CANDIDATE LIMIT REFERENCE POINTS AS A BASIS FOR CHOOSING AMONG ALTERNATIVE HARVEST CONTROL RULES FOR PACIFIC HERRING (*CLUPEA PALLASII*) IN BRITISH COLUMBIA

Photo: Herring. Credit: Fisheries and Oceans Canada

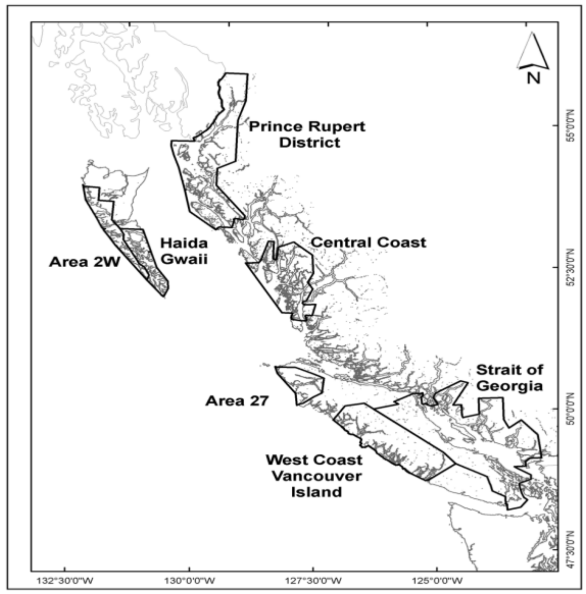

Figure 1: British Columbia Pacific Herring major stock areas: Haida Gwaii (HG), Prince Rupert District (PRD), Central Coast (CC), Strait of Georgia (SOG), West Coast of Vancouver Island (WCVI), and minor stock areas: Area 2W and Area 27.

Context:

British Columbia's Pacific Herring fisheries are managed using a harvest strategy initially designed and adopted in 1986. Part of this harvest strategy was the implementation of a commercial fishing cut-off when the forecasted herring stock biomass is below 25% of the estimated unfished biomass (known as the cut-off level). Since the adoption of this strategy, two major herring stocks - Strait of Georgia (SOG) and Prince Rupert District (PRD) have remained above the cut-off level. However, the other three major stocks, West Coast Vancouver Island (WCVI), Central Coast (CC), and Haida Gwaii (HG), have been below the cut-off level in 32%, 21%, and 46% of years (1986-2013), respectively, which are well below expectations based on the original simulation results.

A closed-loop simulation approach was used to explore the performance of candidate limit reference points (LRPs). An operating model nested within a simulation framework was designed to allow testing of proposed management procedures (the combination of data, assessment model, and harvest control rule) against multiple management objectives for the fisheries. Alternative scenarios of herring stock productivity and dynamics, assessment methods, and frequency of data gathering (annual, biennial *surveys) were tested within this analytical framework. This Canadian Science Advisory Secretariat (CSAS) Regional Peer Review (RPR) reviewed the analytical framework developed for BC Pacific Herring, and provided an initial evaluation of the performance of candidate LRPs under alternative management procedures to inform the renewal of the management framework for BC Pacific Herring in accordance with Canada's Sustainable Fisheries Framework.*

This Science Advisory Report is from the May 27 – 28, 2015 Candidate Limit Reference Points for Pacific Herring in British Columbia using a Closed-loop Simulation Modelling Approach. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

SUMMARY

- British Columbia's Pacific Herring fisheries are managed based on a harvest strategy initially designed in 1986. Since adopting the strategy, two major herring stocks have remained above the management level, permitting commercial fisheries (known as the cut-off), while three stocks have been below the cut-off level in 32%, 21%, and 46% of years between 1986 and 2013.
- Significant decreases in body size have been observed for all BC herring stocks from the early-1980s to 2010; as well as an increase in estimated natural mortality rates in some stocks since 1951 (DFO 2015). The consequences of these time-varying trends in fish stock productivity have not previously been evaluated for Pacific Herring fishery management.
- A review of the literature did not reveal any universally accepted forage fish candidate limit reference points (LRPs) that would apply to BC herring; thus, a suite of candidates were evaluated.
- A closed-loop simulation approach was used to explore candidate LRPs as a basis for evaluating the performance of several management procedures (the combination of data, assessment model, and harvest control rule). Simulations considered alternative theories of herring stock productivity and dynamics, as well as survey frequency (annual or biennial). This represents the first step in a management strategy evaluation (MSE) process that develops the analytical framework for future evaluations and explores the performance of some initial candidate LRPs for the five major Pacific Herring stocks.
- The key components of the analytical framework for Pacific Herring are:
  - operating models for each of the five major Pacific Herring stocks, that represent a range of hypotheses about future changes in growth, natural mortality, and non-stationary productivity dynamics;
  - management procedures providing options in frequency of data collection, stock assessment methods/assumptions, and harvest control rules; and
  - performance indicators for comparing simulated outcomes against a suite of LRPs.
- Management procedure performance was evaluated with respect to potential trends in growth and natural mortality using an age-structured operating model that represented four alternative scenarios of future dynamics of Pacific Herring natural mortality and growth. Natural mortality for each stock area was either held constant at 2013 values or allowed to increase by 50% over the projection period; and, growth was held constant at average 2013 values or trended toward the average historical growth rate for the period 1951-1955.

- Four harvest control rules were evaluated in this analysis. Two harvest control rules were developed to approximate the current practice for Fisheries and Oceans Canada (DFO) management (the difference between the two being biennial or annual spawn surveys) and two harvest control rules were based on proposed conservation rules for forage fish species.
- Three commonly accepted fishery performance metrics were selected to provide an indication of the conservation and yield performance of simulated management procedures. Conservation performance was measured using the probability (P_{cons}) of the spawning stock biomass being below the conservation threshold defined by each of the candidate LRPs.
- A limited number of stock productivity scenarios, management procedures, and candidate LRPs were explored for the five major Pacific Herring stock areas. Nonetheless, results derived from the analytical framework provide proof of the MSE concept for evaluating LRPs, and provide a tool that can be used to update the existing management framework for BC Pacific Herring in accordance with Canada's Sustainable Fisheries Framework.
- The analytical framework has flexibility to explore a broader set of management procedures, ecological hypotheses and First Nations, industry, and other stakeholder objectives.
- The objective of this analysis was not to identify a single LRP for herring management, but to identify characteristics of LRPs that appear to be most informative for assessing the ability of alternative management procedures to achieve management objectives; based on an evaluation of the stock status relative to the candidate LRPs. LRPs based on F_{MSY}, non-stationary unfished biomass, and the lowest biomass from which the stock has recovered, were evaluated to be less informative than fixed (equilibrium) LRPs for this purpose.
- The tested approximation of the current DFO management procedure appears to maintain stocks above the candidate LRPs over a narrow range of assumptions. Increases in natural mortality, similar to those estimated over the past several decades, revealed potential conservation and fishery risks in four of five stocks areas. Specifically:
  - Simulated spawning stock biomass (SSB) for Strait of Georgia (SOG) herring was maintained above the $0.25B_0$ LRP 95% of the time under the DFO1 and DFO2 management procedures, which is consistent with the original evaluation performed for the stock in 1988.
  - The simulations for Prince Rupert District (PRD), the Central Coast (CC) and Haida Gwaii (HG) stocks suggest that both the DFO and the Lenfest management procedures could result in SSB frequently dropping below the LRPs used in this simulation exercise.
  - The LRP that was allowed to change with natural mortality and growth rates (NSB_0) often failed to indicate risk in situations where risks could actually be significant. This was also true for the empirical LRP that reflected the 'worst-case' scenario (Historical B), which was lowest historical biomass from which the stock has recovered.
- To update the Pacific Herring management framework, it is recommended that more realistic representations of the management procedures be developed for evaluation, using the simulation approach and analytical framework reviewed here. For example, consideration should be given to modelling of sequential fisheries based on multiple fleets, uncertainty in the spawn survey scaling parameter (q), and changes in size-at-age.

INTRODUCTION

British Columbia's Pacific Herring fisheries are managed using a harvest strategy initially implemented in 1986. The harvest control rule element of the strategy prescribes a target exploitation rate of 20% for major stock areas when herring stock biomass is predicted in the following year to be above an operational cut-off level of 25% of the estimated unfished biomass and an exploitation rate of 0% when the predicted biomass is below the cut-off level. Subsequent closed-loop simulation test results showed that implementation of this rule would cause the Strait of Georgia herring stock biomass to drop below the cut-off level in less than 5% of years (Hall et al. 1988).

Since adopting the strategy in 1986, two major herring stocks - Strait of Georgia (SOG) and Prince Rupert District (PRD) have remained above the cut-off level. However, the major stocks in West Coast Vancouver Island (WCVI), Central Coast (CC), and Haida Gwaii (HG) have been below the cut-off in 32%, 21%, and 46% of years (1986-2013), respectively, which exceeds expectations based on the original simulations. Contrary to the assumptions underlying Hall et al.'s (1988) simulation testing, long-term declines in body size (weight-at-age) have been observed within all BC herring stocks from the early-1980s to 2010, as well as an increasing trend in the estimated natural mortality rates since 1951 (DFO 2015). The relative contributions of declining body size and increasing natural mortality to stocks falling below the biomass cut-offs are currently not well understood.

One of the challenges of establishing harvest control rules and limit reference points for herring stocks are time-varying directional trends in mean growth and natural mortality, referred to as non-stationarity. Non-stationarity affects harvest control rule performance and the estimation and avoidance of limit reference points. For Pacific Herring stocks, changes in weight-at-age have been observed, and current stock assessments estimate time-varying trends in natural mortality for all stocks. The consequences of non-stationarity in fish stock productivity on performance of management procedures for single species fisheries management have not been explored in detail in either the scientific literature or for Pacific Herring fishery management. Exploring alternative scenarios for future changes is intended to improve the understanding of the harvest control rule performance against conservation objectives as defined by limit reference points (LRPs).

A closed-loop simulation approach was used to test the impact of proposed management procedures (the combination of data, assessment model, and harvest control rule) on stock status, measured against a range of candidate LRPs. Simulations considered alternative theories of herring stock productivity and dynamics as well as survey frequency scenarios (annual or biennial). This approach is an extension of models published by Cox and Kronlund (2008), Cleary et al. (2010) and Cox et al. (2013).

This undertaking represents the first step in a management strategy evaluation process that develops the analytical framework for future analyses and explores the suitability of select candidate limit reference points for the five major Pacific Herring stocks. This process did not explicitly evaluate the current DFO stock assessment and harvest decision making procedure. Instead, it used an approximation to demonstrate proof of concept of the analytical framework. The advice arising from this Canadian Science Advisory Secretariat (CSAS) Regional Peer Review (RPR) will be used to develop an evaluation process to assist in updating the present management framework for BC Pacific Herring in accordance with Canada's Sustainable Fisheries Framework.

ANALYSIS

A review of the literature did not reveal any international best practice for setting objectives for management of forage fish such as BC herring, thus a suite of candidate objectives (LRPs) were considered. These included:

(1) 0.25 B_0, the status quo BC herring cut-off (Hall et al. 1988);

(2) 0.30 B_0 (Sainsbury 2008);

(3) 0.40 B_0 (Pikitch et al. 2012);

(4) a target biomass level that tracks changes in natural mortality and growth rates (NSB_0);

(5) an empirical LRP that reflected the 'worst-case' scenario from which the stock had recovered (Historical B); and

(6) $0.40B_{MSY}$ and F_{MSY} (DFO 2009).

Methods

The key components of this analytical framework for Pacific Herring are:

(1) Operating models for each of the five major Pacific Herring stocks that reflect the current state of the stock, a range of hypotheses about future changes in growth and natural mortality.

(2) Management procedures comprised of monitoring data, stock assessment and harvest control rules, including an approximation of the current DFO rule as alternatives recommended for forage fish (Lenfest).

(3) Performance indicators for comparing simulated outcomes against a suite of LRPs.

Age-Structured Operating Model

Population dynamics are simulated for both the historical and future projection periods. The model is initialized in the deterministic, unfished equilibrium state based on the 2013 stock assessment estimates of unfished equilibrium, recruitment steepness, natural mortality, fishing mortality, individual growth rates and numbers-at-age in 1951. Natural mortality and growth rates were modeled with the historical period (1951-2013) values fixed to estimates from the 2013 herring stock assessments.

For the projection period, state dynamics are driven by stochastic recruitment, natural mortality, growth and fishing mortality processes. Expected age-1 recruitment to the populations is modeled using a Beverton-Holt stock recruitment relationship. Natural mortality and growth rates for the projection period were scaled such that the projections begin at their values at the last time step of the historical period. Simulated future trends in natural mortality and growth rates were linearly interpolated between the last historical value and the scenario-specific target. The challenges in developing management procedures in the presence of non-stationary population dynamics were explored using four scenarios of future dynamics of Pacific Herring natural mortality and growth. For each stock area, natural mortality was either held constant at 2013 values or allowed to increase by 50% over the projection period; growth was held constant at average 2013 values or trended toward the average historical growth rate for the period 1951-1955. The four scenarios modeled were:

(1) Constant Natural Mortality and Constant Growth

(2) Increasing Natural Mortality and Constant Growth

(3) Constant Natural Mortality and Historical Growth

(4) Increasing Natural Mortality and Historical Growth

Management Procedures

Management procedures control the type, frequency and precision of the simulated data. Annual and biennial spawn surveys were simulated as unbiased absolute values of spawning biomass and do not include a scaling or expansion factor. Coefficients of variation of these estimates were constant over time. Age-composition data required for the simulated catch-at-age stock assessments were generated at an annual frequency.

The statistical catch-at-age assessment model used in these simulated management procedures differs from the age-structured operating model in two main ways:

(1) catch in the assessment model is taken assuming a discrete fishery occurring at the beginning of the year, whereas catch occurs continuously in the operating model as well as the actual assessment model used to evaluate BC herring stocks; and

(2) weight-at-age is assumed constant in the assessment model. The assessment model uses data sources generated by the operating model, including catch, spawning biomass survey indices and proportions-at-age in the catch.

Changes in natural mortality rates for scenarios 2) and 4) above are simulated using a random walk over time. Catchability, or the spawn survey scaling parameter (q) is assumed to equal 1 in both the assessment and operating models to stabilize the simulated assessment. This differs from the assumptions used in the actual stock assessment model used to evaluate BC herring stocks, which estimates q with error.

Four harvest control rules were explored to examine performance of alternative methods of setting catch limit for the upcoming year (Table 1). Two of the harvest control rules explored were based on those used in recent years to set total allowable catches for BC Pacific Herring fisheries (DFO 2015), and two were based on those that have been proposed for forage fish species in the literature (Lenfest1 and Lenfest2; Pikitch et al. 2012).

Table 1: Harvest control rules evaluated though closed-loop simulation.

Harvest Control Rule Tested	Description
DFO1	Annual assessment, harvest “cut-off” 0.25 B_0 and fishing mortality rate of 0.225
DFO2	Biennial assessment, harvest “cut-off” 0.25 B_0 and fishing mortality rate of 0.225
Lenfest1	Annual assessment, harvest “cut-off” of 0.4B_0 and fishing mortality rate that gradually increases to a maximum of 0.5F_{MSY} at estimated B_0
Lenfest2	Annual assessment, harvest “cut-off” of 0.4B_0 above which fishing mortality rate is set to 0.5F_{MSY}

Performance Indicators

Three commonly accepted fishery performance metrics were selected to provide an indication of the conservation and yield performance of simulated management procedures. Conservation performance was measured using the probability (P_{cons}) of the spawning stock biomass being below the conservation threshold defined by each of the candidate LRPs. A “no fishing” scenario was simulated to provide an alternate biomass time-series that approximates unfished conditions. To assess yield performance, median average annual yield and average annual variability of yield were estimated.

Results

Performance against Limit Reference Points

To simplify the discussion on the results of the performance against limit reference points, historical natural mortality patterns across the five major herring stocks are grouped into three general types: natural mortality in 2013 is less than natural mortality in 1951 ($M_{2013}<M_{1951}$), e.g. WCVI; natural mortality in 2013 is equal to natural mortality in 1951 ($M_{2013}=M_{1951}$), e.g. SOG, PRD, and CC; and natural mortality in 2013 is greater than natural mortality in 1951 ($M_{2013}>M_{1951}$), e.g. HG. Each of these types interacts with the projected natural mortality scenarios to strongly influence management procedure performance against the candidate LRPs. Results for each of the five stock areas are provided in the Appendix, Tables 1 through 5, and Figures 1 and 2.

Under the Constant M-Historical growth scenario, projected natural mortality trajectories in WCVI start and end below the 1951 level; this makes the simulated WCVI stock more resilient to fishing. Thus for this scenario, all the tested management procedures maintained less than a 5% chance of the spawning stock biomass (SSB) dropping below any LRP. For the SOG, where projected natural mortality levels are equal in 1951 and 2013 under an assumption of constant mortality, most management procedures maintained less than a 5% chance of SSB dropping below any LRP (Appendix Figure 1). In contrast, under the assumption of constant M, mortality for HG is double the 1951 value, and all management procedures generated a greater than 5% probability that equilibrium biomass LRPs would be violated (Appendix Figure 1).

Simulated outcomes against alternative LRPs for BC Pacific Herring stocks suggest that there is probably little value in using LRPs that track productivity, reference the lowest level of biomass from which the stock has recovered, or reference equilibrium-based F_{MSY}. These LRPs, based on B_0 when q=1, showed little to no response to changes in management procedures across stocks and scenarios, and were not informative for differentiating between alternative management procedures.

Management Procedure Evaluation

The DFO1 management procedure seems to perform adequately within the simulations for SOG under the conditions for which it was originally designed (i.e. constant natural mortality, LRP $0.25B_0$, Appendix Figure 1). It also performs well in simulations for WCVI under the range of natural mortality scenarios examined (Appendix Figure 1, 2). However, performance within simulations degrades if natural mortality increases or if management aims to maintain the stock above the higher LRPs suggested for forage fish stocks ($0.4B_0$, Appendix Figure 2). Simulated outcomes obtained from DFO1 are mixed for CC and PRD.

The historical trend and projections for natural mortality for HG were well outside the range for which the DFO1 management procedure was developed and tested. The simulations show the HG stock is expected to decline even in the absence of fishing because of elevated natural mortality rates. Under this scenario, none of the management procedures are considered adequate, regardless of the choice of LRP.

In general, the Lenfest-1 and Lenfest-2 management procedures that set fishing mortality rates to $0.5F_{MSY}$ for forage species consistently resulted in higher variability in catch and more frequent fishery closures across all stocks and scenarios. Operating model SSB levels were consistently below the intended $0.4B_0$ limit implied by these rules. The DFO2 management procedure achieved similar outcomes to DFO1, but generally lead to slightly lower catches and higher annual catch variability for similar levels of depletion. These results should be interpreted with caution as consideration of sampling effort and alternative survey designs were not the focus of this analysis. These results were included to show the flexibility of the analytical framework for addressing issues related to survey frequency and design.

Catchability, or the spawn survey scaling parameter (q) for this exercise was assumed to equal 1 in both the assessment and operating models whereas it has been estimated in recent annual assessments for Pacific Herring (since 2011). By assuming q=1 there is a reduction in the range of biomass estimation errors in the assessment and an optimistic outlook on management procedure performance. The impact of estimating q on the relative performance of the management procedures is uncertain, but implies greater uncertainty in biomass and reference point estimation. A preliminary analysis was conducted in which q was either fixed at 1 or estimated in both operating and assessment models. The comparison showed the effects of fixing q=1 in terms of the probability of breaching $0.25B_0$ and catch, depended on the weighting of the respective operating models in the calculation of mean statistics. This analysis was a proof-of-concept and requires more thorough examination to provide a sound basis for decision making.

Similarly, an alternate harvest control rule was explored for the Central Coast as proof of concept that alternate control rules can be evaluated using the analytical framework. This analysis demonstrates the utility of this framework for evaluating alternate harvest control rules. But the inclusion of this alternate rule should not be an endorsement of any particular rule, but a demonstration of the flexibility of the simulation framework.

Sources of Uncertainty

The suite of operating models examined is not exhaustive with respect to potential future productivity, growth, assessment, fishing, and mortality scenarios. However, they provide a reasonable diversity of scenarios to support the general findings.

There are additional uncertainties that were not included in this work, but that could be explored using expanded simulations, based on the approach presented at this peer review. For example, previous herring assessments have identified that long-term declines in body size (weight-at-age) have been observed for all BC herring stocks and some Alaska herring stocks, from the early 1980s to 2010. There has been a levelling off at the low end of the range in most recent year(s); however, the impacts of these declines on the performance of management procedures have not been fully explored. Similarly, rare or extreme events, outside of the range of historically observed values (e.g. for natural mortality, biomass, etc.) were not considered. Additionally, changes in management actions and potential impacts on results can be explored using the MSE approach as presented.

The performance of management procedures, applied to spatial scales finer than current DFO Management Areas, has not been simulated or evaluated. Additionally, the impacts of spawn on kelp (egg removal) fisheries compared to whole herring removal fisheries have not been assessed. The impact of estimating the spawn survey scaling parameter (q) on the management procedure (MP) evaluation results is uncertain and may not have the same effect in each of the populations around the coast. This also may require further evaluation to represent a more realistic environment in which the management procedures can be evaluated.

CONCLUSIONS AND ADVICE

This simulation exercise illustrates the benefit of conducting case-specific closed-loop simulations to evaluate harvest management procedures. The analytical framework has flexibility to explore a broad set of management procedures, ecological hypotheses and objectives proposed by First Nations, industry, and other stakeholders.

While only a limited number of stock productivity scenarios, management procedures, and candidate LRPs were explored for the five major Pacific Herring stock areas, results derived from the analytical framework provide proof of the MSE concept for identifying conservation objectives (LRPs) and developing a tool which can be used to update the existing management framework for BC Pacific Herring in accordance with Canada's Sustainable Fisheries Framework.

This simulation exercise and analysis was not exhaustive. However, based on the limited scope and assumptions used for these simulations, LRP's based on F_{msy}, NSB_0, and those based on lowest biomass from which the stock has recovered appear to be less capable of assessing the relative risks and performance of management procedures compared with LRPs based on fixed (equilibrium) objectives.

When using this analytic framework to update the existing management framework, it is recommended that more realistic representations of the actual management procedures should be developed for evaluation. For example, consideration should be given to modelling sequential fisheries and using multiple fleets, uncertainty in the spawn survey scaling parameter, (q), and trends in size-at-age.

The approximation of the current DFO management procedure that was tested and analyzed appears to maintain stocks above the candidate LRPs only over a narrow range of conditions. Increases in natural mortality, similar to those estimated over the past several decades, revealed potential conservation and fishery risks in four of five stocks areas. Specifically:

- Simulated spawning biomass for SOG herring was maintained above the 0.25B0 LRP 95% of the time under the DFO1 and DFO2 management procedures, which is consistent with the original evaluation performed for the stock in 1988
- The simulations for PRD, the CC and HG stocks suggest that both the DFO and the Lenfest management procedures could result in SSB frequently dropping below the LRPs used in this simulation exercise
- The LRP that was allowed to change with natural mortality and growth rates (NSB_0) often failed to indicate risk in situations where risks could actually be significant. This was also true for the empirical LRP that reflected the 'worst-case' scenario (Historical B), which was lowest historical biomass from which the stock has recovered.

SOURCES OF INFORMATION

This Science Advisory Report is from the May 27 – 28, 2015 Candidate Limit Reference Points for Pacific Herring in British Columbia using a Closed-loop Simulation Modelling Approach. Additional publications from this meeting will be posted on the [Fisheries and Oceans Canada (DFO) Science Advisory Schedule] as they become available.

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APPENDIX

Appendix Table 1. Management procedure (MP), catch ($\bar{C}$; thousands metric tonnes), catch variability (AAV), depletion ($\bar{D}$; B/B_0), and conservation performance (probability of biomass less than LRP) for SOG under each operating model scenario. Probabilities greater than 5% of depletion or fishing mortality resulting in the LRP being exceeded are marked in bold. LF1 = Lenfest1; LF2 = Lenfest2.

		Simulation outcome			Candidate Limit Reference Points						
Operating Model Scenario	**MP**	$\bar{C}$	**AAV**	$\bar{D}$	**$0.25B_0$**	**$0.30B_0$**	**$0.40B_0$**	**NSB_0**	**Historical B**	**$0.40B_{MSY}$**	**F_{MSY}**
Constant *M*-Constant Growth	NoFish	0.00	0.00	1.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	DFO1	16.49	18.52	1.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	DFO2	15.73	20.40	1.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	LF1	25.68	39.98	0.87	0.00	0.01	0.02	0.00	0.00	0.00	0.01
	LF2	28.83	21.16	0.82	0.00	0.01	0.04	0.00	0.00	0.00	0.02
Constant *M*-Historical Growth	NoFish	0.00	0.00	1.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	DFO1	15.73	18.45	0.94	0.00	0.00	0.01	0.00	0.00	0.00	0.00
	DFO2	15.18	20.22	0.95	0.00	0.00	0.01	0.00	0.00	0.00	0.00
	LF1	24.15	41.71	0.80	0.01	0.01	**0.05**	0.00	0.00	0.00	0.02
	LF2	27.51	21.19	0.74	0.01	0.02	**0.08**	0.01	0.00	0.01	0.03
Increasing *M*-Constant Growth	NoFish	0.00	0.00	0.80	0.00	0.01	0.04	0.00	0.00	0.00	0.00
	DFO1	11.12	20.39	0.67	0.02	**0.05**	**0.16**	0.00	0.00	0.01	0.00
	DFO2	10.95	21.29	0.68	0.03	**0.05**	**0.16**	0.00	0.00	0.01	0.00
	LF1	14.87	55.01	0.61	0.03	**0.08**	**0.20**	0.00	0.00	0.01	0.02
	LF2	19.61	37.13	0.55	**0.09**	**0.14**	**0.32**	0.00	0.00	0.03	**0.06**
Increasing *M*-Historical Growth	NoFish	0.00	0.00	0.76	0.01	0.02	**0.09**	0.01	0.00	0.00	0.00
	DFO1	10.70	20.28	0.62	**0.05**	**0.11**	**0.24**	0.00	0.00	0.02	0.00
	DFO2	10.62	21.15	0.63	**0.05**	**0.12**	**0.24**	0.00	0.00	0.02	0.00
	LF1	14.27	55.25	0.57	**0.07**	**0.13**	**0.29**	0.00	0.00	0.03	0.02
	LF2	18.52	38.97	0.51	**0.14**	**0.23**	**0.42**	0.01	0.00	**0.08**	**0.07**

Appendix Table 2. Management procedure (MP), catch ($\bar{C}$; thousands metric tonnes), catch variability (AAV), depletion ($\bar{D}$; B/B_0), and conservation performance (probability of biomass less than LRP) for WCVI under each operating model scenario. Probabilities greater than 5% of depletion or fishing mortality resulting in the LRP being exceeded are marked in bold. LF1 = Lenfest1; LF2 = Lenfest2.

		Simulation outcome			Candidate Limit Reference Points						
Operating Model Scenario	**MP**	$\bar{C}$	**AAV**	$\bar{D}$	**$0.25B_0$**	**$0.30B_0$**	**$0.40B_0$**	**NSB_0**	**Historical B**	**$0.40B_{MSY}$**	**F_{MSY}**
Constant *M*-Constant Growth	NoFish	0.00	0.00	1.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	DFO1	10.97	18.69	1.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	DFO2	10.71	20.57	1.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	LF1	14.99	43.60	1.17	0.01	0.01	0.03	0.03	0.00	0.03	0.04
	LF2	16.69	25.68	1.03	0.01	0.02	0.04	**0.05**	0.00	0.04	**0.06**
Constant *M*-Historical Growth	NoFish	0.00	0.00	2.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	DFO1	12.49	19.71	1.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	DFO2	11.89	22.61	1.79	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	LF1	17.36	42.33	1.56	0.00	0.00	0.00	0.01	0.00	0.00	0.01
	LF2	19.24	25.94	1.43	0.00	0.00	0.01	0.01	0.00	0.01	0.02
Increasing *M*-Constant Growth	NoFish	0.00	0.00	1.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	DFO1	7.81	19.93	0.92	0.01	0.02	**0.05**	0.00	0.00	**0.05**	0.00
	DFO2	7.92	22.23	0.92	0.01	0.02	**0.06**	0.00	0.00	**0.06**	0.01
	LF1	9.52	57.84	0.86	0.03	0.04	**0.10**	0.02	0.00	**0.10**	**0.05**
	LF2	11.97	42.12	0.72	**0.07**	**0.11**	**0.20**	0.04	0.00	**0.20**	**0.11**
Increasing *M*-Historical Growth	NoFish	0.00	0.00	1.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	DFO1	8.81	20.46	1.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	DFO2	8.61	23.71	1.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	LF1	11.07	60.45	1.08	0.00	0.01	0.02	0.00	0.00	0.02	0.02
	LF2	14.04	34.83	0.95	0.01	0.01	0.04	0.01	0.00	0.04	0.04

Appendix Table 3. Management procedure (MP), catch ($\overline{C}$; thousands metric tonnes), catch variability (AAV), depletion ($\overline{D}$; B/B_0), and conservation performance (probability of biomass less than LRP) for PRD under each operating model scenario. Probabilities greater than 5% of depletion or fishing mortality resulting in the LRP being exceeded are marked in bold. LF1 = Lenfest1; LF2 = Lenfest2.

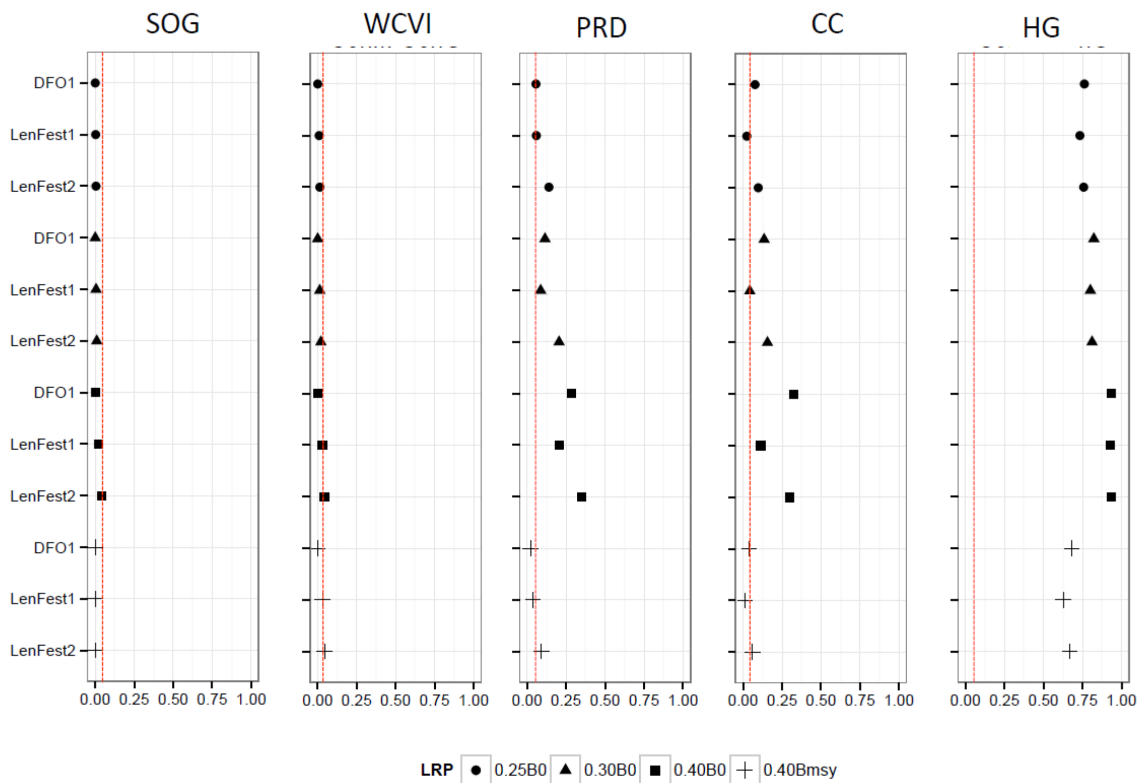
		Simulation outcome			Candidate Limit Reference Points						
Operating Model Scenario	**MP**	$\overline{C}$	**AAV**	$\overline{D}$	**$0.25B_0$**	**$0.30B_0$**	**$0.40B_0$**	**NSB_0**	**Historical B**	**$0.40B_{MSY}$**	**F_{MSY}**
Constant *M*-Constant Growth	NoFish	0.00	0.00	0.81	0.00	0.00	0.02	0.00	0.00	0.00	0.00
	DFO1	5.80	33.54	0.56	**0.06**	**0.11**	**0.28**	0.00	0.00	0.02	0.03
	DFO2	5.81	38.41	0.55	**0.07**	**0.12**	**0.28**	0.00	0.00	0.03	**0.05**
	LF1	4.67	92.90	0.63	**0.06**	**0.09**	**0.21**	0.02	0.00	0.04	**0.08**
	LF2	6.78	92.82	0.51	**0.14**	**0.20**	**0.35**	**0.05**	0.00	**0.09**	**0.19**
Constant *M*-Historical Growth	NoFish	0.00	0.00	0.85	0.00	0.00	0.02	0.00	0.00	0.00	0.00
	DFO1	6.02	31.92	0.59	**0.05**	**0.10**	**0.25**	0.00	0.00	0.02	0.03
	DFO2	5.93	39.16	0.59	**0.06**	**0.11**	**0.26**	0.00	0.00	0.02	0.04
	LF1	4.92	92.00	0.66	**0.05**	**0.08**	**0.19**	0.01	0.00	0.04	**0.07**
	LF2	7.20	89.75	0.55	**0.12**	**0.19**	**0.32**	0.04	0.00	**0.08**	**0.19**
Increasing *M*-Constant Growth	NoFish	0.00	0.00	0.50	0.04	**0.09**	**0.29**	0.04	0.00	0.01	0.00
	DFO1	3.82	47.04	0.36	**0.24**	**0.39**	**0.64**	0.01	0.00	**0.13**	**0.05**
	DFO2	3.82	51.14	0.35	**0.26**	**0.42**	**0.66**	0.01	0.00	**0.14**	**0.08**
	LF1	2.36	113.84	0.42	**0.16**	**0.27**	**0.51**	0.02	0.00	**0.09**	**0.07**
	LF2	3.71	122.94	0.36	**0.30**	**0.42**	**0.64**	0.04	0.00	**0.19**	**0.20**
Increasing *M*-Historical Growth	NoFish	0.00	0.00	0.52	0.03	0.07	**0.25**	0.03	0.00	0.01	0.00
	DFO1	3.96	46.76	0.38	**0.20**	**0.34**	**0.59**	0.00	0.00	**0.10**	**0.05**
	DFO2	3.99	50.26	0.37	**0.22**	**0.36**	**0.61**	0.00	0.00	**0.11**	**0.07**
	LF1	2.45	112.98	0.43	**0.14**	**0.23**	**0.46**	0.01	0.00	**0.08**	**0.07**
	LF2	3.88	116.98	0.38	**0.27**	**0.38**	**0.59**	0.04	0.00	**0.16**	**0.20**

Appendix Table 4. Management procedure (MP), catch ($\overline{C}$; thousands metric tonnes), catch variability (AAV), depletion ($\overline{D}$; B/B_0), and conservation performance (probability of biomass less than LRP) for CC under each operating model scenario. Probabilities greater than 5% of depletion or fishing mortality resulting in the LRP being exceeded are marked in bold. LF1 = Lenfest1; LF2 = Lenfest2.

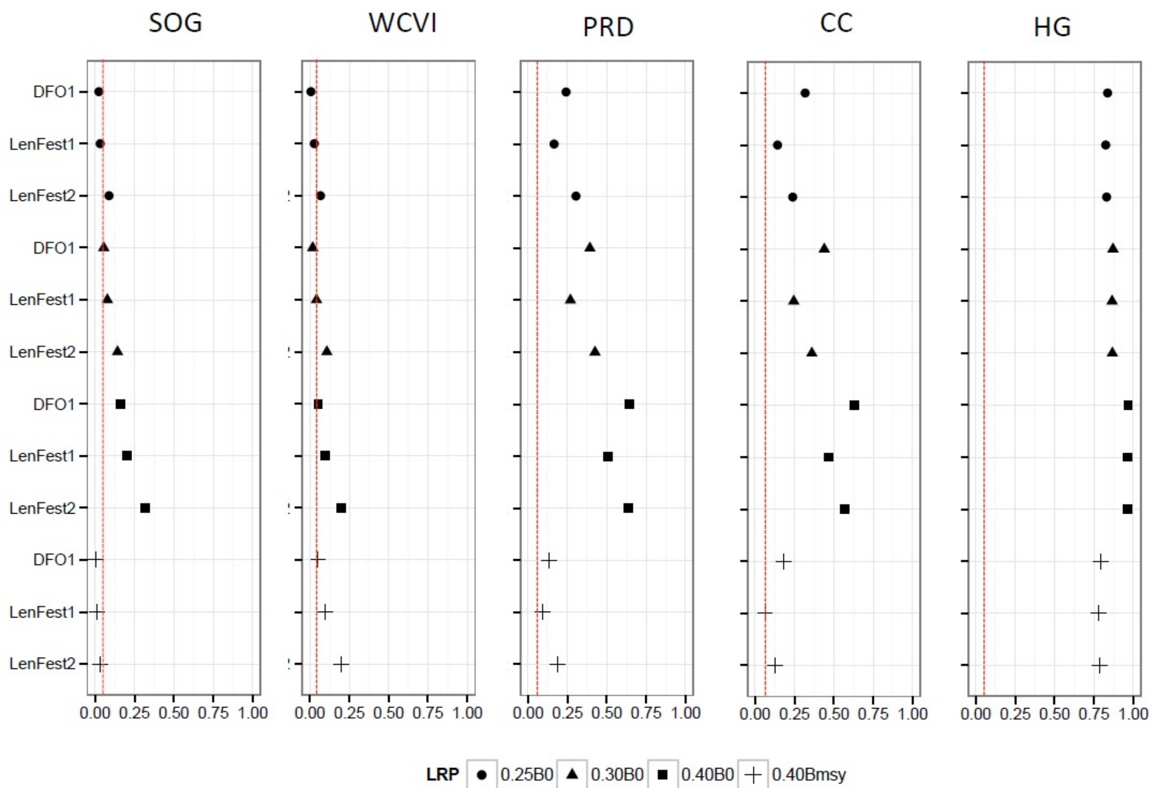
		Simulation outcome			Candidate Limit Reference Points						
Operating Model Scenario	**MP**	$\overline{C}$	**AAV**	$\overline{D}$	**0.25B$_0$**	**0.30B$_0$**	**0.40B$_0$**	**NSB$_0$**	**Historical B**	**0.40B$_{MSY}$**	**F$_{MSY}$**
Constant *M*-Constant Growth	NoFish	0.00	0.00	0.69	0.00	0.00	0.01	0.00	0.00	0.00	0.00
	DFO1	4.17	29.01	0.50	**0.08**	**0.13**	**0.32**	0.00	0.00	0.04	0.01
	DFO2	4.00	36.01	0.49	**0.08**	**0.14**	**0.31**	0.01	0.00	0.04	0.01
	LF1	2.14	71.74	0.61	0.02	0.04	**0.11**	0.00	0.00	0.01	0.00
	LF2	3.87	95.92	0.52	**0.10**	**0.16**	**0.30**	0.02	0.00	**0.06**	0.04
Constant *M*-Historical Growth	NoFish	0.00	0.00	0.95	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	DFO1	5.45	26.72	0.73	0.01	0.02	**0.07**	0.00	0.00	0.00	0.00
	DFO2	5.10	34.72	0.74	0.01	0.02	**0.06**	0.00	0.00	0.00	0.00
	LF1	3.67	72.37	0.83	0.00	0.01	0.03	0.00	0.00	0.00	0.00
	LF2	6.06	73.17	0.71	0.02	0.04	**0.10**	0.01	0.00	0.01	0.02
Increasing *M*-Constant Growth	NoFish	0.00	0.00	0.45	**0.09**	**0.17**	**0.39**	**0.09**	0.00	0.03	0.00
	DFO1	2.23	57.44	0.35	**0.32**	**0.44**	**0.63**	0.00	0.00	**0.18**	0.01
	DFO2	2.25	61.06	0.36	**0.34**	**0.44**	**0.63**	0.01	0.00	**0.22**	0.03
	LF1	0.54	99.17	0.42	**0.14**	**0.25**	**0.46**	0.00	0.00	**0.06**	0.00
	LF2	1.54	136.64	0.39	**0.24**	**0.36**	**0.57**	0.01	0.00	**0.13**	0.03
Increasing *M*-Historical Growth	NoFish	0.00	0.00	0.60	0.00	0.02	**0.09**	0.00	0.00	0.00	0.00
	DFO1	3.34	45.73	0.49	**0.07**	**0.14**	**0.33**	0.00	0.00	0.03	0.00
	DFO2	3.24	51.20	0.49	**0.08**	**0.14**	**0.32**	0.00	0.00	0.04	0.01
	LF1	1.25	100.06	0.57	0.02	**0.05**	**0.16**	0.00	0.00	0.01	0.00
	LF2	2.81	120.21	0.52	**0.08**	**0.14**	**0.29**	0.01	0.00	0.04	0.03

Appendix Table 5. Management procedure (MP), catch ($\bar{C}$; thousands metric tonnes), catch variability (AAV), depletion ($\bar{D}$; B/B_0), and conservation performance (probability of biomass less than LRP) for HG under each operating model scenario. Probabilities greater than 5% of depletion or fishing mortality resulting in the LRP being exceeded are marked in bold. LF1 = Lenfest1; LF2 = Lenfest2. "NA" indicates lack of reliable estimates.

		Simulation outcome			Candidate Limit Reference Points						
Operating Model Scenario	**MP**	$\bar{C}$	**AAV**	$\bar{D}$	**$0.25B_0$**	**$0.30B_0$**	**$0.40B_0$**	**NSB_0**	**Historical B**	**$0.40B_{MSY}$**	**F_{MSY}**
Constant *M*-Constant Growth	NoFish	0.00	0.00	0.19	**0.72**	**0.79**	**0.93**	NA	0.00	**0.61**	0.00
	DFO1	0.33	90.81	0.18	**0.76**	**0.82**	**0.94**	0.00	0.00	**0.68**	0.00
	DFO2	0.35	93.96	0.17	**0.76**	**0.82**	**0.93**	0.00	0.01	**0.68**	0.02
	LF1	0.04	158.79	0.19	**0.73**	**0.80**	**0.93**	0.00	0.00	**0.63**	0.00
	LF2	0.23	200.00	0.18	**0.76**	**0.81**	**0.93**	0.00	0.01	**0.67**	0.03
Constant *M*-Historical Growth	NoFish	0.00	0.00	0.24	**0.58**	**0.70**	**0.89**	NA	0.00	**0.40**	0.00
	DFO1	0.43	88.96	0.22	**0.65**	**0.75**	**0.91**	0.00	0.00	**0.50**	0.00
	DFO2	0.42	94.75	0.22	**0.65**	**0.75**	**0.91**	0.00	0.00	**0.50**	0.01
	LF1	0.07	153.75	0.24	**0.60**	**0.71**	**0.90**	0.00	0.00	**0.42**	0.00
	LF2	0.28	187.56	0.23	**0.63**	**0.74**	**0.91**	0.00	0.00	**0.48**	0.03
Increasing *M*-Constant Growth	NoFish	0.00	0.00	0.12	**0.82**	**0.86**	**0.97**	NA	**0.22**	**0.77**	0.00
	DFO1	0.18	93.83	0.11	**0.84**	**0.87**	**0.97**	0.00	**0.24**	**0.80**	0.01
	DFO2	0.19	103.69	0.11	**0.83**	**0.87**	**0.97**	0.00	**0.25**	**0.79**	0.02
	LF1	0.01	129.21	0.12	**0.82**	**0.87**	**0.97**	0.00	**0.22**	**0.78**	0.00
	LF2	0.13	114.46	0.12	**0.83**	**0.87**	**0.97**	0.00	**0.23**	**0.79**	0.02
Increasing *M*-Historical Growth	NoFish	0.00	0.00	0.14	**0.80**	**0.85**	**0.96**	NA	**0.08**	**0.75**	0.00
	DFO1	0.20	94.12	0.13	**0.83**	**0.86**	**0.96**	0.00	**0.09**	**0.77**	0.00
	DFO2	0.20	102.08	0.13	**0.82**	**0.86**	**0.96**	0.00	**0.09**	**0.77**	0.01
	LF1	0.01	130.52	0.14	**0.81**	**0.85**	**0.96**	0.00	**0.08**	**0.75**	0.00
	LF2	0.13	116.02	0.13	**0.82**	**0.86**	**0.96**	0.00	**0.08**	**0.77**	0.02



Appendix Figure 1. Management procedure performance against biomass-based candidate Limit Reference Points (LRPs) under the Constant M-Constant growth scenario for SOG, WCVI, PRD, CC, and HG. The dashed red line represents the 5% threshold recommended by Shelton and Sinclair (2008).



Appendix Figure 2. Management procedure performance against biomass-based candidate LRPs under the Increase M-Constant growth scenario for SOG, WCVI, PRD, CC, and HG. The dashed red line represents the 5% threshold recommended by Shelton and Sinclair (2008).

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