# Performance evaluation of harvest control rules for Pacific herring management in British Columbia, Canada

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Cleary, J. S., Cox, S. P., and Schweigert, J. F. 2010. Performance evaluation of harvest control rules for Pacific herring management in British Columbia, Canada. – ICES Journal of Marine Science, 67: 2005–2011.

Despite application of a harvest control rule (HCR) since 1986, abundance of several Pacific herring (*Clupea pallasi*) stocks in British Columbia, Canada, are currently below levels considered adequate for exploitation. An alternative HCR, based on default limit and upper stock reference (USR) points at 0.4 $B_{MSY}$ and 0.8 $B_{MSY}$, was recently developed under Canada's precautionary fisheries management policy. We simulated the Pacific herring fishery management system to examine whether (i) realized fishery performance over the past 10 years is an expected consequence of applying the existing herring HCR (with a single lower reference point) and (ii) performance could be improved by adopting the Department of Fisheries and Oceans new HCR with limit and USR points. Both HCRs successfully rebuilt stocks to sustainable levels under a high-productivity scenario, but performed poorly when stock productivity was low. The two HCRs were sensitive to stock productivity, because the effect of a target harvest rate (20%) that is independent of productivity was much larger than the effects of biomass reference-point choices. We therefore recommend further research on estimating reference points and sustainable harvest rates for Pacific herring, so that HCRs may be made more responsive to changes in productivity.

**Keywords:** closed-loop simulation, harvest control rule, management strategy evaluation, Pacific herring, precautionary approach, productivity, reference points, stock recovery.

Received 8 November 2009; accepted 8 June 2010; advance access publication 10 September 2010.

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## Introduction

The Pacific herring (*Clupea pallasi*) fishery has operated along the coast of British Columbia, Canada, since 1877 (Pearse, 1982). Commercial landings from an early reduction fishery peaked in the 1960s, followed by stock collapse by 1965 (Hourston, 1980). After a coast-wide fishery closure of 3 years, stock biomass recovered rapidly and the subsequent roe fishery established in 1972 remains the major fishery today.

Pacific herring fisheries are currently managed in five major and two minor stock areas. A formal harvest control rule (HCR), previously shown to permit a sustainable harvest under a range of conditions (Hall *et al*., 1988; Zheng *et al*., 1993), has been used to provide quota advice for the five major stocks since 1986 (Stocker, 1993). However, despite consistent application of this rule, the spawning-stock biomass in three of these stocks is currently below the threshold considered adequate for exploitation (i.e. 25% of the estimated unexploited biomass, 0.25 $B_0$).

Canada's commitments to international agreements, such as the FAO (1995) Code of Conduct for Responsible Fisheries, the UN (1995) Fish Stock Agreement, and the Johannesburg Agreement (UN, 2002), have shaped the development of a national Sustainable Fisheries Framework (SFF; DFO, 2009a). Included under the SFF is a formal harvest policy compliant with the precautionary approach (DFO, 2006), which reaffirms Canada's commitment to the precautionary approach, as well as to restoring stocks to a level associated with their maximum sustainable yield ($B_{MSY}$). The Department of Fisheries and Oceans (DFO) harvest policy recommends the establishment of critical, cautious, and healthy stock status zones delimited by limit and upper stock reference (USR) points, as well as a predetermined decision rule that defines acceptable fishing mortality rates within each zone. The default limit reference point (LRP; DFO, 2009b), defined as 0.4 $B_{MSY}$, separates the critical and cautious stock zones, whereas the default USR point, defined as 0.8 $B_{MSY}$, separates the cautious and healthy stock zones. The removal reference defines the maximum acceptable removal rate (i.e. fishing mortality rate), which is constant in the healthy zone, proportional to abundance in the cautious zone, and negligible (i.e. little or no targeted catch) in the critical zone.

The HCR currently used for management of the Pacific herring fishery was introduced in 1986, when the focus centred primarily on sustaining the fishery and minimizing the number of years in which the fishery was closed (Stocker, 1993). It is a hybrid constant harvest rate/minimum escapement strategy; it therefore differs considerably from that described in the DFO harvest policy. The 20% harvest rate (initially established in 1983) originated from analyses of stock dynamics that indicated that this rate would stabilize both catch and spawning biomass, although foregoing little long-term yield (Hall *et al*., 1988; Zheng *et al*., 1993).

These studies also indicated that a 20% harvest rate would sustain British Columbia herring stocks during low-productivity regimes (Haist *et al.*, 1986; Hall *et al.*, 1988).

However, the harvest rate is conditional on a single LRP ($0.25\ B_0$) representing a fixed minimum-escapement level. The lack of recovery of two major stocks (i.e. the west coast Vancouver Island—WCVI, and the Queen Charlotte Islands—QCI) despite fishery closures for 6 and 8 years, respectively, during the past decade, motivated us to compare the expected performance of the herring HCR as currently used to DFO's new harvest policy (DFO HCR) in terms of their ability to rebuild depleted herring stocks.

We used closed-loop simulations of the management system to evaluate the performance of the two HCRs under scenarios of high and low stock productivity, because the current lack of recovery is assumed to be caused by a low-productivity regime. Performance was evaluated by the extent to which conservation objectives were achieved under each rule.

## Conservation objectives

Performance of the two HCRs under scenarios of high and low stock productivity is evaluated against the conservation objectives specified in Table 1. Each objective consists of three components: (i) the target stock biomass relative to $B_{MSY}$; (ii) the time-frame in which to achieve the target; and (iii) the probability of achieving the target. The first two objectives (maintain healthy stock size and avoid critical stock sizes) were adapted from the New Zealand harvest strategy (NZMF, 2008), with probabilities assigned according to Shelton and Sinclair (2008), who suggest that Canada could use these values in conjunction with target and soft LRPs. Specifically, we attempted to incorporate their suggested modifications to the New Zealand Standard as described in Shelton and Sinclair (2008, p. 2311). DFO (2009b) states 1.5–2 generations as a target time-frame for stock recovery; consequently, the time-frames evaluated represent two, four, and six generations for Pacific herring. The third objective (reach target stock size) follows from Canada's commitment to rebuild depleted stocks to $B_{MSY}$ by 2015, beginning in 2002 when the Johannesburg Agreement (UN, 2002) was signed, with the $p$-value of 90% chosen as a reasonable value. The desired probability of achieving a given objective is worded as per cent certainty, the term typically used in discussions with fisheries managers.

All three objectives were originally designed for the National Workshop on Linking Fishery-Independent Surveys to Management Advice (Ottawa, Canada, from 24 to 26 March, 2009).

**Table 1.** Conservation objectives used for performance evaluation of the two HCRs.

| Conservation objectives | Target biomass | Time-frame | $P$ (%) |
|---|---|---|---|
| a. Maintain healthy stock size | $\geq B_{MSY}$ | 10, 20, and 30 years | 50 |
| b. Avoid critical stock sizes | $<0.5\ B_{MSY}$ | 10, 20, and 30 years | 95 |
| c. Reach target stock size | $B_{MSY}$ | 13 years (2015) | 90 |

Objectives (a) and (b) were derived from the harvest strategy used in New Zealand (NZMF, 2008), whereas objective (c) follows from Canada's commitment to rebuild depleted stocks to $B_{MSY}$ by 2015, beginning in year 2002 when the Johannesburg Agreement was signed ($p$ refers to minimum probability of achieving target in percentage of years or reaching target in 2015).

## Simulation framework

The operating model describes a simulation of fish population dynamics, fishery catches, and data generation mechanisms (Appendix Tables A1 and A2). The population dynamics component represents an age-structured population with recruitment following a Beverton–Holt stock–recruitment relationship. Two simplifying assumptions are important: (i) survey and fishery selectivity patterns follow the maturity ogive equation (A4), which means that spawning, survey, and exploitable biomasses are identical; and (ii) all individuals of age $A$ and older in the "plus group" age have the same selectivity, maturity, and body weight.

Pacific herring stocks have demonstrated wide fluctuations in abundance, determined largely by variability of the annual recruitment of 3-year-old fish to the spawning population, although factors such as changes in predator abundance, zooplankton biomass, and oceanic conditions may also affect abundance (Ware, 1991). Recruitment of age 1 individuals to the population happens in a single pulse at the beginning of the year. Interannual variability of recruitment has two components: (i) a deterministic Beverton–Holt relationship between spawning biomass in year $t-1$ and expected age 1 recruitment in year $t$, Equations (A5)–(A8) and (A13); and (ii) lognormally distributed, lag-1 autocorrelated random variation around the expected recruitment, Equation (A12). The shape of the stock–recruitment relationship is determined by the steepness parameter ($h$), defined as the proportion of maximum recruitment produced when spawning biomass is 20% of the unfished equilibrium level (Mace and Doonan, 1988). We investigated the effects of variability of stock productivity by changing $h$ (0.9 and 0.4 for high and low productivity, respectively) at low spawner abundances. These values represent plausible extremes, based on past stock assessments and qualitative information on stock productivity. Within each scenario, all other model parameters are held constant (Appendix Table A1).

Where possible, parameter values were derived from the 2009 stock assessment (Appendix Table A1; Cleary *et al.*, 2009; Schweigert *et al.*, 2009). However, two modifications were necessary. First, the existing assessment framework uses a statistical catch-at-age model to estimate spawning biomass and forecast biomass and recruitment for the coming year. In the operating model, annual assessments are simulated using a Kalman filter. Although this approach does not explicitly represent an assessment model, it provides estimates with similar statistical properties and retrospective biases as quantitative assessment models (Walters, 2004). Second, the simulation framework considers only one purse-seine fishery (omitting the gillnet fishery) operating on a single herring population, without immigration or emigration.

## Management procedures

The management procedure (MP) represents data collection, stock assessment, and regulatory components of the system. We evaluate two MPs distinguished only by the form of the HCR (Figure 1).

The current herring HCR combines a constant harvest rate with a minimum escapement policy ($\text{LRP} = 0.25\ B_0$). The first step is to compute the forecast spawning-stock biomass (fSSB). If $\text{fSSB} \leq \text{LRP}$, the harvest rate is set to zero. Otherwise, the harvest rate $U_{\text{HERRING}}$ is set equal to the harvest rate needed to achieve at least an escapement equal to the LRP or 0.2, whichever is

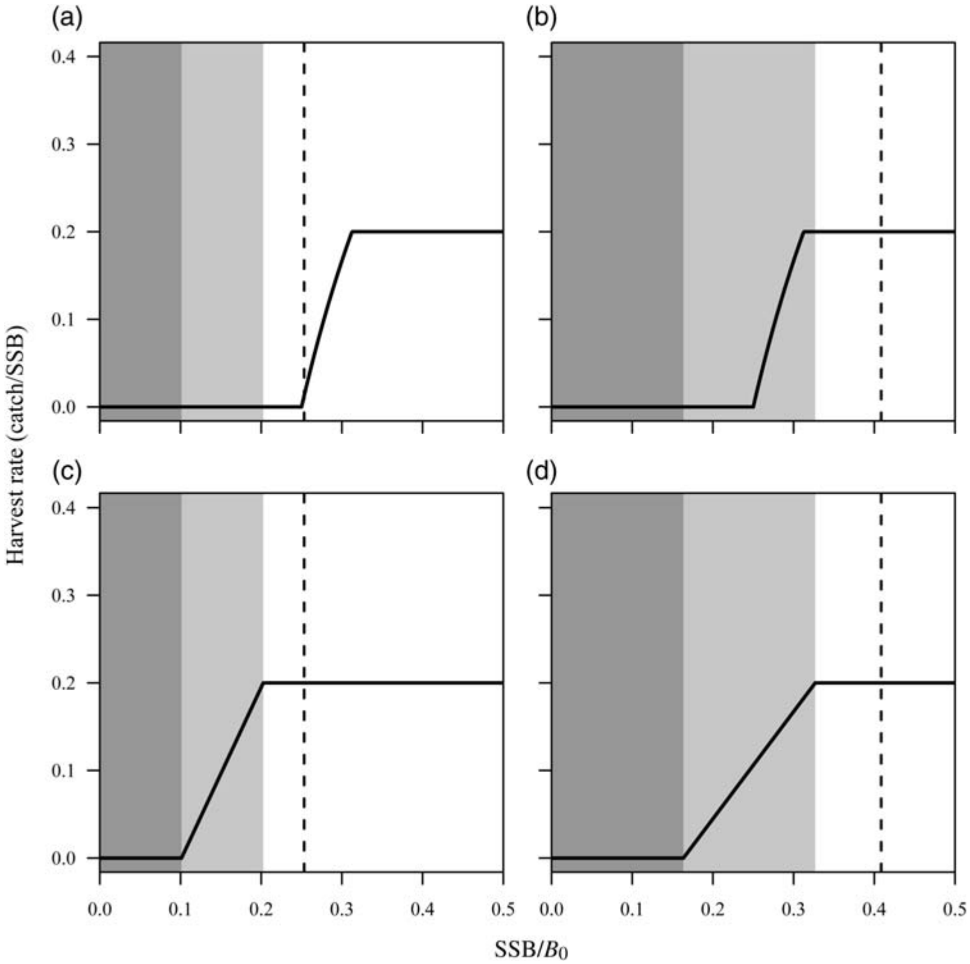


**Figure 1.** The herring HCR (a and b) and DFO HCR (c and d) under scenarios of high (a and c) and low (b and d) stock productivity. Vertical dashed lines indicate $B_{MSY}$ levels for each scenario, indicated as $B_{MSY}/B_0 = 0.253$ for high stock productivity (a and c) and $B_{MSY}/B_0 = 0.409$ for low stock productivity (b and d). Thick black lines indicate each HCR, whereas shaded zones represent the critical (left), cautious (middle), and healthy (right) zones, as defined by the DFO harvest strategy (using default zone boundaries of 0.4 $B_{MSY}$ and 0.8 $B_{MSY}$). The rising part of the herring HCR (between 0.25 $B_0$ and 0.31 $B_0$) represents the minimum escapement portion; the inflection points of the DFO HCR are defined as 0.4 $B_{MSY}$ and 0.8 $B_{MSY}$.

smaller (Hall *et al.*, 1988; Stocker, 1993), i.e.

$$U_{\text{HERRING}} = \begin{cases} \min\left(\dfrac{\text{fSSB} - 0.25B_0}{\text{fSSB}}, 0.2\right) & \text{fSSB} > 0.25B_0 \\ 0 & \text{fSSB} \leq 0.25B_0 \end{cases}. \quad (1)$$

The annual catch is then computed as $\text{TAC}_{\text{HERRING}} = U_{\text{HERRING}} \times \text{fSSB}$.

The DFO HCR uses the default parameterization suggested in the harvest policy; that is, a LRP = 0.4 $B_{MSY}$ and USR = 0.8 $B_{MSY}$ (DFO, 2009b). For stock levels above the USR, the total allowable catch (TAC) is derived by applying a 20% harvest rate to the forecast spawning-stock biomass in the same manner as the herring HCR. For stock levels below the USR, the fishing mortality is reduced in proportion to the amount by which biomass is below the USR. Below the LRP, the target harvest rate is zero. Therefore, the DFO HCR is defined by

$$F_t = \begin{cases} 0.223 & B_t \geq 0.8B_{\text{MSY}} \\ 0.223\left(\dfrac{B_t - 0.4B_{\text{MSY}}}{0.4B_{\text{MSY}}}\right) & 0.4B_{\text{MSY}} \leq B_t < 0.8B_{\text{MSY}} \\ 0 & B_t < 0.4B_{\text{MSY}} \end{cases}, \quad (2)$$

and $\text{TAC}_{\text{DFO}} = (1 - e^{-F})\text{fSSB}$. Hence, the two HCRs differ in how reference points are parametrized, as well as how the TAC is adjusted when the biomass falls within the cautious zone.

## Results

Both HCRs succeeded in managing high-productivity stocks at levels $\geq B_{MSY}$ in 50% of the years, and over all time-frames considered (Table 2). However, in the low-productivity scenario, both fail to achieve this objective, regardless of time-frame. The probability of achieving stock biomass levels of $B_{MSY}$ or greater ranged from $p = 0.20$ to 0.33, with the highest probabilities achieved using the herring HCR over a 30-year projection period. In both scenarios and for all time-frames, the probability

**Table 2.** Probability of achieving two conservation objectives (maintain healthy stock sizes and avoid critical stock sizes) under assumptions of high and low productivity when simulated population is managed according to the herring HCR or the DFO HCR within 10, 20, and 30 years.

| Management | Maintain healthy stock sizes | | | Avoid critical stock sizes | | |
|---|---|---|---|---|---|---|
| | 10 | 20 | 30 | 10 | 20 | 30 |
| High productivity | | | | | | |
| Herring HCR | **0.81** | **0.86** | **0.86** | **0.97** | **0.97** | **0.98** |
| DFO HCR | **0.78** | **0.84** | **0.83** | **0.96** | **0.97** | **0.97** |
| Low productivity | | | | | | |
| Herring HCR | 0.21 | 0.30 | 0.33 | 0.69 | 0.71 | 0.71 |
| DFO HCR | 0.20 | 0.28 | 0.31 | 0.64 | 0.68 | 0.68 |

Emboldened values denote scenarios that achieve the objective.

of managing the stock at a level $\geq B_{MSY}$ was slightly higher when using the herring HCR.

Similar results were obtained for the objective to avoid critical stock sizes $<0.5\ B_{MSY}$ with 95% certainty: both HCRs successfully achieved the objective in the high-productivity scenario, but not in the low-productivity one (Table 2). Although the objective to reach a target stock size of $B_{MSY}$ with 90% certainty by 2015 was only just reached in the high-productivity scenario, neither HCR would ensure that stock biomass would remain at that level in later years (Figure 2). In the low-productivity scenario, the chances were only around 30%. Overall, and in all cases, the herring HCR outperformed the DFO HCR slightly.

## Discussion

The shift in demand for precautionary management (Shelton and Sinclair, 2008) prompted us to revisit the HCR currently used, because fishery objectives increasingly prioritize conservation outcomes over economic concerns. When our analyses assumed that stock productivity was high, persistent application of either the DFO or the herring HCR permitted successful management of the stock around $B_{MSY}$ with >50% probability. They also proved adequate to avoid critical stock sizes with greater than a 95% probability and they met the terms of the Johannesburg Agreement by rebuilding depleted stocks to at least $B_{MSY}$ by

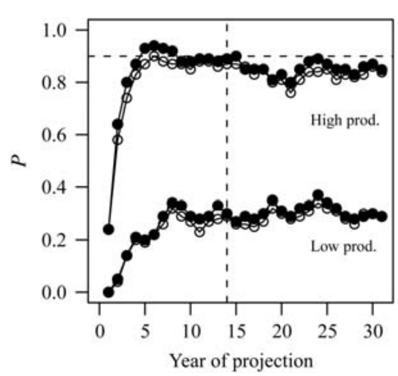


**Figure 2.** Probability ($p$) of rebuilding the stock to $B_{MSY}$ using the herring HCR (dots) and the DFO HCR (open circles) under the assumption of high and low productivity of the stock. The horizontal dashed line indicates the objective of reaching $p = 0.9$; the vertical dashed line represents 2015 in the simulated time-series.

2015 in 90% of the simulation trials. However, when we assumed stock productivity was low, neither HCR met any of the conservation objectives within a 30-year time-frame. This finding is consistent with previous HCR evaluations (Schweigert *et al.*, 2007) and suggests that defining rules based on average biomass and productivity levels may not necessarily be appropriate when biomass is low and in need of rebuilding. Although the 20% harvest rate may prevent long-term declines in low-productivity herring stocks, as demonstrated in the original simulation studies, it may not allow rebuilding of stocks that have been depleted seriously.

HCRs designed to rebuild spawning biomass from overfished conditions may also fail if the productivity regime changes substantially during recovery (Cooke, 1999). For example, in the distant past, the QCI and the WCVI stocks have recovered from prolonged periods of decline, because of a series of consecutive good year classes (Hourston, 1980; Ware, 1991). However, stock dynamics and environmental conditions that previously allowed for such recovery apparently changed, because the current HCR has been unsuccessful at maintaining either stock above 0.25 $B_0$ in recent years, although it is presumably more conservative than any former management strategy. This highlights the importance of designing a management strategy that is robust to both short- and long-term fluctuations in stock productivity.

Although our results revealed similar conservation performance between the two HCRs under both high- and low-productivity regimes, the results suggest that the herring HCR is slightly more conservative. However, there may be other scenarios where the narrow recovery window (i.e. the biomass range over which the harvest rate is adjusted) of the herring HCR may impede stock recovery relative to the DFO HCR. The limit and the USR points of the DFO HCR are defined relative to $B_{MSY}$, so when stock productivity is low (Figure 1d), the absolute biomass difference between 0.4 $B_{MSY}$ and 0.8 $B_{MSY}$ is larger than when productivity is high (Figure 1c). This creates a wider range of biomass where harvest rates are reduced to promote stock recovery. Conversely, the herring HCR is defined relative to unfished biomass; therefore, reference points, as well as the biomass range over which the harvest rate is reduced, are independent of stock productivity. In the example presented, the recovery window falls inside the boundary of the cautious zone, as defined by the new harvest policy (i.e. below 0.8 $B_{MSY}$). If we had assumed a productivity regime that was even lower, the herring HCR may not reduce harvest rates at all until the stock biomass falls into the critical region. We therefore run the risk of exploiting the stock at the 20% harvest rate, even though stock rebuilding would be clearly necessary.

In an evaluation of common biological reference points used in fisheries management, Haltuch *et al.* (2009) suggest that control rules based on estimated $B_0$ and stock depletion may perform better than those based on the estimates of $B_{MSY}$, mainly because of the difficulty in estimating the latter. Our results essentially compared the performance of these alternatives under ideal conditions, where each is known exactly. For instance, we provided the true $B_0$ to the simulated manager who also assumed (correctly) that $B_0$ is constant and independent of productivity regime. This mimics the existing stock-assessment framework whereby $B_0$ for each stock is estimated outside the assessment model (over a predefined historical period) and has not changed since 1996. Similarly, the DFO HCR was based on assuming that $B_{MSY}$ was known exactly under both productivity regimes. Yet, despite such unrealistically good knowledge, both rules failed to rebuild the stock to $B_{MSY}$ under low-productivity conditions. If we had simulated a realistic assessment procedure where $B_0$- or $B_{MSY}$-based reference points were estimated from accumulating data (*sensu* Haltuch *et al*., 2009), performance would have been even worse in both cases. The DFO HCR would obviously suffer from using assessment model estimates of $B_{MSY}$, whereas the herring HCR would suffer from failure to incorporate assessment information into the constant harvest rate or minimum escapement threshold (both quantities being constants). Therefore, further research should include the simulation of quantitative stock assessments, so that conservation properties of both HCRs can be assessed in the context of more realistic information becoming available in future. It is straightforward to estimate $B_{MSY}$ in management strategy simulations, as required for testing the DFO HCR. Testing the herring HCR in the context of actual stock assessments would be more challenging, because the appropriate constant harvest rate and LRP do not have analytical solutions and must therefore be determined using Monte Carlo simulations. Nevertheless, such additional computational demands may be worthwhile, given our results demonstrating that even an incorrectly parameterized (i.e. for the low-productivity regime) constant harvest rate/minimum escapement policy may be better than a variable harvest rate policy based on $B_{MSY}$.

We have only considered a fraction of the actual uncertainty involved in Pacific herring management. For instance, we did not vary other factors affecting uncertainty, such as observation error in abundance indices, temporal correlation of annual recruitment, or changes in natural mortality. Further evaluation of HCRs should involve robustness testing with respect to these other variables, as well as to the actual statistical catch-at-age assessment model used in annual stock assessments, because such analyses often represent a substantial source of error and uncertainty in harvest-strategy evaluations (NRC, 1998).

Stock biomass is a dependent variable, influenced by both fishing and the environment (Cadrin and Pastoors, 2008). Declining trends in prey availability for juvenile herring, as well as increasing trends in abundance of marine mammal predators and potential competitors (Pacific sardine *Sardinops sagax*), imply that ecosystem processes should be considered when evaluating harvest strategies for Pacific herring. Changes in food availability (bottom-up) and/or predator communities (top-down) have recently been correlated with increases in model estimates of natural mortality of Pacific herring stocks (Schweigert *et al*., 2010), suggesting that both processes may affect herring population dynamics via changes in growth and survival. Periodic re-evaluation of HCRs therefore remains necessary to ensure compliance with the precautionary approach in the context of ecosystem change.

Although it is recognized that herring play a critical role in the ecosystem and are a food source for a variety of species (Schweigert *et al*., 2010), there is little information available to develop ecosystem-based conservation limits for herring. The harvest rate of 20% of the mature biomass should ensure that a large fraction of the spawning-stock biomass is available to predator species or is protected for future production. Because no targeted commercial harvest takes place on immature herring, most juveniles are available to support ecosystem processes anyway. Nevertheless, research is continuing to understand better these ecosystem processes and the role that herring play in maintaining the integrity and functioning of the ecosystem.

## Acknowledgements

The evaluation framework used was initially developed by SPC, JSC, and A. R. Kronlund (Fisheries and Oceans Canada) for the workshop "Linking Fishery-Independent Surveys to Management Advice". We thank A.R. Kronlund for continual support on this project, K. Holt (Fisheries and Oceans Canada) and A. J. Benson (Simon Fraser University) for helpful feedback during project development, and J. DiCosimo (North Pacific Fishery Management Council) for providing very helpful reviewer comments.

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## Appendix

The population at time $t = 1$ is initialized in the deterministic, unfished equilibrium state using Equations (A9)–(A11). State dynamics are driven by recruitment and fishing mortality rate ($F$), other factors remaining constant. In calculating the catch equation (A17), $F$ and natural mortality rate ($M$) are assumed to operate continuously and simultaneously throughout the year. The simulation time-frame is divided into an initialization ($t \le T_1 - 1$) and a projection ($T_1 \le t \le T_2$) period. Stock status at $t = T_1 - 1$ (just prior to the projection period) is initialized at a predetermined level of spawning biomass by solving for the $T_1 - 1$ $F$s that maximize the cumulative catch over $1 \le t \le T_1 - 1$ subject to the constraint that realized depletion $d = B_{T_1-1}/B_0$ is approximately equal to a prespecified level $d^*$. This optimization step involves maximizing the objective function:

$$G(\mathbf{F}') = \sum_{t=1}^{t=T_1-1} D_t - 1000(d - d^*)^2.$$

We managed to limit the time needed to solve this optimization by: (i) specifying a reduced set of $n$ fishing mortality parameters $\mathbf{F}' = (F'_1, F'_2, \ldots, F'_n)$ corresponding to a uniformly spaced grid of $n$ points in time between $t = 1$ and $t = T_1 - 1$; (ii) using a cubic spline interpolation of these $n$ points to generate the complete fishing mortality history at all $t$: $\mathbf{F} = (F_1, F_2, \ldots, F_{T_1-1})$; and (iii) performing the optimization with respect to $\mathbf{F}'$. We found that, in most cases, a convergence tolerance of 0.0001 on $G$ gives realized depletion values that are within 0.01–0.03 of the prespecified level using $n = 5$.

During the projection period, the HCR determines the TAC. $D_t$ and $F_t$ are computed by solving the catch equation (A17) for the given exploitable biomass and $M$. Simulated surveys, Equation (A19), generate the estimates of the absolute spawning and exploitable biomass at the beginning of the year. A lognormal distribution of random survey observation errors is determined by the standard error $\tau$ of log-survey residuals.

**Table A1.** Parameter notation for the operating model (age-structured population, survey, and fishery).

| Symbol | Value | Description |
|---|---|---|
| $T_0$ | $T_1/2$ | Midpoint of initialization period |
| $T_1$ and $T_2$ | 50 and 80 | Year of HCR implementation and last year of simulation, respectively |
| $A$ | 9 | Number of age classes |
| $t$ | $1, 2, \ldots, T$ | Time-step |
| $a$ | $1, 2, \ldots, A$ | Age class in years |
| $B_0$ | 100 | Unfished spawning biomass |
| $d^*$ | 0.2 | Stock depletion at $T_1$ |
| $h_H$ and $h_L$ | 0.9 and 0.4 | Recruitment function steepness |
| $M$ | 0.5 | Instantaneous natural mortality rate |
| $L_\infty$ | 30.0 | Asymptotic length (cm) |
| $L_1$ | 10.0 | Length-at-age 1 (cm) |
| $k$ | 0.20 | von Bertalanffy growth constant |
| $c_1$ and $c_2$ | 0.0000043 and 3.232 | Allometric growth parameters, respectively |
| $a_{50}$ and $a_{95}$ | 2.5 and 3.0 | Age-at-50% and -90% maturity, respectively |
| $q$ | 1.0 | Survey catchability coefficient |
| $\sigma_R$ and $\sigma_L$ | 0.70 and 0.25 | Standard error of log-recruitment and length-at-age, respectively |
| $\gamma_R$ | 0.50 | Lag-1 autocorrelation in log-recruitment deviations |
| $\tau$ | 0.36 | Survey standard error |
| $R_0$ | | Recruitment to unfished population |
| $m_a$ | | Proportion mature-at-age |
| $w_a$ | | Individual weight-at-age |
| $\phi$ | | Equilibrium spawning biomass per recruit |
| $N_{a,t}$ and $B_{a,t}$ | | Number and biomass of age $a$ fish in year $t$, respectively |
| $N_t$ and $B_t$ | | Spawning numbers and biomass in year $t$, respectively |
| $I_t$ | | Survey biomass estimate |
| $\omega_{R,t}$ | | Autocorrelated recruitment residual |
| $\delta_t$ | Normal (0.1) | Uncorrelated log-recruitment residual |
| $\epsilon_t$ | Normal (0.1) | Uncorrelated log-survey residual |
| $C_t$ | | Fishery catch numbers |
| $D_t$ | | Fishery catch biomass |

**Table A2.** Operating model (age-structured population, survey, and fishery) using a set of input parameters $\Theta$.

**Parameters**

$$\boldsymbol{\Theta} = (B_0, h, \boldsymbol{\delta}, q, \boldsymbol{\sigma}, \tau, \boldsymbol{\gamma}, L_\infty, L_1, k, M, a_{50}, a_{95}) \quad \text{(A1)}$$

Life-history schedules

$$l_a = L_\infty + (L_1 - L_\infty)e^{(-k(a-1))} \quad \text{(A2)}$$

$$w_a = c_1 l_a^{c_2}(1 + 0.5c_2(c_2 - 1)\sigma_L^2) \quad \text{(A3)}$$

$$m_a = \frac{1}{1 + \exp[-\ln(19)(a - a_{50})/(a_{95} - a_{50})]} \quad \text{(A4)}$$

Stock–recruitment relationship

$$\phi = \sum_{a=1}^{A-1} e^{-M(a-1)} m_a w_a + \frac{e^{-M(A-1)} m_A w_A}{1 - e^{-M}} \quad \text{(A5)}$$

$$R_0 = \frac{B_0}{\phi} \quad \text{(A6)}$$

$$a = \frac{4hR_0}{B_0(1-h)} \quad \text{(A7)}$$

$$b = \frac{5h - 1}{B_0(1-h)} \quad \text{(A8)}$$

Initial population

$$N_{a,1} = R_0 e^{-M(a-1)}, \quad 1 \le a \le A - 1 \quad \text{(A9)}$$

$$N_{A,1} = \frac{N_{A-1,1}}{1 - e^{-M}} \quad \text{(A10)}$$

$$B_{a,1} = N_{a,1} w_a \quad \text{(A11)}$$

State dynamics

$$\omega_{R,t} = \begin{cases} \dfrac{\sigma_R}{\sqrt{1 - \gamma_R^2}}\delta_t, & t = 1 \\ \gamma_R \omega_{R,t-1} + \sigma_R \delta_t, & t > 1 \end{cases} \quad \text{(A12)}$$

$$N_{1,t} = \frac{aB_{t-1}}{1 + bB_{t-1}} \exp\left[\omega_{R,t} - 0.5\frac{\sigma_R^2}{1 - \gamma_R^2}\right] \quad \text{(A13)}$$

$$N_{a,t} = N_{a-1,t-1} e^{-M + m_a F_{t-1}} \quad 2 \le a \le A - 1 \quad \text{(A14)}$$

$$N_{A,t} = N_{A-1,t-1} e^{-M + m_{A-1} F_{t-1}} + N_{A,t-1} e^{-M + m_A F_{t-1}} \quad \text{(A15)}$$

$$B_t = \sum_{a=1}^{A} m_a w_a N_{a,t} \quad \text{(A16)}$$

$$C_{a,t} = \frac{m_a F_t}{M + m_a F_t}(1 - e^{-m_a F_t}) N_{a,t} \quad \text{(A17)}$$

$$D_t = \sum_{a=1}^{A} C_{a,t} w_a \quad \text{(A18)}$$

Survey observations

$$I_t = qB_t \exp[\varepsilon_t - 0.5\sigma_S^2] \quad \text{(A19)}$$

Catches $D_t$ are determined using the MP and HCRs defined in Equations (1) and (2).



doi:10.1093/icesjms/fsq129