP criteria in stocks with a decreasing or constant projected trend in *M*, but failed to meet the criteria for stocks with increasing future *M*. A more exhaustive MSE would consider a range of operating and assessment models, as discussed in the section below.

Conclusions & Advice

A management strategy evaluation (MSE) process was initiated for the Pacific Herring fishery in May 2015. This multi-year, wide-ranging, and collaborative process is intended to clarify the goals of management, the strategies and tactics that will achieve those goals, and the science needed to support the management process. The work presented here builds on simulations presented in Cox et al. (2015, in prep.[2]) using the same analytical framework, but with alternative operating and assessment models. Accordingly, the results presented here differ from those presented in Cox et al. (2015, in prep.[2]), driven largely by differences in *M* scenarios.

There remains a need to provide management advice for at least the 2015-16 fishing year. Part 1 of this SR provides stock-specific science advice on spawning biomass trends, stock status in 2015, and projected pre-harvest spawning biomass for 2016 using two alternative stock assessments: AM1 and AM2. Decision tables for 2016 present the probabilities of projected spawning biomass falling below the $0.25SB_0$ level (AM1) or fixed cut-off levels (AM2) and of the harvest rate exceeding the 20% or 10% target rates for a range of constant catch levels. Area specific summaries of Part I results are provided below.

To guide interpretation of the assessment advice presented in Part 1, and to provide guidance for selection of an interim management procedure for 2015-2016, the potential future consequences of adopting either the current management procedure (estimated cut-off and estimated *q*s, MP1), or the historical management procedure (fixed cut-off and q=1, MP2) were evaluated using a closed-loop simulation approach. Also, evaluated is an alternate MP for the CC (ccRule). All MPs were evaluated with respect to avoiding candidate limit reference points, average annual catches, and average annual variability in catch. Key results from the Part 2 simulation analysis are also presented below.

While the simulation analysis included in this assessment is a sound first step toward a more exhaustive MSE that could consider a range of operating and assessment models, future simulation work should consider alternative future natural mortality rate scenarios. In addition, the simulation analysis did not evaluate the management implications of multiple/sequential fisheries (e.g. SOK), predators of Pacific Herring, or alternative scenarios involving key life history parameters such as maturity, growth, or spatial distribution. Such evaluations will require different operating/assessment models that could include spatial structure, in-season management, and ecosystem impacts of fishing. Such model scenarios and management procedures could be developed in a management strategy evaluation process for BC Pacific Herring fisheries. However, establishing the priority of the analytical activities to address alternative hypotheses that are relevant for determining if management options meet desired outcomes is required.

Given the short timelines available in which to establish the DFO- First Nations-Commercial Harvesters Pilot Technical Working group, and to conduct such extensive stock assessment and simulation analysis for the provision of Science advice for the development of the 2016 Integrated Fisheries Management Plan, progress in both regards is commendable. To build upon these collaborations, and advance the MSE for Pacific Herring work, a review of the pilot technical working group process and governance is recommended.

Summary Part 1: Stock Assessment

A summary of biomass trend information and the status of the stocks relative to estimated or fixed cut-offs using AM1 and AM2, respectively from Part 1 is as follows for each stock area:

Haida Gwaii

- Both AM1 and AM2 estimate the HG stock to have declined from 2013 to 2015, and both models project a decline in median spawning biomass in 2016. At the root of the declines in projected spawning stock biomass using both stock assessment models is that recruitment in 2013 and 2015 is estimated to be below average so that recruitment is not replacing losses to the biomass from natural mortality.
- AM1 estimates the median spawning biomass in 2015 (SB_{2015}) at 23,354 t and SB_{2015} is estimated to be 68% (median) of the unfished level, SB_0. AM2 estimates the median spawning biomass in 2015 (SB_{2015}) at 11,892 t and 44% of SB_0.
- AM1 projects the median pre-harvest spawning stock biomass in 2016 at 19,795 t; 10,450 t for AM2. In the absence of fishing, AM1 estimates that there is a 2% probability the stock will be below the cut-off of 25% SB_0 in 2016 and AM2 estimates a 52% probability of being below the fixed cut-off level of 10,700 t in 2016.

Prince Rupert District

- Both AM1 and AM2 estimate the PRD stock to have increased from 2014 to 2015, and both models project an increase in median spawning biomass in 2016. AM1 and AM2 estimate a relatively large recruitment of age 2 fish to the population in 2015, owing in large part a high proportion of age 2 fish in the 2015 samples.
- AM1 estimates the median spawning biomass (SB_{2015}) at 20,759 tonnes and SB_{2015} is estimated to be 33% (median) of the unfished level, SB_0. AM2 estimates the median spawning biomass in 2015 (SB_{2015}) at 19,728 t and 32% of SB_0.
- AM1 projects the median pre-harvest spawning stock biomass in 2016 at 26,580 t; 25,530 t for AM2. When comparing predictions from AM1 and AM2, unlike the other stock areas, AM1 predicts a higher probability of being below the $0.25SB_0$ level (when estimating q) and AM2 predicts a lower probability of being below the fixed cut-off of 12,100 t (with q=1) for the same proposed catch. In the absence of fishing AM1 predicts a 10% probability the PRD stock will be below the $0.25SB_0$ level and AM2 predicts a 3% probability the of being below the fixed cut-off level of 12,100 t.

Central Coast

- The inclusion of Area 08 in the Central Coast assessment area was identified by the HTC-DFO Technical Team as an area of concern for First Nations. Specifically, concern was raised as to whether the process of including spawn from Area 08 in the aggregate CC spawning biomass has resulted in Areas 06 and 07 being fished more heavily than would be expected based on their relative contribution to the aggregate CC spawning biomass.
- As a starting point, the degree the available size at age data support the continued inclusion of Area 08 in the Central Coast assessment was investigated. Fish are consistently smaller on average in Area 08 than fish of the same age found in Areas 06 or 07, providing evidence to suggest that the stocks in Area 08 may be distinct from those in Area 06 and 07, requiring further investigation.
- In light of this information and past patterns of removals occurring in Areas 06 and 07 only, and because these analyses were specifically requested, estimates of spawning stock biomass and pre-harvest projections and decision tables for 2016 for Central Coast herring under two scenarios: inclusion and exclusion of Area 08 data were included.
- Both models estimate the spawning biomass to have been increasing since 2012; these observations are consistent across scenarios of including/ excluding Area 08 data.

- Under the scenario of aggregating all CC data, the median estimates of spawning biomass in 2015 (SB_{2015}) for AM1 and AM2 are 44,900 t and 24,832 t, and SB_{2015}) is estimated to be 74% and 46% of the unfished level, SB_0. Under the scenario of excluding the Area 08 data from the CC assessment, the median estimates of spawning biomass in 2015 (SB_{2015}) for AM1 and AM2 40,981 t and 23,126 t and SB_{2015} is estimated to be 75% and 46% of SB_0.
- Projected biomass for 2016 is almost identical to the biomass estimates for 2015. This holds for both AM1 and AM2, and is true irrespective of whether Area 08 is included or excluded from the assessment area. Under the scenario of aggregating all CC data, AM1 projects the median pre-harvest spawning stock biomass in 2016 at 44,210 t; 25,570 t for AM2. Under the scenario of excluding the Area 08 data from the CC assessment, AM1 projects a median pre-harvest spawning stock biomass in 2016 of 40,945 t; 24,170 t for AM2.
- In the absence of fishing, AM1 estimates that there is a 0% probability the stock will be below the cut-off of 25% SB_0 in 2016 (under both data scenarios). AM2 estimates a 12% and 16% probability of being below fixed cut-off levels of 17,600 t and 16,016 t in 2016 (include and exclude Area 08, respectively).
- Decision tables for CC herring include an alternate cut-off of 0.60 SB_0 and harvest rates of 5%, 10% and 20%, as was requested through the HTC-DFO Technical Team. This alternate cut-off reflects Heiltsuk concerns about continuing poor FSC harvests, as well as continuing absence of spawners from many of the traditional spawning areas of importance to the Heiltsuk. Also, following from the May 2015 CSAS meeting, there was a request to use an empirical biomass forecasting methodology (forecast = spawn index + catch), and using this method, the pre-harvest spawning biomass for 2016 is estimated as 32,772 t (Area 06,07,08) or 30,473 t (Area 06,07 only).

Strait of Georgia

- Both AM1 and AM2 estimate the SOG stock to have increased from 2014 to 2015, and both models project an increase in median spawning biomass in 2016. The upward trajectory in spawning biomass and projections for 2016 are the result of the upward trajectory in the spawn index since 2000.
- AM1 and AM2 estimate the median spawning biomass in 2015 (SB_{2015}) at 174,687 t and 92,511 t and stock status in 2015 is estimated at 122% (AM1) and 78% (AM2) of the unfished level.
- AM1 projects a median pre-harvest spawning stock biomass in 2016 of 217,800 t; 123,000 t for AM2.
- In the absence of fishing, AM1 estimates that there is a 0% probability the stock will be below the cut-off of 25% SB_0 in 2016 and AM2 estimates a 0% probability of being below the fixed cut-off level of 21,200 t in 2016.

West Coast Vancouver Island

- There were some small increases in the median spawning stock estimates from 2014 to 2015, however absolute magnitude of the increases was small and there is large uncertainty in the estimates. Both models fit the 2015 spawn survey index value, but under-fit the 2013 and 2014 values, thus explaining how the model can estimate a stock that is apparently increasing even though the most recent spawn index data indicate it has decline from 2014 to 2015.
- AM1 estimates the median spawning biomass (SB_{2015}) at 25,338 tonnes and SB_{2015} is estimated to be 44% (median) of the unfished level, SB_0. AM2 estimates the median spawning biomass in 2015 (SB_{2015}) at 12,708 t and 28% of SB_0.
- There are pronounced differences in the probabilities of being below estimated and fixed cut-offs in 2016. AM1 projects a median pre-harvest spawning stock biomass in 2016 of 34,450 t; AM2 projects a median pre-harvest spawning stock biomass of 17,830 t. AM1 results suggest there is a 1% chance of the stock being below the estimated 0.25 SB_0, whereas AM2 results suggest there is a 56% chance of being below the fixed cut-off of 18,800 t.

Area 2W

- Both assessments models estimate the stock biomass as stable, with median biomass levels fluctuating from 3,260 – 4,004 t (AM1) and 1,428 – 1,715 t (AM2) from 2011 to 2015. Both models fit the 2014 observation and under-fit observations from 2006-2013, estimating a downward trajectory in recent years with a high degree of uncertainty. AM1 and AM1 estimate the median spawning biomass in 2015 (SB_{2015}) to be 3,260 t and 1,428 t, and median stock status (SB_{2015}) relative to the unfished level (SB_0) is estimated to be 101% and 72% (AM1, AM2).
- Both models project an increase in median spawning biomass in 2016, with AM1 and AM2 predicting SB_{2016} of 2,834 t and 1,255 t, respectively.

Area 27

- Both assessments estimate the stock as increasing from 2012 to 2015. There is little contrast in the spawn index from 2000-2015, and both models fit the majority of these survey observations. AM1 and AM2 estimate median spawning biomass in 2015 (SB_{2015}) of 2,176 t and 1,738 t, and SB_{2015} is estimated at 99% and 95% of SB_0.
- Both models project a decrease in median spawning biomass in 2016, with AM1 and AM2 predicting median biomass levels of 2,834 t and 1,255 t, respectively (Table 4).

Summary Part 2: Simulation Analysis

- Simulated management procedure performance is contingent on how future patterns of natural mortality are simulated in the operating model. The historical *M*s used in this analysis produce some results inconsistent with recent experiences. Notably, application of either MP1 or MP2, in HG and WCVI stock areas is predicted to have a less than 5% chance of dropping below $0.25B_0$ reference points, whereas SOG has a greater than a 10% chance. This difference is due to the optimistic future productivity scenarios simulated for HG and WCVI.
- Across all stocks, all MPs failed to meet the high-biomass LRP objectives ($0.40B_0$, CC-LRP of average biomass between 1985 and 1994);
- When examined over both short- and long-term, MP1 generally results in a lower biomass relative to unfished state and higher catch than MP2;

By area, the key conclusions are as follows:

- Both model-based MPs failed to meet the $0.25B_0$ and $0.30B_0$ LRP criteria for SOG. This is because the *M*s sampled for the simulation analyses were higher for the SOG than have been estimated over the past 15-years;
- No MP met any LRP criteria for CC;
- Both model-based MPs met the $0.25B_0$ and $0.30B_0$ LRP criteria for HG, PRD;
- Only MP2 met the $0.25B_0$ and $0.30B_0$ LRP criteria for WCVI;

Contributors

Name	Affiliation
Jaclyn Cleary	DFO, Science Pacific Region
Nathan G. Taylor	DFO, Science Pacific Region
Ashleen Benson	Landmark Fisheries Research
Sean P. Cox	Landmark Fisheries Research
M. Hargreaves (Editor)	DFO, Science Pacific Region

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Approved by

Carmel Lowe
Regional Director
Science Branch, Pacific Region
Fisheries and Oceans Canada

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Appendix

Table A.1. Time series of spawn index data for BC herring stocks.

Year	HG	PRD	CC	SOG	WCVI	Area 2W	Area 27
1951	4,213	27,149	15,390	66,143	19,597	-	-
1952	2,578	24,047	10,295	72,376	13,310	-	-
1953	7,555	28,468	18,237	111,307	39,571	-	-
1954	12,408	13,535	13,967	82,141	20,648	-	-
1955	6,437	14,482	13,564	69,854	15,112	-	-
1956	6,042	14,533	6,626	25,667	27,183	-	-
1957	1,592	27,518	4,607	24,465	44,114	-	-
1958	815	9,882	3,549	16,911	18,986	-	-
1959	8,981	40,961	3,904	47,864	12,979	-	-
1960	6,599	16,545	12,615	55,709	6,015	-	-
1961	8,981	12,059	4,265	44,326	10,556	-	-
1962	5,730	26,329	11,948	35,531	34,470	-	-
1963	7,297	16,981	6,485	37,381	11,245	-	-
1964	4,104	26,919	6,464	35,954	22,761	-	-
1965	1,378	6,055	2,097	38,390	11,891	-	-
1966	2,824	7,105	1,863	7,211	3,722	-	-
1967	710	3,386	5,434	9,647	4,813	-	-
1968	833	5,197	5,790	9,442	11,029	-	-
1969	2,075	965	1,837	14,039	10,465	-	-
1970	5,552	8,814	8,230	34,163	26,912	-	-
1971	13,291	8,480	4,156	38,921	36,206	-	-
1972	9,542	8,774	3,572	25,139	41,857	-	-
1973	7,960	10,959	12,434	16,191	19,481	-	-
1974	14,510	9,244	8,852	40,571	25,540	-	-
1975	9,686	10,565	8,037	70,208	49,149	-	-
1976	15,986	15,199	13,849	60,511	64,200	-	-
1977	15,717	10,425	14,613	78,113	58,679	-	-
1978	16,885	4,734	7,747	101,784	45,607	832	3,595
1979	12,236	7,600	5,669	63,973	66,397	494	6,909
1980	30,455	11,001	12,957	85,679	62,308	2,114	14,419
1981	18,823	12,939	15,811	54,754	52,014	1,811	1,828
1982	22,159	16,108	16,239	101,025	31,926	4,781	4,137
1983	19,470	23,575	18,214	66,201	16,771	4,869	2,501
1984	22,120	25,702	13,788	26,054	23,872	2,522	3,004
1985	17,232	39,606	8,483	25,024	30,010	1,719	1,382
1986	5,679	25,580	20,056	41,575	39,514	684	3,495
1987	10,750	38,673	12,431	41,737	16,858	989	952
1988	13,631	33,957	26,457	24,976	46,242	3,380	1,612

Year	HG	PRD	CC	SOG	WCVI	Area 2W	Area 27
1989	23,638	14,876	21,098	66,052	47,718	2,719	4,612
1990	25,404	21,177	29,106	67,150	46,464	10,946	5,212
1991	16,204	24,305	18,429	45,827	29,996	2,985	3,213
1992	11,068	38,585	42,594	82,710	42,366	3,909	2,779
1993	6,462	23,328	31,717	90,197	34,408	89	5,576
1994	12,807	14,683	28,790	67,138	25,249	248	5,229
1995	4,737	16,879	21,343	64,898	27,128	-	2,484
1996	7,423	22,664	20,344	71,325	33,121	-	1,332
1997	10,778	23,565	27,016	58,181	45,362	-	1,963
1998	20,681	17,997	29,738	74,616	41,011	469	2,156
1999	9,472	27,742	30,723	85,094	19,734	-	658
2000	5,359	17,943	30,810	72,688	12,799	288	1,301
2001	13,860	35,070	24,334	99,703	13,414	35	221
2002	2,286	20,503	20,343	117,862	21,242	149	917
2003	7,398	34,561	24,504	152,150	31,375	1,462	963
2004	5,263	31,104	28,245	122,839	16,432	2,996	1,223
2005	3,614	28,172	23,935	102,755	9,663	584	1,918
2006	4,097	10,255	9,084	50,258	2,875	1,828	2,044
2007	9,436	15,669	9,264	38,524	2,246	1,469	2,248
2008	4,213	12,728	4,255	34,507	2,739	2,000	796
2009	9,794	11,961	10,771	53,652	10,607	2,871	1,201
2010	6,845	28,590	8,654	51,039	2,464	2,725	846
2011	7,554	21,097	10,533	85,001	9,644	2,641	547
2012	11,984	22,716	7,592	52,636	5,407	2,180	744
2013	16,025	25,755	20,359	83,693	12,342	2,076	914
2014	10,566	17,125	13,309	120,468	13,901	1,368	1,307
2015	13,102	17,408	32,146	104,481	11,323	-	2,169

Table A.2. Notation used for operating and assessment models.

Symbol	Description
T_0	Mid-point of initialisation period
T_1	Year in which the management procedure begins
T_2	Year in which the simulation ends
A	Number of age-classes
t	Time step
a	Age-class in years
B_0	Unfished spawning biomass (units determined by units of weight-at-age)
h	Recruitment function steepness

Symbol	Description
M_t	Instantaneous natural mortality rate in year *t*
L_∞	Asymptotic length (cm)
L_1	Mean length-at-age-1 (cm)
k	von Bertalanffy growth constant (/yr)
a_{50}^{mat}	Age-at-50% maturity
a_{95}^{mat}	Age-at-95% maturity
$a_{50}^{sel,X}$	Age-at-50% selectivity by survey (X=S) and fishery (X=F)
$a_{95}^{sel,X}$	Age-at-95% selectivity by survey (X=S) and fishery (X=F)
q	Survey catchability coefficient
R_0	Unfished recruitment
m_a	Proportion mature-at-age
s_a^X	Proportion selected-at-age by survey (X=S) and fishery (X=F)
w_a	Individual weight-at-age
ϕ_x	Equilibrium yield (x=y) or spawning biomass (x=ssb) per recruit
$N_{a,t}$	Number of age *a* fish in year *t*
$B_{a,t}$	Biomass of age *a* fish in year *t*
B_t^{Sp}	Spawning biomass in year *t*
B_t^{Ex}	Exploitable biomass in year *t*
$C_{a,t}$	Number of age *a* fish in year *t* catch
C_t	Fishery catch numbers
$u_{a,t}$	True proportion-at-age *a* in time *t* catch
Q_t	Fishery catch biomass
I_t	Survey biomass estimate
σ_R	Standard error of the random walk in recruitment
σ_M	Standard error of the random walk in natural mortality rate
σ_α	Standard error of the random walk in Walford intercept (growth rate)

Symbol	Description
y^X	Lag-1 autocorrelation in log-natural mortality rate (*X* = *M*), log-recruitment (*X* = *R*), and the growth parameter ($X = \alpha$).
w_t^X	Auto-correlated error in log-natural mortality rate (*X* = *M*), log-recruitment (*X* = *R*), and the growth parameter ($X = \alpha$).
δ_t^X	*Normal*(0,1) error component in log-natural mortality rate (*X* = *M*), log-recruitment (*X* = *R*), and the growth parameter ($X = \alpha$).
$\tau_{I,t}$	Survey coefficient of variation in year *t*
τ_P^X	Standard error of proportions-at-age in fishery catch (*X* = *F*) and surveys (*X* = *S*)
ε_t	Uncorrelated *Normal*(0,1) error in log-survey
$\eta_{a,t}^X$	Uncorrelated *Normal*(0,1) error in logistic-transformed proportions-at-age
$\boldsymbol{x}_{a,t}^X$	Zero-centred log-residual of proportion-at-age
$\boldsymbol{p}_{a,t}^X$	Observed proportion-at-age *a* in year *t* catch

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Centre for Science Advice
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3190 Hammond Bay Road
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Telephone: 250 756-7208
E-Mail: csap@dfo-mpo.gc.ca
Internet address: www.dfo-mpo.gc.ca/csas-sccs/

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