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

Canadian Science Advisory Secretariat (CSAS)

Research Document 2019/050

Pacific Region

Candidate Limit Reference Points as a Basis for Choosing Among Alternative Harvest Control Rules for Pacific Herring (*Clupea pallasii*) in British Columbia

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Novembre 2019

Foreword

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

Published by:

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

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

ISSN 1919-5044

Correct citation for this publication:

Cox, S.P., Benson, A.J., Cleary, J.S, and Taylor, N.G. 2019. Candidate Limit Reference Points as a Basis for Choosing Among Alternative Harvest Control Rules for Pacific Herring (*Clupea pallasii*) in British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/050. viii + 47 p.

Aussi disponible en français :

Cox, S.P., Benson, A.J., Cleary, J.S, et Taylor, N.G. 2019. Points de référence limites potentiels comme base pour choisir parmi les autres règles de contrôle des prises pour le hareng du Pacifique (Clupea pallasii) en Colombie-Britannique. Secr. can. de consult. sci. du MPO. Doc. de rech. 2019/050. viii + 52 p.

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ABSTRACT

British Columbia's (BC) Pacific Herring (*Clupea pallasii*) fisheries are managed using a harvest control rule (HCR) that was initially designed in 1986. The HCR includes a stock-specific minimum biomass threshold below which commercial fisheries are not permitted (the “cut-off”) and a target harvest rate of 20%. Since adopting the HCR, two of five major herring stocks have remained above the cut-off level each year and continue to support fisheries, while three stocks have recently dropped below cut-off for up to eight consecutive years. Significant increases in estimated natural mortality (M) and decreases in body size have been observed for some stocks the same timeframe. The relative contributions of these factors to stocks falling below cut-offs are currently not well understood.

This paper represents the first step in a management strategy evaluation (MSE) process that develops the analytical framework for future analyses and explores the suitability of candidate conservation objectives (limit reference points) for the five Pacific Herring stocks. The key components of the framework are:

1. operating models that reflect a range of potential future changes in growth and natural mortality;
2. management procedures (MP) comprised of data, stock assessment models, and harvest control rules (HCR) including the current DFO rule and alternatives recommended for forage fish; and,
3. biological limit reference points (LRP) that are used in determining the expected conservation performance of alternative management procedures.

The LRPs explored in this paper include:

i. equilibrium reference points that remain fixed over time;

ii. a dynamic reference point that tracks changes in productivity;

iii. a historical reference point that defines LRP in terms of lowest observed biomass; and,

iv. DFO policy values of $0.4B_{MSY}$ and F_{MSY}.

This study suggests that future work to identify LRPs for BC herring fisheries should focus on fixed (equilibrium) objectives related to biomass. Fishing mortality-based LRPs were not generally useful for distinguishing between candidate MPs on the basis of conservation performance. Furthermore, our analysis indicates that the current DFO MP performs well only over a narrow range of conditions for particular stocks. Increases in M similar to those estimated over the past several decades revealed relatively poor conservation performance in 4 of 5 stock areas. We therefore recommend exploring alternative MP that can provide good performance across a range of future scenarios for Herring population dynamics.

1. INTRODUCTION

British Columbia's (BC) Pacific Herring (*Clupea pallasii*) fisheries are managed based on a harvest strategy that was implemented in 1986 (Hall et al. 1988, Stocker 1993). The harvest control rule (HCR) element of the strategy prescribes a target exploitation rate of 20% when the forecasted stock biomass is above a stock-specific minimum biomass threshold of 25% of the estimated unfished spawning biomass (the “cut-off”). The target harvest rate is reduced to 0% when the estimated biomass is below the cut-off level.

Closed-loop simulation tests occurred subsequent to the harvest strategy’s implementation in 1986. Hall et al. (1988) used simulation analysis to compare constant escapement, constant harvest rate, and the herring harvest strategy that was implemented in 1986 for a simulated roe herring fishery. The analysis indicated that the herring harvest strategy combined the safety of the constant escapement strategy and the catch variance reducing features of the harvest rate strategy without compromising mean catches. One key assumption of the analysis was that growth and natural mortality were assumed to remain constant over time. Importantly, the analysis indicated that this rule would only cause herring stock biomass to drop below the cut-off level in 5% of years (Hall et al. 1988).

The experience of applying the herring harvest strategy in practice has been very different from the predictions of the simulation tests. Since adopting the strategy in 1986, two of five 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) were forecasted to have been below the cut-off level in 32% (2001, 2006-2011, 2013), 21% (2008-2013), and 46% (1988, 1995, 1996, 2001, 2003, 2005-2012) of years, respectively, exceeding expectations indicated by the original simulations. Long-term declines in body size (size-at-age) have been observed for all BC herring stocks from the early-1980s to 2010. Estimated natural mortality increased since the 1970s for WCVI, CC and HG stocks, while remaining relatively constant for SOG and PRD stocks (DFO, 2014a). The relative contributions of changes in growth and natural mortality to stocks falling below the cut-offs are currently not well understood. The disparity both between the assumed and observed biological assumptions underlying the simulation tests as well as the predicted vs. observed management outcomes indicates that alternative management approaches should be considered for Pacific Herring fisheries in BC.

This paper represents the first step in a management strategy evaluation (MSE) process that develops the analytical framework for future analyses and explores the suitability of candidate conservation objectives (limit reference points) for Pacific Herring. The key components of the framework are:

i. operating models for five herring stocks that reflect a range of hypotheses about future changes in growth and natural mortality, as well as possible non-stationary dynamics in productivity over time;

ii. management procedures comprised of monitoring data, stock assessment models, and HCRs used to implement management policies; and,

iii. biological limit reference points (LRP) that are used in determining the expected conservation performance of alternative management procedures.

Non-stationarity (Walters 1986) in productivity affects both elements (2) and (3). For HCRs, systematic variation in population productivity over time reduces our ability to estimate rule parameters such as unfished biomass (B_0) or F_{MSY} (Haltuch et al. 2008), which may lead to errors in applying operational management procedures (e.g., over- or under-estimating stock sizes and available harvest). Temporal variation in population productivity also leads to temporal changes in the biological reference points (BRP) such as the B_0, B_{MSY}, or F_{MSY}, which leads to unclear definitions of over-harvesting and conservation risk. For example, if productivity decreases, then even an unfished population is expected to decline relative to biological limit reference points derived from historical or equilibrium biomass estimates. These consequences of non-stationarity in fish stock productivity have not been explored in detail within the scientific literature nor have they been evaluated for Pacific Herring fishery management. Although we do not fully understand what drives non-stationarity of herring population productivity, exploring alternative scenarios for future changes could help us better understand the properties of different HCRs at avoiding alternative LRPs under such conditions.

1.1. CANDIDATE LIMIT REFERENCE POINTS

Recommended management targets and limits reflect differences in life history of fish species (Pikitch et al. 2012), the scope of the management problem (e.g. single- or multi-species management; Collie et al. 2001), and interest in identifying generic approaches for management decision-making (Caddy and Mahon 1995; Froese et al. 2011; Sainsbury 2008). The difference between biological reference points, which represent the biological objectives of management, and operational control points that define HCRs used to achieve the objectives is seldom recognized (Cox et al. 2013). Biological reference points are typically derived on theoretical grounds and reflect quantities related to B_0 or maximum sustainable yield (MSY; B_{MSY}, F_{MSY}) (Caddy and Mahon 1995), while operational control points are chosen based on practical issues of data availability, stock assessment error, risk tolerance, and stakeholder preferences (Cox et al. 2013).

Biological limit reference points (LRPs) define the limits of exploitation in terms of the biomass or fishing mortality rate that must be avoided with a high probability, but they tend to be poorly understood and articulated. Obvious goals of management include avoiding low biomass levels (i.e. overfished stock status) and preventing overfishing. However, states of overfishing and overfished can be difficult to define, and in most cases are policy-driven management choices rather than scientifically determined criteria (Hilborn and Stokes 2010). For example, an LRP of $0.5B_{MSY}$ (the biomass that provides maximum sustainable yield or MSY), $0.25B_0$ (unfished biomass, B_0), $0.48B_0$, and $0.20B_0$ are used in Australia and the United States, depending on the economic and conservation goals of the regional and national management agencies (Hilborn and Stokes 2010). Confusion surrounding the choice of LRP (or other biological reference points) has prompted the search for general rules for their use in management.

One comprehensive review of ‘best practices’ in the use of LRPs (Sainsbury 2008) found substantial variety in the types of LRP used to manage fisheries around the world. LRPs currently in use include quantitative estimates of theoretical values (e.g. B_0) as well as quantities based on direct, empirical observations (e.g. lowest level of observed biomass). Model-based LRPs can be either fixed at an equilibrium level or can dynamically track changes in productivity over time. Common values for biomass-based equilibrium LRPs range between $0.25B_0$-$0.5B_0$, whereas common proxies for B_{MSY} average $0.25B_0$-$0.40B_0$ with Clupeiformes values closer to $0.25B_0$ (Sainsbury 2008; Thorson et al. 2012). Sainsbury (2008) defines dynamic LRPs as the greater of a time-varying fraction of predicted B_0 and a static fraction of B_{MSY} or B_0 ($0.3B_0$). LRPs are required for both biomass and fishing mortality rate. The best practice LRP for fishing mortality is F_{MSY}, meaning that the fishing mortality rate should not exceed that which provides MSY (Sainsbury 2008).

The DFO fisheries decision-making framework (DFO, 2009) also provides provisional recommendations for limit and upper stock reference points corresponding to 40% and 80% of B_{MSY}, respectively. It broadly reflects the best practices identified by Sainsbury (2008) and

Shelton and Sinclair (2008). While it is not prescriptive, defaults suggested in the policy are for a biomass-based LRP of $0.40B_{MSY}$ and a maximum removal rate corresponding to F_{MSY} or less. The DFO policy allows flexibility in defining LRPs to accommodate practical considerations including local variations in productivity, fishery dynamics, and management attitudes towards risk.

Practical considerations used to determine LRPs are not well understood for Pacific Herring fisheries and this is especially the case given the apparent time-varying productivity of the stocks. In this paper, we investigate how four classes of LRP create different perceptions of risk arising from alternative harvest management procedures. Specifically, we consider

1. equilibrium reference points that remain fixed over time,
2. a dynamic reference point that tracks changes in productivity,
3. a historical reference point that defines LRP in terms of lowest observed biomass, and
4. DFO policy values of $0.40B_{MSY}$ and F_{MSY}.

We used a closed-loop simulation approach to generate potential spawning stock biomass and yield outcomes of applying four alternative management procedures (MPs) under four scenarios for the future dynamics of BC Pacific Herring stocks. The alternative MPs only differed in the form, control points, and fishing mortality targets used in harvest control rules.

2. METHODS AND STUDY DESIGN

Management strategy simulations for output quota fisheries require three main components:

i. an operating model to represent population dynamics of the stock, the mechanisms generating survey and age-composition data, and relationships between harvest decisions and fishing mortality on the stock;

ii. a management procedure consisting of (at least) monitoring data, stock assessment models, and harvest control rules for setting target fishing mortality and total allowable catch; and,

iii. performance indicators for comparing simulated outcomes against fishery objectives.

The following sections describe how these components are modelled for BC Pacific Herring fisheries. Our model notation attempts to maintain consistent conventions for state variables and parameters across both the operating model and stock assessment model, while also making clear the differences between operating model variables, equilibrium solutions, parameters estimated in stock assessment models, and variables derived from these parameter estimates. As a general rule, any parameter or variable (e.g., B_0) that does not show a "^" or "~" symbol is part of the operating model. Variables without subscripts for time (e.g., $F_{\mathrm{MSY}}, B_{\mathrm{MSY}}, B_0$) are considered constant and usually represent equilibrium quantities. The symbol "^" over a variable indicates a parameter (e.g., $\hat{B}_0$) or variable estimated by the stock assessment model.

The combination of "^" and "~" symbols and time subscripts (e.g., $\widehat{\widetilde{B}}_{MSY,T}$) indicates a quantity that is a function of estimated stock assessment model parameters while time subscripts (e.g., "*T*") on parameters such as the one shown above indicate an estimate of that quantity given data up to the time step indicated. Vector objects are denoted using notation such as 1:*T* in subscripts (e.g., $\hat{B}_{1:T}$).

2.1. AGE-STRUCTURED OPERATING MODEL

2.1.1. Equilibrium characteristics and biological reference points

Abundance dynamics were simulated via an age-structured model with *A* age classes, where the index *A* represents a plus-group. Notation, parameter settings, and equations for the operating model are given in Tables 1, 2, and 3, respectively. Equilibrium biomass and fishing mortality reference points for the age-structured model (Table 4) are derived from either the yield-per-recruit (EQ3.4) and spawning biomass-per-recruit functions (EQ3.5), which involve only life history and selectivity parameters, or the total recruitment (EQ3.6), biomass (EQ3.7), and yield (EQ3.8) relationships, which involve all life history, selectivity, and stock-recruitment parameters. Operating model biological reference points B_{MSY} and F_{MSY}, and harvest control points $\widehat{\mathrm{MSY}}_T, \widehat{F}_{\mathrm{MSY},T}, \widehat{B}_{\mathrm{MSY},T}$ (defined below) derived from age-structured stock assessment model parameters are computed using these functions. Reference and control point proxies derived from yield-per-recruit (e.g., $F_{0.1}$) or spawning potential ratios (e.g., $F_{40\%}$) are also computed using these equilibrium relationships, although none of these are implemented here for Pacific Herring.

2.1.2. Population dynamics

The total simulation time frame is divided into historical ($t \le T_1 - 1$) and projection ($T_1 \le t \le T_2$) periods. The operating model is initialized with the 1951 numbers-at-age from the 2013 herring stock assessment (DFO 2015). State dynamics are then driven by stochastic recruitment (OM2.12 and OM2.15), natural mortality (OM2.13-2.14), growth, and fishing mortality processes (OM2.16-2.17). Expected age-1 recruitment to the population is modeled using a Beverton-Holt stock recruitment relationship where addition of these recruits to the population is assumed to occur in a single pulse at the beginning of the year. The shape of the Beverton-Holt stock-recruitment relationship, and thus population productivity, is determined by the steepness parameter *h*, which is defined as the proportion of maximum recruitment produced when spawning biomass is 20% of the unfished equilibrium level (Mace and Doonan 1988). Deviations in recruitment about the stock-recruitment relationship are assumed to be log-normal with the same standard error used in recent stock assessments.

During the projection period $T_1 \le t \le T_2$, values for recruitment deviations ω_t^R were drawn from $N\left(0, \sigma_R\right)$ distribution. Values for fishing mortality F_t were computed by solving the catch equation (OM2.21) given annual quotas output from the management procedures described below.

2.1.3. Natural mortality and growth rates

Natural mortality and the Walford length intercept (hereafter referred to as growth rate) were modelled as trending AR(1) processes (OM2.10-2.11). For the historical period (1951-2013), values were fixed to estimates from the most recent herring stock assessment. The Walford intercept (α_t) and slope (ρ_t) estimates based on historical cohort-specific growth data were highly correlated; therefore, we chose to model the growth coefficient as a linear function of the intercept (OM2.12).

Natural mortality and growth rates for the projection period were scaled such that values of the historical and projection periods match exactly at the end of the historical period ($t = T_1 - 1$). Simulated future trends in natural mortality and growth rates were linearly interpolated between the last historical value and a scenario-specific target (defined below) for the final time step T_1 while preserving the random walk process defined in OM2.10.

2.1.4. Data generation from the operating model

At each time step, the operating model generates a log-normally distributed exploitable biomass estimate or index (OM2.23) and vectors of observed age-proportions in the fishery catch and survey, respectively. Age-composition is modelled using multivariate logistic distributions with independent errors (OM2.24-2.26; Schnute and Richards 1995). Standard errors for simulated assessment data are all determined as part of the management procedure (described below).

2.1.5. Parameterization from historical data

Historically, the five major Pacific Herring stocks in BC exhibit different biomass dynamics in response to fisheries, recruitment variability, trends in size-at-age, and the mean, variability, and trends in natural mortality rates. We represented these differences by parameterizing each operating model from recent (2013) stock-specific assessment estimates of unfished spawning biomass, stock-recruitment steepness, natural mortality, fishing mortality, individual growth rates, and numbers-at-age in 1951, which is the beginning of the data time series used in the 2013 DFO stock assessment for the historical period (1951-2013), $2 \le t \le T_1 - 1$, we forced the population dynamics using 2013 assessment estimates of recruitment deviations (ω_t^R), natural mortality (M_t), fully-selected fishing mortality (F_t), and estimated cohort-specific Walford growth parameters (α_t, ρ_t).

2.1.6. Operating model projection scenarios

We used four operating model scenarios to represent uncertain future dynamics in Pacific Herring natural mortality and growth rates. While this limited suite of scenarios is far from exhaustive, it suffices to demonstrate some of the challenges in developing management procedures in the presence of non-stationary population dynamics and in judging performance with respect to LRPs. The scenarios represent combinations of future

1. natural mortality: Constant M (ConM) = constant average natural mortality at 2013 values or Increasing M (IncM) = a 1.5-fold increase in average natural mortality over the projection period and
2. growth rate: Constant Growth (ConG) = constant average growth rate at 2013 values or Historical Growth (HisG) = a trend toward historical growth rates given by the average α_t over the first five years of observations (i.e., 1951-1955). Scenario combinations are labeled ConM-ConG, IncM-ConG, ConM-HisG, and IncM-HisG.

Natural mortality differs substantially between herring stocks and has the strongest effect on projected stock trajectories (Figure 1). These scenarios were expected to have the strongest impact on conservation outcomes as calculated by the LRPs. The opposite approach (i.e. decreasing natural mortality) would be less useful for distinguishing between LRPs because it would lead to stock status having a more optimistic response to candidate management procedures.

2.2. MANAGEMENT PROCEDURES

Simulated management procedures (MPs) consist of three components:

1. a fishery data set involving time-series (t = 1, 2,…,T) of total catch, a time-series of exploitable biomass indices, and proportions-at-age in the fishery catch and survey;
2. a stock assessment model that estimates historical biomass, recruitment, natural mortality, selectivity, and stock-recruitment parameters up to time step t (AM.1, Table 5) as well as operational control points derived from these parameters as required by harvest control rules (Cox et al. 2013); and,
3. a harvest control rule for computing a catch limit based on stock assessment results. The sections below describe how each of these components is implemented in the simulations.

2.2.1. Fishery data

Although the operating model simulates the data used in fishery stock assessments, the MP controls the types, frequency, and precision of the simulated data because these are typically under management control. Annual estimates of projected herring spawning biomass are required by MPs with annual surveys (DFO1), and biennially for MPs with surveys every two years (DFO2). For this study, we generated unbiased, absolute values of spawning biomass as the biomass index data (OM2.23). The coefficients of variation (CVs) of these estimates were constant over time. In cases where extra heterogeneity in survey variances are desired, the CVs can be made to vary from year to year via independent and identically distributed draws from inverse-gamma (IG) distributions specified by period. The IG distribution parameters are obtained via moment matching to user-defined means and standard deviations for each period. Although such extra variation is really an operating model issue, providing all survey specifications in the MP seems less complicated.

Fishery and survey age-composition data required for the simulated catch-at-age stock assessments (defined below) are generated from OM2.24-2.26 at an annual (DFO1) or biennial (DFO2) frequency.

2.2.2. Catch-at-age stock assessment models

Assessment model equations are described in Table 5 and likelihood functions in Table 6. The statistical catch-at-age assessment model (AM) used in the simulated management procedures differs slightly from the age-structured operating model. The three main differences are that

i. recruitment process errors are assumed uncorrelated in the AM (AM.6 and L.4),
ii. catch in the AM is taken assuming a discrete fishery (i.e. a single fleet) occurring at the beginning of the year (AM.7) instead of continuously as it is in the operating model, and
iii. weight-at-age is assumed constant in the AM.

Equations AM.1-AM.8 show how the relevant calculations in the AM are affected by these differences. The AM estimator uses all potential data sources generated by the operating model, including catch, spawning biomass survey indices, and proportions-at-age in the catch. Operating model schedules of maturity-at-age are assumed constant and known in the AM and are therefore part of the assessment input data. Recruitment deviations $\hat{w}_t^R$ are only estimated for years $t = 2, 3, ...T - a_{50}^{mat}$ because there is otherwise little information in the data to estimate them. We use age-at-50% maturity instead of age-at-50% selectivity to define the size of the recruitment deviation vector because the former is a known input whereas the latter is based on estimated model parameters and therefore violates AD Model Builder rules of differentiation. Natural mortality rate is estimated in the AM as a random walk to allow estimation of changes in natural mortality over time. In all cases, we use a somewhat informative prior on the initial M_t value at t = 1.

Maximum likelihood estimates of error variances are computed analytically in the AM by conditioning on the leading parameters. For this study, we assumed that catchability q = 1 in both the OM and the AM because there is currently some uncertainty about whether to treat the annual spawning biomass surveys as relative indices or absolute estimates. This uncertainty was beyond the scope of this analysis since we are focusing on LRP choices and not on choosing specific MPs for each herring stock. Catchability should be a key issue in future MSE work for herring where the objectives may be more focused on choosing formal MPs for each area. Table 6 provides the likelihood components and calculations involved in the negative-log-posterior distribution function (G; L.10). The AM uses an errors-in-variables maximum likelihood formulation for modeling the combined biomass index and process error likelihood (ℓ_{IR}; L.1-L.6) in which the total error variance (k^2) is assumed to be comprised of observation error (t_I^2) and age-1 recruitment process error (s_R^2) components, i.e., $k^2 = t_I^2 + s_R^2$. Assuming that the observation error proportion of this total is known ($r_{CAA} = 0.1$), the individual variance estimates are $\hat{t}_I^2 = r_{CAA}\hat{k}^2$ and $\hat{s}_R^2 = \left(1 - r_{CAA}\right)\hat{k}^2$, where the estimate of the total variance $\hat{k}^2$ is given by L.5. We use a robust normal likelihood (Fournier et al. 1998) for the age-proportion data (L.7) assuming sample sizes are all equal to an effective size $n = 50$. The total negative log-posterior distribution function includes an informative Beta prior distribution on the stock-recruitment steepness parameter (h; L.8) and an informative prior distribution $N\left(0.50, 0.05^2\right)$ on the natural mortality rate at t=1. The shape parameters (b_1, b_2) of the Beta distribution (L.8) for steepness are derived via moment matching to a prior mean ($m_h = 0.82$), standard deviation ($s_h = 0.05$) given the constraint $0.2 < h < 1$. Note that these informative prior distributions improve stability of the AM parameter estimation procedure, which then reduces inter-annual variability of MSY and F_{MSY} estimates, giving a somewhat optimistic impression of performance of MSY-based harvest control rules (i.e., both Lenfest rules).

The AM outputs include predicted values for all the input data sources given above as well as derived equilibrium quantities (MSY, F_{MSY}, B_{MSY}), and time-series of exploitable biomass ($\hat{\hat{B}}_{1:T+k}^{Ex}$), spawning biomass ($\hat{\hat{B}}_{1:T+k}^{Sp}$), fishing mortality rates ($\hat{\hat{F}}_{1:T}$), and age-1 recruitment ($\hat{\hat{R}}_{1:T} = \hat{\hat{N}}_{1,1:T}$). Finally, for survey frequencies less than annual (i.e., DFO2), the AM runs with only catch during interim years.

2.2.3. Harvest control rules

The feedback harvest control rules we examined use data on the past and present (i.e., t = 1, 2,…T) state of the stock to determine a catch limit for the upcoming year (T+1). We examined three specific harvest control rules that have been either used in setting total allowable catches (TACs) for BC Pacific Herring fisheries (DFO1 and DFO2) or have been proposed as sustainable approaches to managing forage fish fisheries (Lenfest1 and Lenfest2; Pikitch et al. 2012). Examples of all three rules are shown in Figure 2. The DFO rules are identical except that DFO2 uses a biennial survey frequency during the projection period, whereas DFO1 uses an annual survey frequency.

Both the DFO and Lenfest rules compute the target fishing mortality rate $\hat{F}_{T+1}$ via a piece-wise linear function of the stock status B'_T estimated from the assessment, an estimated reference biomass level B''_T, a reference fishing mortality rate F''_T, and control points C_1 and C_2, i.e.,

$$\hat{F}_{T+1} = \begin{cases} 0 & B'_T \le C_1 B''_T \\ F''_T \left(\dfrac{B'_T - C_1 B''_T}{C_1 B''_T} \right) & C_1 B''_T < B'_T < C_2 B''_T \\ F''_T & B'_T \ge C_2 B''_T \end{cases}$$

Both the DFO and Lenfest rules use the estimated unfished spawning stock biomass as the reference biomass level (i.e., $B''_T = \hat{B}_{0,T}$). DFO rules use control constants $C_1 = 0.25, C_2 = 0.31$ and a constant reference fishing mortality rate $F''_T = 0.225$ (equates to 20% proportional exploitation rate) that is independent of the stock assessment and substantially smaller than the operating model F_{MSY}. The Lenfest rules both use a conservative, yet dynamic reference fishing mortality rate $F''_T = 0.5\hat{\hat{F}}_{\text{MSY},T}$ estimated from the stock assessment model. Lenfest1 uses control constants $C_1 = 0.4, C_2 = 1.0$ to gradually ramp up the target fishing mortality rate as spawning biomass approaches the estimated unfished level $\hat{B}_{0,T}$, while Lenfest2 uses control constants $C_1 = 0.4, C_2 = 0.41$ to invoke a knife-edged harvest rule approach.

Once the target fishing mortality rate is determined, both DFO and Lenfest HCRs compute the annual quota using the Baranov catch equation,

$$Q_{T+1} = \frac{\hat{F}_{T+1}}{\hat{M}_T + \hat{F}_{T+1}} \left(1 - e^{-\hat{M}_T - \hat{F}_{T+1}}\right) \hat{\hat{B}}^{Ex}_{T+1}$$

where $\hat{\hat{B}}^{Ex}_{T+1}$ is a 1-year-ahead stock assessment model projection of the exploitable biomass for the coming year. These projections use estimated recruitments off the spawner-recruit relationship for age-1 abundances in years $T - a^{mat}_{50}$ to $T+1$.

2.2.4. Performance measures

We chose three commonly accepted fishery performance metrics to provide a general indication of the conservation and yield performance of simulated management procedures. Conservation performance was measured using the probability (P_{cons}) of spawning stock biomass being at or below conservation thresholds defined by each of the candidate LRPs. Following Shelton and Sinclair (2008), we define poor conservation outcomes as occurring when $P_{cons} > 5\%$. We approximate P_{cons} for each combination of MP and scenario as the mean across simulation trials of the proportion of years that the operating model spawning biomass is at or below each LRP. LRPs based on B_0 and F_{MSY} are derived from the equilibrium properties of the operating model based on historical conditions at t=1 (Table 4). These equilibrium reference points may not be meaningful under non-stationary operating model scenarios in which natural mortality and growth rates change over time as they do in Increasing-M and Constant-Growth operating model scenarios. Therefore, we included a no fishing scenario, in which all future quotas are set equal to zero, to provide an alternative reference biomass time-series that approximates unfished conditions. The P_{cons} statistic for the non-stationary unfished biomass (NSB_0) LRP uses 25% of the spawning biomass in each projection year from a NoFishing management procedure in calculating depletion (biomass relative to B_0) statistics.

We used the median average annual yield and average annual variability of yield (AAV) to summarize yield performance of each MP. The AAV statistic is computed via

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

where Q_t is the simulated quota obtained from applying a given MP in year t.

3. RESULTS

3.1. SIMULATION MODEL DYNAMICS

We selected four example simulation replicates to illustrate the dynamics of the IncM-HisG operating model scenario, the assessment model, and realized spawning biomass, catch, and fishing mortality outcomes from the closed-loop simulation. The four examples show DFO1 and Lenfest2 MP behaviour for relatively constant productivity (SOG) and increasing productivity (WCVI) stocks (Figures 3-6).

For DFO1-SOG (Figure 3a,b), the operating model spawning stock biomass (SSB) declines on average during the projection period as M increases in the presence of fishing. In the projection period, the AM consistently under-estimates SSB and shows a potentially important retrospective pattern, frequently estimating only half and in one instance estimating double the true operating model SSB (Figure 3a, blue spaghetti lines). Realized catch from the HCR remains relatively constant but fluctuates as the AM attempts to track wide changes in spawning biomass (Figure 3c). As the SSB declines rapidly toward B_{MSY} about half way through the projection period, catch reductions of 30-40% are too slow to avoid fishing mortality increases to F ~ 0.4. Nevertheless, SSB never actually drops below B_{MSY} over the projection period.

The Lenfest2-SOG case shows drastically different patterns of SSB, catch and realized fishing mortality over the projection period (Figure 4b). For instance, the Lenfest2 HCR immediately increases the catch because the target F ~ 0.5 (Figure 4c) is much higher than the recent historical F, which was approximately 0.2. Initially, SSB is under-estimated in the AM, so the realized F on the stock is only about 0.4 (Figure 4d); however, further increases in catch combined with over-estimates of SSB cause realized F to increase rapidly to F ~ 0.6 as SSB declines (recall that M is increasing during this time). The Lenfest2 rule closes the fishery at t = 75 when the stock initially drops below B_{MSY}. This occurs because the Lenfest2 HCR cutoff control point is high at $0.4B_0$, which happens to be near the true B_{MSY}. The fishery re-opens the following year, but the realized F increases rapidly from 0.4 to 1.2 even though the catch did not change very much. After a substantial SSB drop to nearly half of B_{MSY}, the fishery is closed for the final four projection years (Figure 4c,d). Although the SSB ends up nearly identical for the DFO1 and Lenfest2 MPs, the fishery was closed in 25% (5/20) of the projection years for Lenfest2 and none for DFO1.

Patterns of SSB, catch, and realized F were similar for DFO1-WCVI (Figure 5) and Lenfest2-WCVI cases (Figure 6); however, despite the stock being above B_{MSY} for the entire projection period, the Lenfest2 HCR generated consistently greater catch variability and closed the fishery in 20% of years.

The general pattern of declining SSB and increasing F for both DFO1 and Lenfest2 MPs is consistent with the expected behaviour of output control quota fisheries that rely on periodic stock assessments. The main difference between the MP behaviours is that the DFO1 rule generates less extreme realized fishing mortality rates because (1) the target F is much lower than the theoretical F_{MSY} and (2) the target F is fixed and independent of the AM and accordingly does not suffer from estimation errors in the key selectivity, recruitment, and natural mortality parameters on which F_{MSY} depends. In contrast, the Lenfest HCRs both aim for a theoretical $0.5F_{MSY}$, which can be as high as 0.6 for some stocks. Realized Fs are even higher on the stock after accounting for stock assessment model errors in both the estimated biomass and F_{MSY}.

Outcomes for 100 simulations under the same IncM-HisG scenario further highlight the difference between MPs, and show that the Lenfest2 procedure leads to more frequent fishery closures and variable catch while maintaining relatively lower levels of depletion in both SOG (Figure 7) and WCVI stocks (Figure 8). General behavior of these MPs under other operating model scenarios and simulation trials was similar. Lenfest1, which uses the same lower control point as Lenfest2 but ramps fishing mortality rates up slower (Figure 2) generally sets more conservative catch and fishing mortality rates than Lenfest2, but is also based on F_{MSY} estimates, which leads to mixed performance relative to the DFO rules when examined over all scenarios and stocks (Tables 7-11,one table for each herring stock). The DFO2 procedure achieves similar outcomes to DFO1, leading to slightly lower catches (in most cases) and higher AAV for similar levels of depletion (Tables 7-11).

3.2. PERFORMANCE AGAINST LIMIT REFERENCE POINTS

As expected, equilibrium-based LRPs generated a predictable pattern in which higher biomass fractions of B_0 resulted in more frequent violations of the LRP (Tables 7-11). This effect is emphasized across all OM assumptions in PRD, CC, HG, and in the IncM Scenarios in SOG and WCVI where these LRPs cannot be achieved even under NoFish MP. The rank order of MPs, based on perceived conservation risk, as defined by the realized stock state in the operating model, differed among herring stocks depending on the current level of natural mortality relative to equilibrium (i.e., M_{2013}/M_{1951}) and the choice of LRP used to measure conservation risk. To simplify the following discussion, we classified historic natural mortality patterns across the five herring stocks into three general types: $M_{2013} < M_{1951}$ (WCVI), $M_{2013} = M_{1951}$ (SOG, PRD, CC), and $M_{2013} > M_{1951}$ (HG). These types interact with the projected natural mortality scenarios to strongly influence MP performance against the LRPs. For example, under the Constant M-Constant Growth scenario, WCVI ($M_{2013} < M_{1951}$) projected natural mortality trajectories start and end below the 1951 level, which makes the simulated WCVI stock more resilient to fishing. It is not surprising, then, that all MPs maintained less than a 5% chance of SSB dropping below any LRP when $M_{2013} < M_{1951}$ (Figure 9a, numerical values appear in Table 8 for WCVI).

Projected natural mortality levels for SOG (used to represent $M_{2013} = M_{1951}$; Figure 1) are maintained near their historical values under Constant M. Thus, most MPs maintained less than a 5% chance of SSB dropping below any LRP. Exceptions occurred where both Lenfest MPs generated 5% or greater chances of SSB dropping below the $0.4B_0$ LRP (Figure 9b, numerical values appear in Table 7 for SOG). The DFO1 MP shows similar expected performance for SOG (all $P_{cons} < 5\%$) in our simulations as the original results from Hall et al. (1988), who also assumed a Constant M–Constant Growth scenario. For PRD ($M_{2013} = M_{1951}$), all MPs had $P_{cons} > 5\%$ for all LRPs except $0.4B_{MSY}$; only the Lenfest2 MP had $P_{cons} > 5\%$ for all LRPs

(Figure 9c, numerical values appear in Table 9 for PRD). In this case, P_{cons} values were similar for DFO1 and Lenfest1 against $0.25B_0$, but diverged as Lenfest1 maintained lower P_{cons} values as the LRP increased toward $0.4B_0$.

For the Constant M scenario, projected natural mortality for HG ($M_{2013} > M_{1951}$) is maintained at nearly double the 1951 value (Figure 1). In this case, all MPs generated $P_{cons} > 5\%$ under all equilibrium biomass LRPs (Table 11, Figure A5). Results for HG were so uniformly poor that we choose not include them in Figure 9 (there was little to compare); however, readers may find all HG results in Table 11 and Figure A5.

For the Increasing M scenario, natural mortality increases to a level that is still below the historical equilibrium for WCVI, is 50% above equilibrium for SOG, PRD, and CC, and is 290% above equilibrium for HG (Figure 1). Under this scenario, DFO1 maintained the lowest P_{cons} values against all LRPs when $M_{2013} < M_{1951}$ (WCVI) or $M_{2013} = M_{1951}$ (SOG, Figure 9d,e), whereas Lenfest1 had the lowest P_{cons} values for PRD (also $M_{2013} = M_{1951}$, Figure 9f). The higher cut-off and ramping F (instead of knife-edged F) used in Lenfest1 generates more conservative outcomes as the lower SSB levels result in lower catch and more frequent fishery closures. The expected catch levels for Lenfest1 (PRD) under Increasing M-Constant Growth are therefore only 68% of catches realized under the DFO1 MP, while the catch variability for Lenfest1 is double that of DFO1 (Table 9 – AAV). Nevertheless, when $M_{2013} \geq M_{1951}$ and future natural mortality is increasing, $P_{cons} >> 5\%$ for all MPs we considered and all LRPs except $0.25B_0$ for SOG. (See Appendix Figures A1-A5 for stock-specific versions of Figure 9 for all operating model scenarios.). Thus, despite more conservative performance of Lenfest1 compared to DFO1, none of the MPs maintained $P_{cons} < 5\%$ for the $0.3B_0$ and $0.4B_0$ LRPs (and no $P_{cons} < 5\%$ for any LRPs in PRD).

Simulated outcomes against alternative LRPs for BC Pacific Herring stocks suggest that there is probably little value in using LRPs that track the dynamics of natural mortality and growth (NSB_0), reference the lowest level of biomass from which the stock has recovered (Historical B), or reference equilibrium-based F_{MSY}. These LRPs showed little to no response to changes in MP across stocks and scenarios, even when MPs seriously violated all equilibrium biomass-based LRPs (e.g., Table 10 for CC herring, Figure A5 for HG).

3.3. MANAGEMENT PROCEDURE EVALUATION

The DFO1 management procedure seems to perform adequately for SOG under the conditions for which it was originally designed (Constant M scenario, LRP $0.25B_0$, Table 7). It also performs well for WCVI under the range of M scenarios we examined (Table 8). However, performance degrades if M increases, or if stocks are maintained above the higher LRPs suggested for forage fish stocks (e.g. Pikitch et al., 2012). Outcomes obtained from DFO1 are mixed for CC and PRD, which suggests that variations on DFO1 may need to be evaluated for these stocks (Tables 9, 10).

The historical trend and projections for natural mortality for HG were well outside the range over which the DFO1 MP was developed and tested. In particular, the HG stock is expected to decline even in the absence of fishing (NoFish MP) because of elevated natural mortality rates. Our results indicate that none of the MPs considered here would be considered adequate regardless of LRP choice (Table 11). Our results suggest that, in contrast to CC and PRD, which may benefit from slight variations to DFO1, herring fisheries in HG may require a substantially different management procedure than any of the ones we examined.

In general, the Lenfest MPs that are recommended for forage species (Pikitch et al., 2012) consistently result in higher variability in catch and more frequent fishery closures across all stocks and scenarios (Tables 7-11). Furthermore, operating model SSB levels were also consistently below the intended $0.4B_0$ biomass limits implied by these rules. Thus, setting harvest control rule cutoff control points equal to the LRP did not guarantee success in avoiding the LRP, nor does setting the cut-off below the LRP imply failure. For instance, the DFO1 rule uses a cut-off control point of $0.25B_0$ and often showed equivalent or better conservation performance than Lenfest rules. The key advantage is the low, fixed target fishing mortality rate: the DFO1 rule aims lower and does not compound biomass estimation errors with poor estimates of F_{MSY}, thereby achieving lower realized fishing mortality rates and higher SSB levels.

4. DISCUSSION

Biological limit reference points are needed to derive conservation objectives for fisheries management. Canadian fisheries policy (DFO 2009) recognizes that specific choices for LRPs should reflect practical considerations such as the context (e.g., forage species), diversity of stakeholder interests, and the types and quality of supporting scientific data. These factors are important because more conservative LRPs will likely lead to more conservative choices for the operational management procedures used to set annual fishing regulations (e.g., output quotas).

In this paper, we developed a simulation framework for evaluating the expected conservation and yield performance of alternative management procedures for BC Pacific Herring stocks. Alternative LRPs were defined based on best scientific practice as well as historical precedent (i.e., the $0.25B_0$ LRP). We used the 2013 stock assessments for five major BC Pacific Herring stocks to condition four operating model scenarios for the future herring biomass dynamics. We then executed four output quota management procedures (MPs) under each operating model. The MPs were derived from the current DFO approach as well as alternatives (i.e., Lenfest rules) suggested in the scientific literature for forage fisheries. Simulation outcomes demonstrated several things. First, the DFO harvest control rule performed well against all LRPs for SOG herring fisheries, which was consistent with the original evaluation performed for this stock by Hall et al. (1988). In contrast, the simulations for PRD, CC, and HG stocks suggested that the DFO and Lenfest rules are expected to result in relatively frequent SSB outcomes below LRPs included herein, highly variable yields, and fishery closures – most of these results are consistent with realized outcomes for these fisheries over the past two decades. The DFO management procedure generally provided the most robust performance with respect to all LRPs except in a few extreme cases where Lenfest1 was better. However, where the DFO procedure could not meet a 5% probability limit of breaching an LRP, the Lenfest rules generally couldn't either. Given the strong potential that herring stocks will continue to experience some periods of high natural mortality (Schweigert et al. 2010), our results imply that the current DFO management procedure may need to be revised regardless of the choices for LRPs.

Second, our results indicate that theoretical LRPs should be fixed over time and that potential empirical LRPs (e.g. based on previously observed stock or biomass index levels) should not reflect worst-case scenarios. The probability of breaching both the dynamic and empirical LRPs was usually near or equal to zero, so both often failed to indicate risks in situations where risks could actually be significant. For instance, if natural mortality rates increase in the SOG, only the DFO MPs maintained SSB above the equilibrium-based 0.30B0 more than 95% of the time. In contrast, all MPs maintained SSB above the non-stationary (i.e., $0.25NSB_0$) LRP 100% of the time, suggesting that the NSB_0 (and Historical B) LRP would not necessarily help managers find robust management procedures that can meet conservation objectives. The key limitation of NSB_0 is that it reinforces the so-called "shifting baseline syndrome" in which the LRP is set to lower levels as the stock declines, while the Historical B reference point appears to be too low for stocks that currently sustain fisheries (SOG, PRD) or for recovering populations (WCVI, CC).

Third, our results reinforce the notion that case-specific closed-loop simulations should always be used to design harvest management procedures. Studies suggesting generic harvest control rules such as the Lenfest alternatives we examined did not fully consider the limitations of estimating theoretical quantities such as F_{MSY} or the effect of biomass estimation errors on the ability to maintain stocks above harvest control points such as $0.4B_0$. Furthermore the fishing mortality rates calculated using Lenfest were quite large compared to other studies (Schweigert et al. 2007, Zheng et al. 1993). At the root of the differences between the F_{MSY} estimates given by our analysis and those in Zheng et al. (1993), are substantial differences in key life history parameters. While there are some similarities in selectivity and weight at age between BC stocks and Prince William Sound (PWS) stocks, BC Pacific Herring are assumed to mature at younger ages relative to the age at which they are selected in the fishery than both Eastern Bering Sea (EBS) and PWS stocks. EBS stocks grow more slowly, and to larger sizes than BC Pacific Herring. Natural mortality is also estimated to be higher for BC Pacific Herring stocks than either EBS or PWS stocks. However, differences in the estimation of F_{MSY} between all these stocks requires a much more complicated analysis to fully explain the differences: most notably, Zheng et al. (1993) and Schweigert et al. (2007) used several different parameterizations of recruitment for their estimation of F_{MSY} (including Beverton-Holt, Ricker, and cyclic parameterizations), and the effects of these parameterizations on the F_{MSY} estimates would need to be compared side by side which is outside the scope of this paper.

Finally, there may be strong potential for increasing M due to increasing predation pressure on herring along with potential changes in oceanographic regimes (Schweigert et al. 2010). Although the DFO rule performed well against the $0.25B_0$ LRP, this may leave lower SSB under future conditions than is adequate to provide resources for dependent species (Pikitch et al. 2012: Tyrrell et al. 2011). If higher LRPs are considered for BC Pacific Herring, it will be critical to evaluate fishery consequences such as the frequency of fishery closures, while exploring harvest control rules with higher biomass cut-offs and/or lower harvest rates.

4.1. LIMITATIONS

The suite of operating models examined here is not exhaustive with respect to potential future productivity, growth, fishing, and mortality scenarios. However, we believe that the diversity of scenarios and incorporation of realistic assessment errors is sufficient to support our general findings that management procedures for BC Pacific Herring may require revisions to meet standard LRPs suggested for forage fish fisheries, as well as the needs of a diverse First Nations and stakeholder community. Nevertheless, there is considerable room for improving the realism behind the operating models and implementation of management procedures. For instance, our somewhat optimistic results for WCVI can be attributed to the current estimate of M (M_{2013}), which is well below the initial M (M_{1951}) used to initialize the model and compute equilibrium-based LRPs. Thus, biomass in WCVI is expected to increase even in the presence of substantial fishing. We cannot comment on the likelihood of this scenario actually occuring for WCVI because we have not explored the uncertainties underlying the stock assessments from which we derived the operating models. However, considering that WCVI is currently a ‘rebuilding’ population, we advise closer evaluation of model assumptions in future analyses. Similarly, catchability is currently estimated in the stock assessment for SOG, whereas our simulated assessments assume that catchability is equal to 1. This reduces the range of biomass estimation errors in the assessment and provides a relatively optimistic outlook on MP performance if the actual assessment estimates catchability.

Our objective was not to conduct an exhaustive study of potential management strategies for Pacific Herring. However, our analysis points to elements of MPs that appear to promote better conservation outcomes. In particular, the benefit of the DFO MP (DFO1) is its low, fixed F, while good conservation performance of the Lenfest1 MP relative to the Lenfest 2 MP can be attributed to the slow ramp in F for higher biomass. Conversely, poor performance of both Lenfest MPs relative to the DFO MP, and especially Lenfest2, is due to a high target F and the rapid increase in F across a small range of biomass. This achieves an “on-off” type of MP that increases variability in catch while simultaneously driving stocks to low levels when the biomass is over-estimated. We did not examine the impact of uncertainty in estimation of the target F in performance of the Lenfest rules, but recommend doing so if they are to be considered in a MP for Pacific Herring or other species in the future. In addition, MP evaluations should consider modifying the DFO rule to improve conservation performance for some stocks. In particular, a lower target exploitation rate could maintain higher biomass while allowing for low variability in yield. In a separate simulation study (unpublished results, not shown here) we modified the DFO rule to use a 10% harvest rate and showed that reasonable catches can be achieved while improving conservation outcomes for stocks subject to high and/or increasing natural mortality.

4.2. FUTURE WORK

There is ongoing concern about the suitability of assumptions about the spawn survey scaling parameter *q* as well as broad interest in exploring alternative management procedures beyond those presented here (e.g. empirical control rules). We recommend using the analytical framework to explore the implications of alternative assumptions and choices, including survey frequency, and to better understand the tradeoffs and risks associated with each (for examples see Appendices B and C which illustrate the flexibility of the approach). The framework will need to be modified to address questions related to spatial structure, sequential fisheries, and multiple fleets.

5. CONCLUSION

We re-emphasize that the objective of this paper was not to conduct an exhaustive evaluation of potential management procedures and limit reference points. Our conclusions are therefore restricted to strategic management considerations. Limit reference points establish the tradeoffs between conservation and yield, and therefore should reflect both types of objectives. This tradeoff is likely to vary between stocks, given diverse stock dynamics, local stakeholder interests, and the economics of fishing in the different management areas. We therefore expect that future management evaluations will consider different LRPs for each stock area. It is important to recognize that the evaluation of MP performance against a set of LRP requires scientific analyses and can draw on a set of scientific ‘best practices’ (e.g. Smith 1994; Sainsbury 2008); however, the process of defining the objectives for the fishery requires input from First Nations, fishery stakeholders, and managers.

This study suggests that future work to identify LRPs for BC Pacific Herring fisheries should focus on fixed (equilibrium) objectives related to biomass. The LRP based on F_{MSY} was not generally useful for distinguishing between candidate MPs on the basis of conservation performance. Furthermore, our analysis indicates that the current DFO MP performs well only over a narrow range of conditions for particular stocks. Increases in M similar to those estimated over the past several decades revealed relatively poor conservation performance in 4 of 5 stock areas. We therefore recommend exploring alternative MPs that can provide good performance across a range of future scenarios for Herring population dynamics.

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7. TABLES

Table 1. Notation used in the operating model.

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
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	Spawn survey scaling parameter
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
f_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*

Symbol	Description
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
s_R	Standard error of the random walk in recruitment
s_M	Standard error of the random walk in natural mortality rate
s_a	Standard error of the random walk in Walford intercept (growth rate)
g^X	Lag-1 autocorrelation in log-natural mortality rate ($X = M$), log-recruitment ($X = R$), and the growth parameter ($X = a$).
w_t^X	Auto-correlated error in log-natural mortality rate ($X = M$), log-recruitment ($X = R$), and the growth parameter ($X = a$)
d_t^X	*Normal*(0,1) error component in log-natural mortality rate ($X = M$), log-recruitment ($X = R$), and the growth parameter ($X = a$)
$t_{I,t}$	Survey coefficient of variation in year *t*
t_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
$h_{a,t}^X$	Uncorrelated *Normal*(0,1) error in logistic-transformed proportions-at-age
$x_{a,t}^X$	Zero-centred log-residual of proportion-at-age
$p_{a,t}^X$	Observed proportion-at-age *a* in year *t* catch

Table 2. Operating model parameter values used to specify simulation scenarios for the five herring stocks. Equilibrium values in the final three columns are computed using M1951 and the HisG values for a.

Stock	Scenario	B_0	h	M_{1951}	M_{2013}	M_{2033}	a_{2013}	a_{2033}	s_R	t_I	t_P^F	t_P^S	F_{MSY}	B_{MSY}	MSY
SOG	ConM-ConG	137.10	0.77	0.57	0.56	0.56	10.65	10.65	0.50	0.30	0.19	0.30	-	-	-
	ConM-HisG	137.10	0.77	0.57	0.56	0.56	10.65	8.73	0.50	0.30	0.19	0.30	1.09	46.99	25.01
	IncM-HisG	137.10	0.77	0.57	0.56	0.84	10.65	8.73	0.50	0.30	0.19	0.30	-	-	-
	IncM-ConG	137.10	0.77	0.57	0.56	0.84	10.65	10.65	0.50	0.30	0.19	0.30	-	-	-
WCVI	ConM-ConG	54.70	0.76	0.64	0.43	0.43	9.45	6.92	0.50	0.40	0.19	0.40	-	-	-
	ConM-HisG	54.70	0.76	0.64	0.43	0.43	9.45	10.13	0.50	0.40	0.19	0.40	1.23	19.54	10.85
	IncM-HisG	54.70	0.76	0.64	0.43	0.65	9.45	10.13	0.50	0.40	0.19	0.40	-	-	-
	IncM-ConG	54.70	0.76	0.64	0.43	0.65	9.45	6.92	0.50	0.40	0.19	0.40	-	-	-
CC	ConM-ConG	58.81	0.82	0.48	0.46	0.46	6.33	6.33	0.70	0.40	0.21	0.28	-	-	-
	ConM-HisG	58.81	0.82	0.48	0.46	0.46	6.33	12.45	0.70	0.40	0.21	0.28	0.96	18.72	9.59
	IncM-HisG	58.81	0.82	0.48	0.46	0.69	6.33	12.45	0.70	0.40	0.21	0.28	-	-	-
	IncM-ConG	58.81	0.82	0.48	0.46	0.69	6.33	6.33	0.70	0.40	0.21	0.28	-	-	-
PRD	ConM-ConG	60.80	0.73	0.46	0.50	0.50	9.86	9.86	0.70	0.50	0.36	0.48	-	-	-
	ConM-HisG	60.80	0.73	0.46	0.50	0.50	9.86	11.00	0.70	0.50	0.36	0.48	0.79	19.90	8.94
	IncM-HisG	60.80	0.73	0.46	0.50	0.75	9.86	11.00	0.70	0.50	0.36	0.48	-	-	-
	IncM-ConG	60.80	0.73	0.46	0.50	0.75	9.86	9.86	0.70	0.50	0.36	0.48	-	-	-
HG	ConM-ConG	34.07	0.76	0.41	0.80	0.80	11.40	11.40	0.80	0.50	0.21	0.34	-	-	-
	ConM-HisG	34.07	0.76	0.41	0.80	0.80	11.40	11.32	0.80	0.50	0.21	0.34	0.73	10.73	4.69
	IncM-HisG	34.07	0.76	0.41	0.80	1.19	11.40	11.32	0.80	0.50	0.21	0.34	-	-	-
	IncM-ConG	34.07	0.76	0.41	0.80	1.19	11.40	11.40	0.80	0.50	0.21	0.34	-	-	-

Table 3. General age-structured, continuous fishery operating model used in closed loop simulations of BC Pacific herring fisheries. The generic superscript "X" is used wherever a function is identical for the fishery (X=F) and survey (X=S).

Parameters

Equation	Description
OM2.1	$\Theta = \left(B_0, h, M_1, \gamma_R, \gamma_M, \sigma_R, \sigma_M, q, \tau_I, \tau_P, L_\infty, L_1, k, a_{50}^{mat}, a_{95}^{mat}, a_{50}^{sel,F}, a_{95}^{sel,F}, a_{50}^{sel,S}, a_{95}^{sel,S}\right)$

Fixed life history schedules

Operating Model	Formula
OM2.2	$m_a = \dfrac{1}{1+\exp\left[-\log(19)\left(a - a_{50}^{mat}\right)/\left(a_{95}^{mat} - a_{50}^{mat}\right)\right]}$
OM2.3	$s_a^{X=F,S} = \dfrac{1}{1+\exp\left[-\log(19)\left(a - a_{50}^{sel,X}\right)/\left(a_{95}^{sel,X} - a_{50}^{sel,X}\right)\right]}$

Stock-recruitment parameters and equilibrium population

Equation	Description
OM2.4	$R_0 = B_0 / \phi_{\text{ssb}}$
OM2.5	$a = \dfrac{4hR_0}{B_0\left(1-h\right)}$
OM2.6	$b = \dfrac{5h-1}{B_0\left(1-h\right)}$
OM2.7	$N_{a,1} = R_0 e^{-M_1(a-1)}, \qquad 1 \le a \le A-1$
OM2.8	$N_{A,1} = N_{A-1,1}/\left(1-e^{-M_1}\right)$
OM2.9	$B_{a,1} = N_{a,1} w_{a,1}$

State dynamics

Equation	Description
OM2.10	$\omega_t^{X=R,M,\alpha} = \begin{cases} \dfrac{\sigma_X}{\sqrt{1-\gamma_R^2}}\delta_t^X & t=1 \\ \gamma_X \omega_{t-1}^X + \sigma_X \delta_t^X & t>1 \end{cases}$
OM2.11	$M_t = \begin{cases} M_1 & t=1 \\ M_t e^{\omega_t^M - 0.5\sigma_M^2/\left(1-\gamma_M^2\right)} & t>1 \end{cases}$
	$\rho_t = \beta_1^\rho + \beta_2^\rho \alpha_t$
	$L_{\infty,t} = \dfrac{\alpha_t}{1-\rho_t}, \kappa_t = -\log \rho_t$
OM2.12	$\ell_{a,t} = L_{\infty,t-a} + \left(L_{1,t-a} - L_{\infty,t-a}\right)e^{\left(-\kappa_{t-a}(a-1)\right)}$
OM2.13	$w_{a,t} = c_1 \ell_{a,t}^{\;c_2}$
OM2.14	$N_{1,t} = \dfrac{\alpha B_{t-1}^{Sp}}{1+\beta B_{t-1}^{Sp}} \exp\left[\omega_t^R - 0.5\sigma_R^2/\left(1-\gamma_R^2\right)\right]$
OM2.15	$N_{a,t} = N_{a-1,t-1}e^{-M_{t-1}+s_a^F F_{t-1}} \qquad 2 \le a \le A-1$
OM2.16	$N_{A,t} = N_{A-1,t-1}e^{-M_{t-1}+s_{A-1}^F F_{t-1}} + N_{A,t-1}e^{-M_{t-1}+s_A^F F_{t-1}}$
OM2.17	$B_t^{Sp} = \sum_{a=1}^{A} m_a w_{a,t} N_{a,t}$
OM2.18	$B_t^{Ex} = \sum_{a=1}^{A} s_a^S w_{a,t} N_{a,t}$
OM2.19	$C_{a,t} = \dfrac{s_a^F F_t}{M_t + s_a^F F_t}\left(1 - e^{-s_a^F F_t}\right)N_{a,t}$

Equation	Description
OM2.20	$Q_t = \sum_{a=1}^{A} C_{a,t} w_{a,t} \quad t \le T_1 - 1$

Survey and proportion-at-age observations

Equation	Description
OM2.21	$I_t = qB_t^{Ex} \exp\left[\tau_{I,t}\varepsilon_t - 0.5\tau_{I,t}^2\right]$
OM2.22	$u_{a,t}^X = s_a^X B_{a,t} \Big/ \sum_{j=1}^{A} s_j^X B_{j,t}$
OM2.23	$x_{a,t}^X = \log u_{a,t}^X + \tau_P^X \eta_{a,t}^X - \frac{1}{A}\sum_{j=1}^{A}\left[\log u_{j,t}^X + \tau_P^X \eta_{j,t}^X\right]$
OM2.24	$p_{a,t}^X = \exp\left[x_{a,t}^X\right] \Big/ \sum_{j=1}^{A} \exp\left[x_{j,t}^X\right]$

Table 4. Equilibrium solutions for spawning biomass, $\bar{B}^{Sp}$, exploitable biomass, $\bar{B}^{Ex}$, and yield, $\bar{Q}$, given a fishing mortality rate, $\bar{F}$. Top set of parameters, Q, is used to calculate operating model reference points. Elements of the parameter set, $\hat{\tilde{\Theta}}_T$ are estimates updated to time T by the assessment model – these are substituted for their operating model counterparts to compute equilibrium quantities B_0 and F_{MSY} as required by the harvest control rules. Values for F_{MSY} are obtained by numerically maximizing $\bar{Q}$ with respect to $\bar{F}$.

Equation	Description
EQ3.1	$\mathrm{Q} = \left(a, b, m_{1:A}, s^F_{1:A}, w_{1:A}, M_1\right)$
EQ3.2	$\hat{\tilde{\Theta}}_T = \left(\hat{\tilde{a}}_T, \hat{\tilde{b}}_T, \hat{\tilde{s}}^F_{1:A,T}, \hat{M}_T\right)$
EQ3.3	$\ell_a = \begin{cases} 1 & a = 1 \\ \ell_{a-1} e^{\left(-M_1 - s^F_{a-1}\bar{F}\right)} & 2 \le a < A \\ \ell_{A-1} e^{\left(-M_1 - s^F_{A-1}\bar{F}\right)} \Big/ \left(1 - e^{\left(-M_1 - s^F_A \bar{F}\right)}\right) & a = A \end{cases}$
EQ3.4	$\phi_{\mathrm{y}} = \sum_{a=1}^{A} \ell_a s^F_a w_a \bar{F}\left(1 - e^{\left(-M_1 - s^F_a \bar{F}\right)}\right) \Big/ \left(M_1 + s^F_a \bar{F}\right)$
EQ3.5	$\phi_{\mathrm{ssb}} = \sum_{a=1}^{A} \ell_a m_a w_a$
EQ3.6	$\bar{R} = \left(a f_{\mathrm{ssb}} - 1\right) \Big/ b f_{\mathrm{ssb}}$
EQ3.7	$\bar{B}^{Sp} = \bar{R} f_{\mathrm{ssb}}$ $\bar{B}^{Ex} = \bar{R} f_{\mathrm{y}}$
EQ3.8	$\bar{Q} = \bar{B}^{Ex} \dfrac{\bar{F}}{M + \bar{F}}\left(1 - e^{-\bar{F}}\right)$

Table 5. Catch-at-age assessment model (AM) quantities that differ from operating model values. The generic superscript "X" is used for selectivity because fishery F and survey S selectivity functions only differ in the parameters given in AM.1.

Equation	Description
AM.1	$\hat{\Pi}_T = \left(\widehat{B_0}, \hat{h}, \hat{M}_1, \hat{a}_{50}^{sel,F}, \hat{a}_{95}^{sel,F}, \hat{a}_{50}^{sel,S}, \hat{a}_{95}^{sel,S}, \hat{\omega}_{2:T}^{M}, \hat{\omega}_{2:T-a_{50}^{mat}}^{R}\right)$
AM.2	$\hat{\hat{s}}_a^X = \dfrac{1}{1+\exp\left[-\log(19)\left(a-\hat{a}_{50}^{sel,X}\right)\Big/\left(\hat{a}_{95}^{sel,X}-\hat{a}_{50}^{sel,X}\right)\right]}$
AM.3	$\hat{\hat{u}}_{a,t}^X = \hat{\hat{s}}_a^X w_a \hat{\hat{N}}_{a,t} \Big/ \sum_j \hat{\hat{s}}_j^X w_j \hat{\hat{N}}_{j,t}$
AM.4	$\hat{\hat{C}}_{a,t} = Q_t \hat{\hat{u}}_{a,t}^F \big/ w_a$
AM.5	$\log \hat{M}_t = \begin{cases} \log \hat{M}_1 & t=1 \\ \log M_{t-1} + \hat{w}_t^M & t>1 \end{cases}$
AM.6	$\hat{\hat{N}}_{1,t} = \begin{cases} \hat{\hat{R}}_0 & t=1 \\ \dfrac{\hat{\hat{a}}\hat{\hat{B}}_{t-1}^{Sp}}{1+\hat{\hat{b}}\hat{\hat{B}}_{t-1}^{Sp}} e^{\hat{\omega}_t^R} & 2 \le t \le T-a_{50}^{mat} \\ \dfrac{\hat{\hat{a}}\hat{\hat{B}}_{t-1}^{Sp}}{1+\hat{\hat{b}}\hat{\hat{B}}_{t-1}^{Sp}} & t \ge T-a_{50}^{mat} \end{cases}$
AM.7	$\hat{\hat{N}}_{a,t} = \begin{cases} e^{-\hat{M}_t}\left(\hat{\hat{N}}_{a-1,t-1} - \hat{\hat{C}}_{a-1,t-1}\right) & 2 \le a < A \\ e^{-\hat{M}_t}\left(\hat{\hat{N}}_{a-1,t-1} + \hat{\hat{N}}_{A,t-1} - \hat{\hat{C}}_{a,t-1} - \hat{\hat{C}}_{A,t-1}\right) & a = A \end{cases}$
AM.8	$\hat{\hat{F}}_t = Q_t \Big/ \hat{\hat{B}}_t^{Exp}$

Table 6. Components of the total negative log-posterior density function (G) given data up to time T. Negative log-likelihood functions for biomass index and recruitment (ℓ_{IR}) and age-proportion data (ℓ_P), prior distributions for stock-recruitment steepness (ℓ_h) and natural mortality (ℓ_M including M_1 and deviations in the random walk).

Equation	Description
L.1	$z_t = \log\left(\frac{I_t}{\hat{B}_t^{Ex}}\right)$
L.2	$\log q = \frac{1}{T}\sum_{t=1}^{T} z_t$
L.3	$Z_I = \sum_{t=1}^{T}\left(z_t - \log q\right)^2$
L.4	$Z_R = \sum_{t=2}^{T-a_{50}^{mat}} \left(\hat{\omega}_t^R\right)^2$
L.5	$\hat{\kappa}^2 = \frac{1}{2T + a_{50}^{mat} - 1}\left(\frac{Z_I}{r_{CAA}} - \frac{Z_R}{1 - r_{CAA}}\right)$
L.6	$\ell_{IR} = \frac{2T + a_{50}^{mat} - 1}{2}\log\left(\hat{\kappa}^2\right)$
L.7	$\ell_P^X = \sum_{t=1}^{T}\sum_{a=1}^{A}\log\left[\exp\left(-\frac{n\left(p_{a,t}^X - \hat{u}_{a,t}^X\right)^2}{2p_{a,t}^X\left(1 - p_{a,t}^X\right)} + 0.1/A\right) + 0.01\right]$
L.8	$\ell_h = -\left[\left(b_1^h - 1\right)\log\hat{h} + \left(b_2^h - 1\right)\log\left(1 - \hat{h}\right)\right]$
L.9	$\ell_M = \frac{1}{2\sigma_M^2}\left(\hat{M}_1 - \mu_M\right)^2 + \frac{1}{2\sigma_\delta^2}\sum_{t=2}^{T}\left(\omega_t^M\right)^2$
L.10	$G = \ell_{IR} + \ell_P^F + \ell_P^S + \ell_h + \ell_M$

Table 7. Management procedure (MP) outcomes: median average annual catch ($\bar{C}$, thousand metric tonnes), catch variability (AAV), depletion ($\bar{D}$ = B_t/B_0), and conservation performance (probability of biomass less than or equal to LRP) for SOG under each operating model scenario. Bold values indicate probabilities greater than 5% of depletion or fishing mortality exceeding the LRP.

		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**

Table 8. Management procedure (MP) outcomes: median average annual catch ($\bar{C}$, thousand metric tonnes), catch variability (AAV), depletion ($\bar{D}$ = B_t/B_0), and conservation performance (probability of biomass less than or equal to LRP) for WCVI under each operating model scenario. Bold values indicate probabilities greater than 5% of depletion or fishing mortality exceeding the LRP.

		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

Table 9. Management procedure (MP) outcomes: median average annual catch ($\bar{C}$, thousand metric tonnes), catch variability (AAV), depletion ($\bar{D}$ = B_t/B_0), and conservation performance (probability of biomass less than or equal to LRP) for PRD under each operating model scenario. Bold values indicate probabilities greater than 5% of depletion or fishing mortality exceeding the LRP.

		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	0.81	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**

Table 10. Management procedure (MP) outcomes: median average annual catch ($\bar{C}$, thousand metric tonnes), catch variability (AAV), depletion ($\bar{D}$ = B_t/B_0), and conservation performance (probability of biomass less than or equal to LRP) for CC under each operating model scenario. Bold values indicate probabilities greater than 5% of depletion or fishing mortality exceeding the LRP.

		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	0.69	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

Table 11. Management procedure (MP) outcomes: median average annual catch ($\bar{C}$, thousand metric tonnes), catch variability (AAV), depletion ($\bar{D}$ = B_t/B_0), and conservation performance (probability of biomass less than or equal to LRP) for HG under each operating model scenario. Bold values indicate probabilities greater than 5% of depletion or fishing mortality exceeding the LRP. "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

8. FIGURES

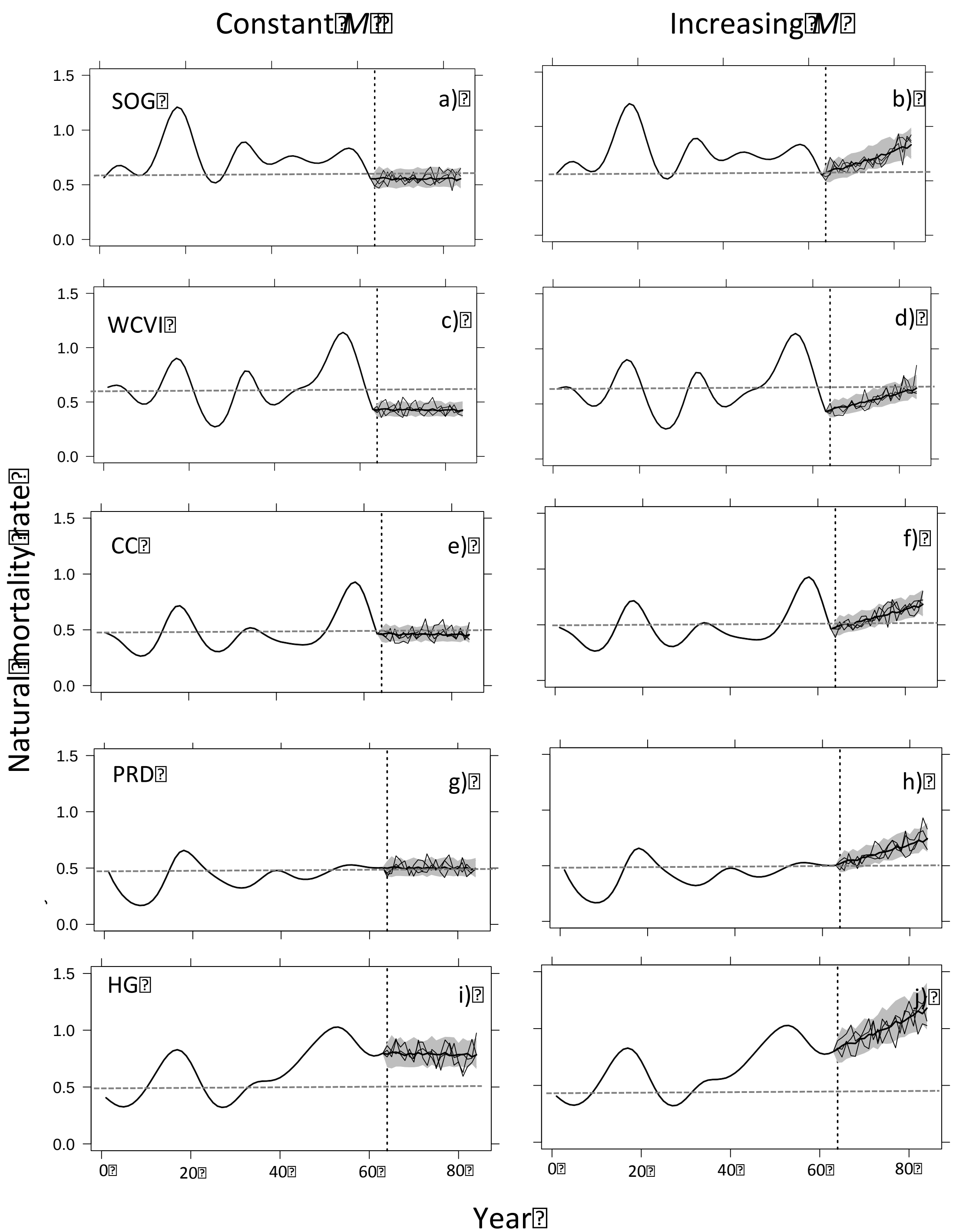

Figure 1. Natural mortality rate (M) envelopes by stock under Constant-M (a,c,e,g,i) and Increasing-M (b,d,f,h,j) scenarios. Dashed horizontal line represents the starting M in 1951 from the stock assessment model. Vertical line represents the first year of the projection period. Simulation envelopes include the median (thick black line) and central 90% of M trajectories over 100 simulations (grey shaded region), and three individual simulation replicates (thin lines).

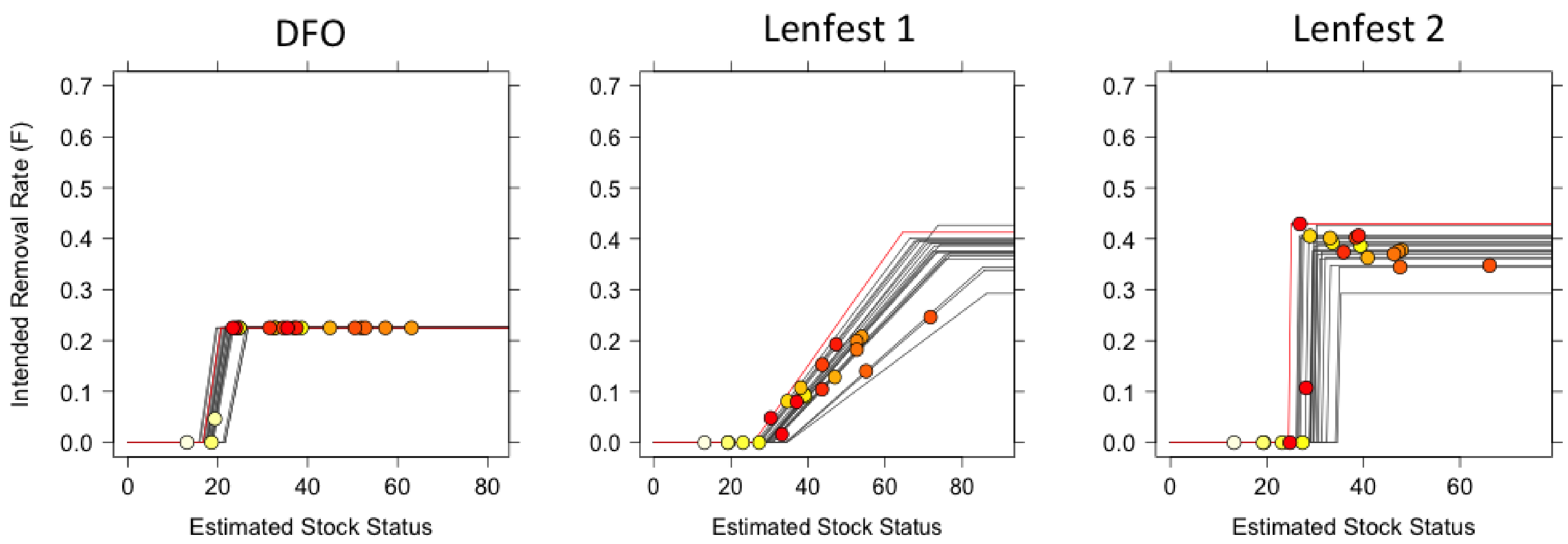

Figure 2. Harvest control rules defining relationships between the spawning stock status estimated from the CAA assessment model (Estimated Stock Status) and the target fishing mortality rate (Intended Removal Rate). All rules use multiples of the unfished biomass (B_0) estimated in the assessment model to compute control points DFO = $0.25B_0$,$0.31B_0$; Lenfest1 = $0.4B_0$,$1.0B_0$; Lenfest 2 = $0.4B_0$,NA. The DFO rule uses a fixed reference fishing mortality rate F = 0.225, while both Lenfest rules use an estimated F = $0.5F_{MSY}$ reference. Each individual line represents the rule used in one of the 20 projection years. Horizontal variation among the HCRs is caused by variation in annual estimates of B_0, while vertical variation is caused by variation in F_{MSY} (Lenfest only) among years. The stock status estimates and F targets implemented in each year are indicated by circles, which get darker as Year increases from 64 to 84.

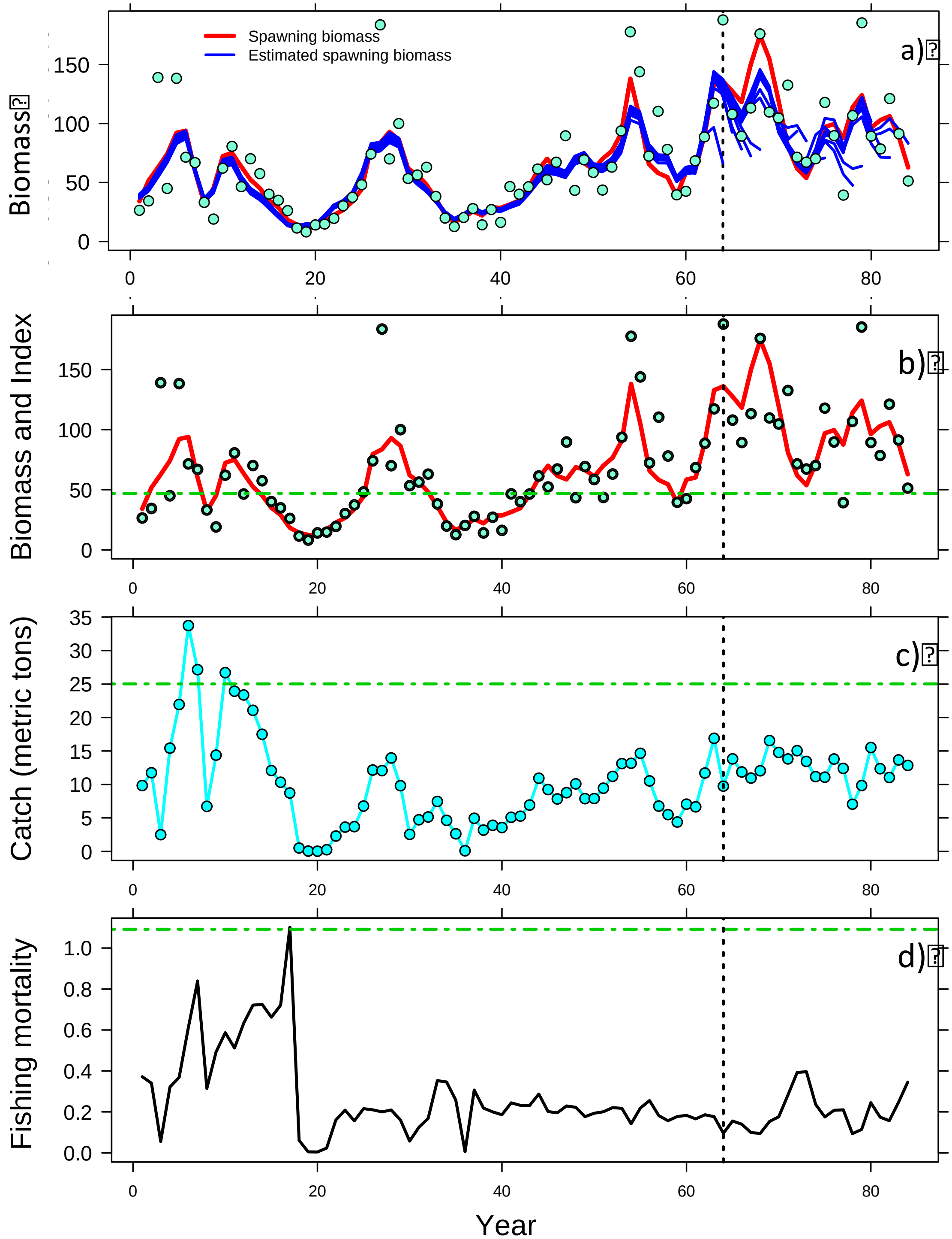

Figure 3. Single simulation replicate of the DFO1 management procedure for SOG under the Increasing M-Historical growth scenario. a) retrospective stock assessment performance, b) operating model spawning biomass trajectory and survey index of abundance, c) realized catch and d) realized fishing mortality. Horizontal dashed lines represent B_{MSY} (b), MSY (c), and F_{MSY} (d), respectively. Vertical dashed line represents end of historical period.

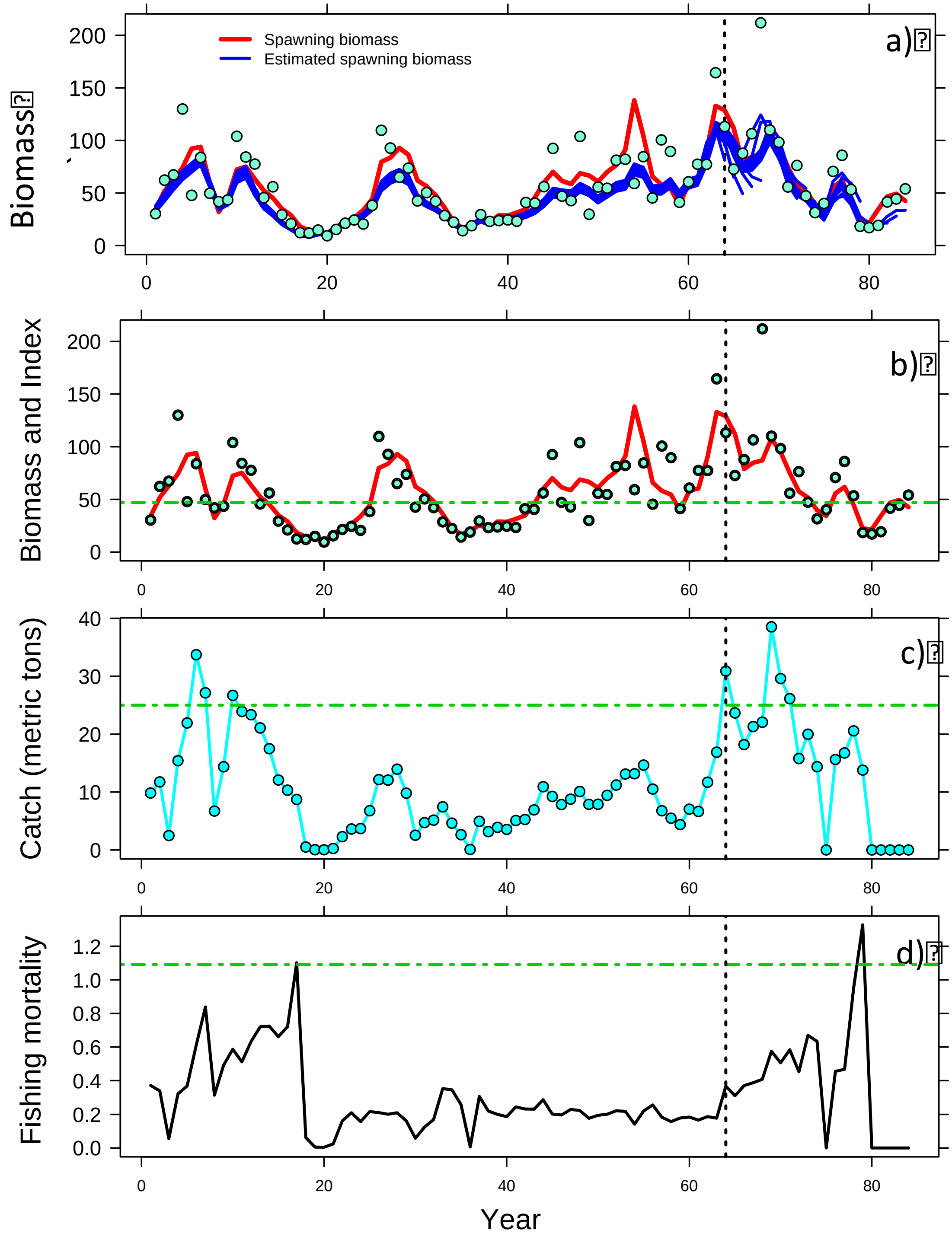

Figure 4. Single simulation replicate of the Lenfest2 management procedure for SOG under the Increasing M-Historical growth scenario. a) retrospective stock assessment performance, b) operating model spawning biomass trajectory and survey index of abundance, c) realized catch and d) realized fishing mortality. Horizontal dashed lines represent B_{MSY} (b), MSY (c), and F_{MSY} (d), respectively. Vertical dashed line represents end of historical period.

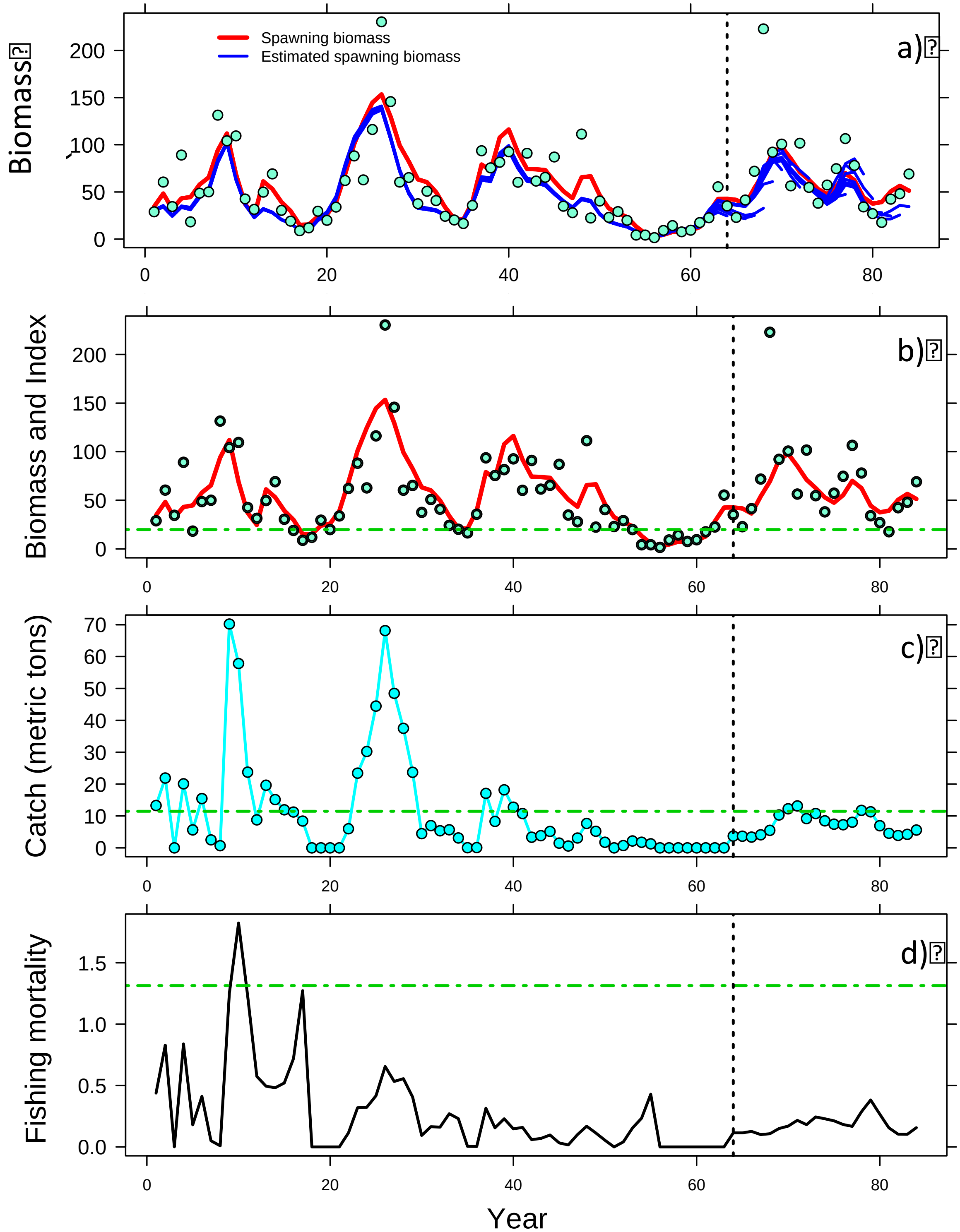

Figure 5. Single simulation replicate of the DFO1 management procedure for WCVI under the Increasing M-Historical growth scenario. a) retrospective stock assessment performance, b) operating model spawning biomass trajectory and survey index of abundance, c) realized catch and d) realized fishing mortality. Horizontal dashed lines represent B_{MSY} (b), MSY (c), and F_{MSY} (d), respectively. Vertical dashed line represents end of historical period.

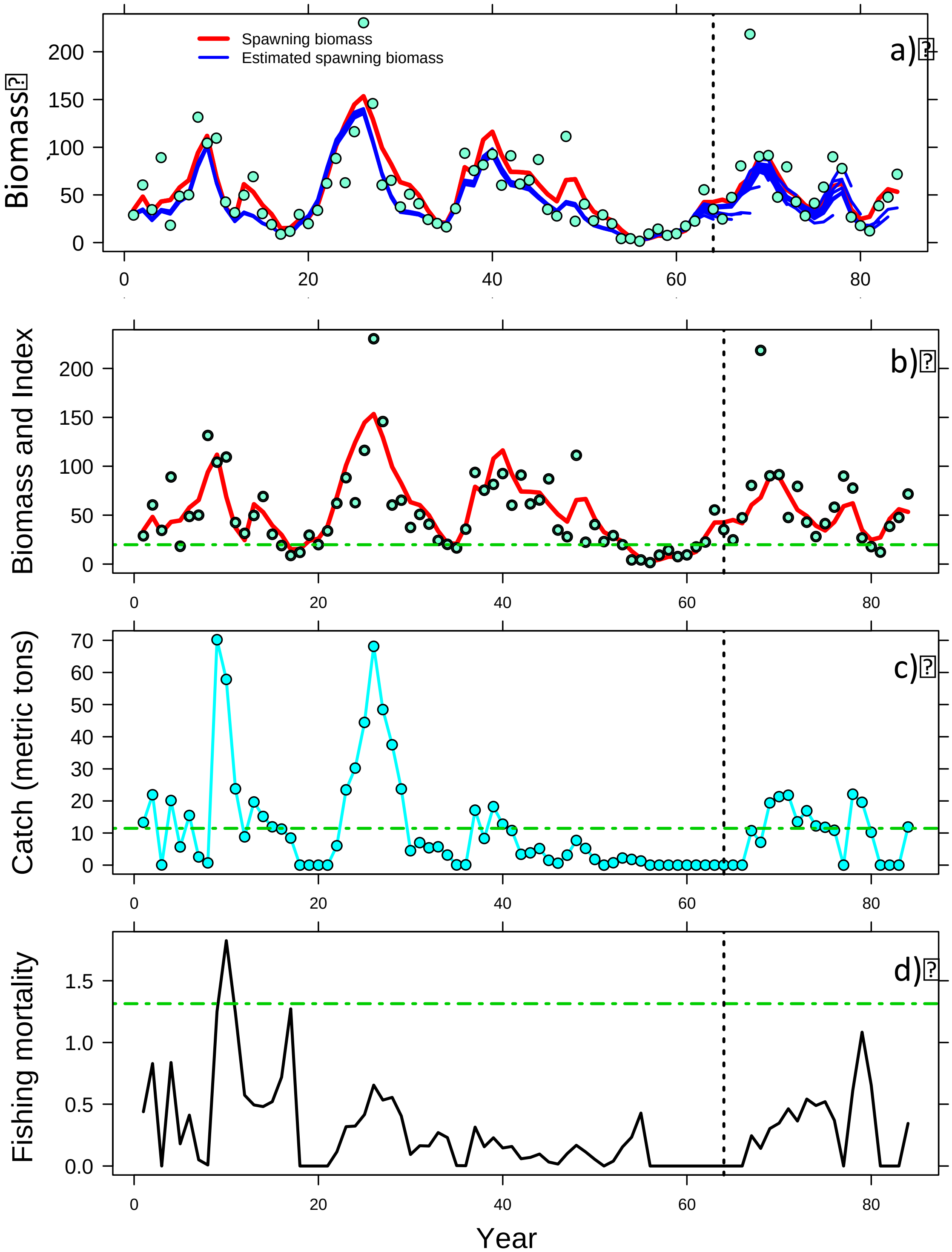

Figure 6. Single simulation replicate of the Lenfest2 management procedure for WCVI under the Increasing M-Historical growth scenario. a) retrospective stock assessment performance, b) operating model spawning biomass trajectory and survey index of abundance, c) realized catch and d) realized fishing mortality. Horizontal dashed lines represent B_{MSY} (b), MSY (c), and F_{MSY} (d), respectively. Vertical dashed line represents end of historical period.

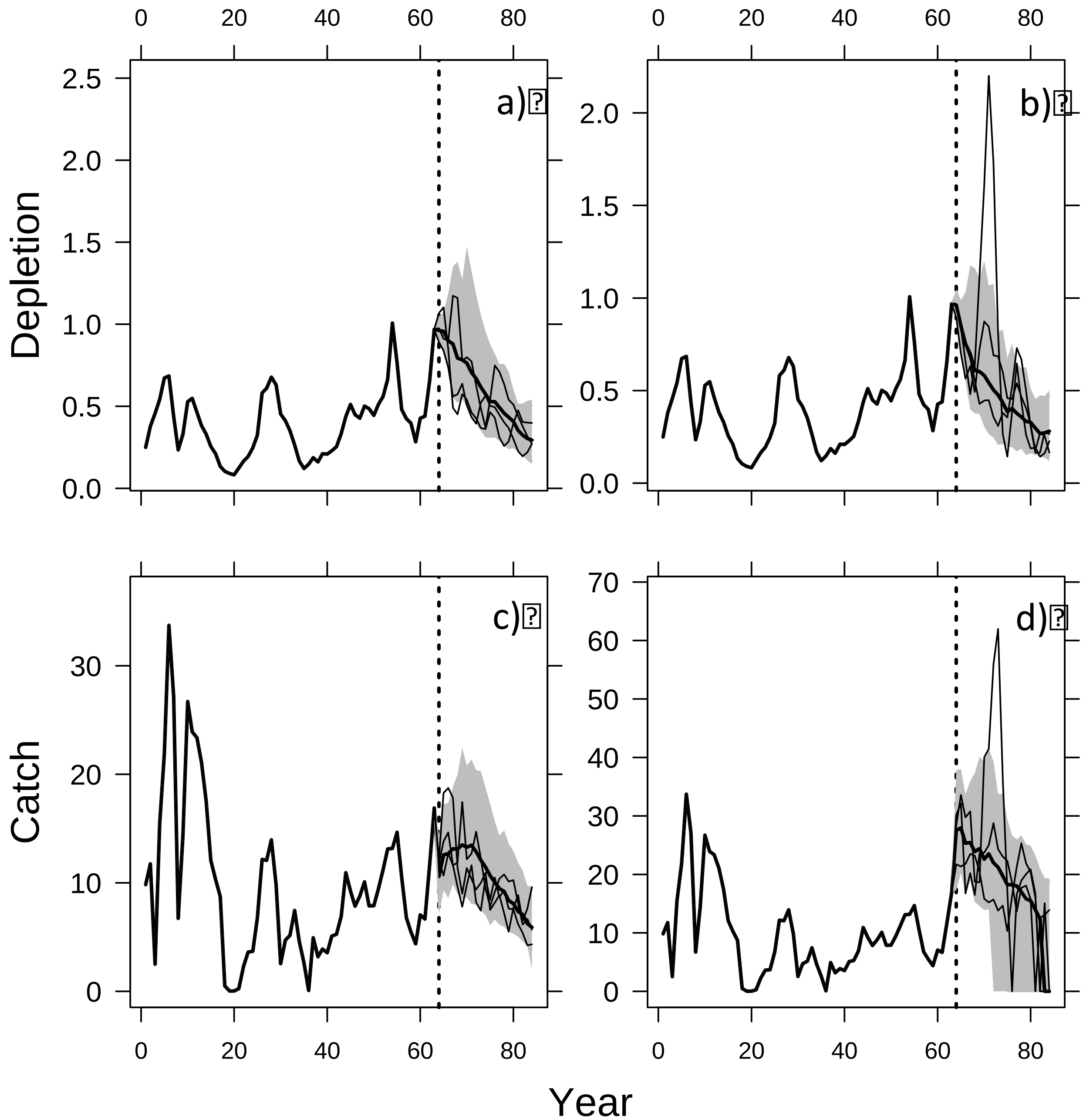

Figure 7. Spawning biomass depletion (top) and catch (bottom) envelopes for SOG under the Increasing M-Historical growth scenario using the DFO1 (a, c) and the Lenfest 2 (b, d) management procedures. Simulation envelopes include the median (thick black line) and central 90% of depletion and catch outcomes over 100 simulations (grey shaded region), and three individual simulation replicates (thin lines).

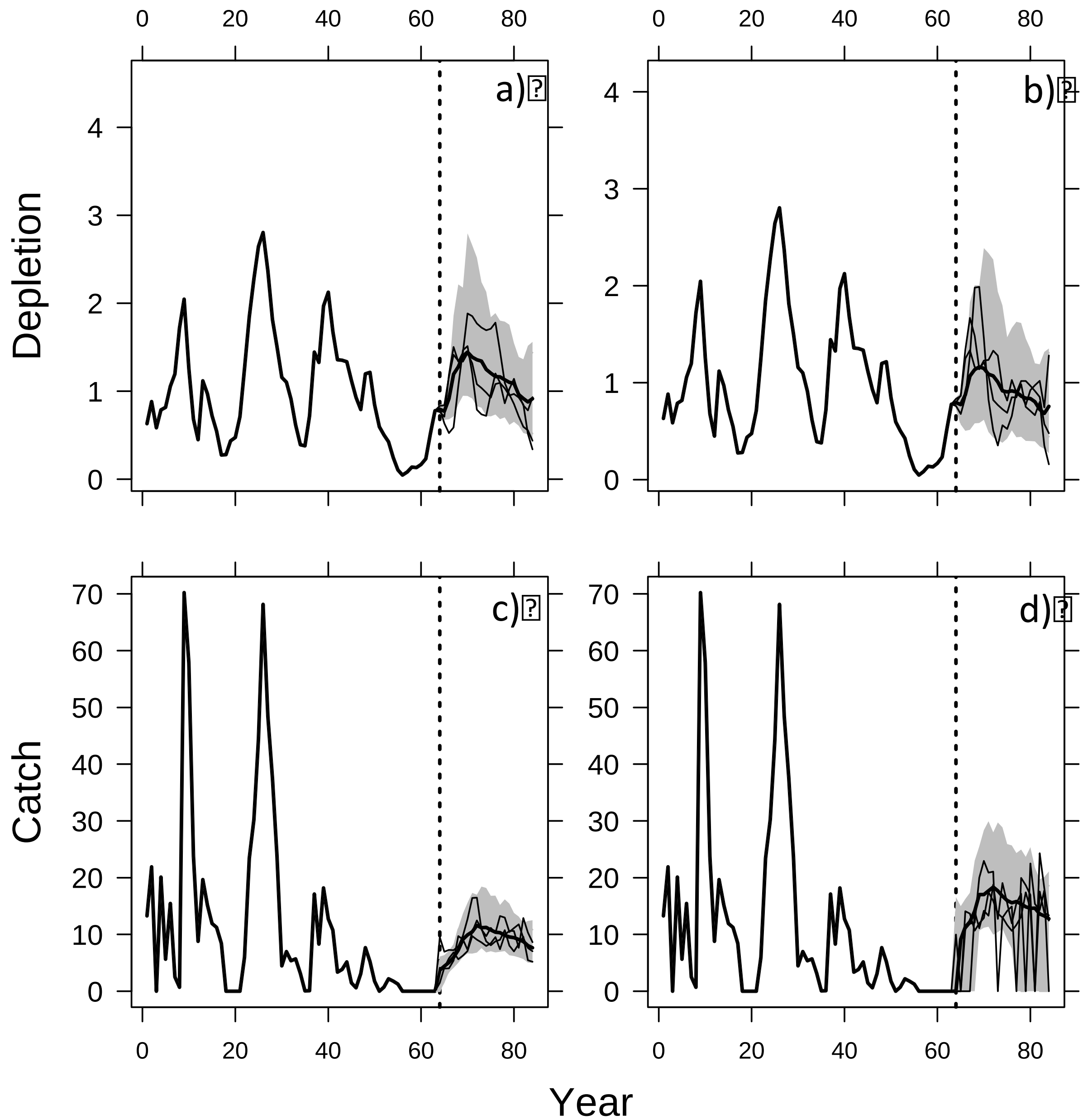

Figure 8. Spawning biomass depletion (top) and catch (bottom) envelopes for WCVI under the Increasing M-Historical growth scenario using the DFO1 (a, c) and the Lenfest 2 (b, d) management procedures. Simulation envelopes include the median (thick black line) and central 90% of depletion and catch outcomes over 100 simulations (grey shaded region), and three individual simulation replicates (thin lines).

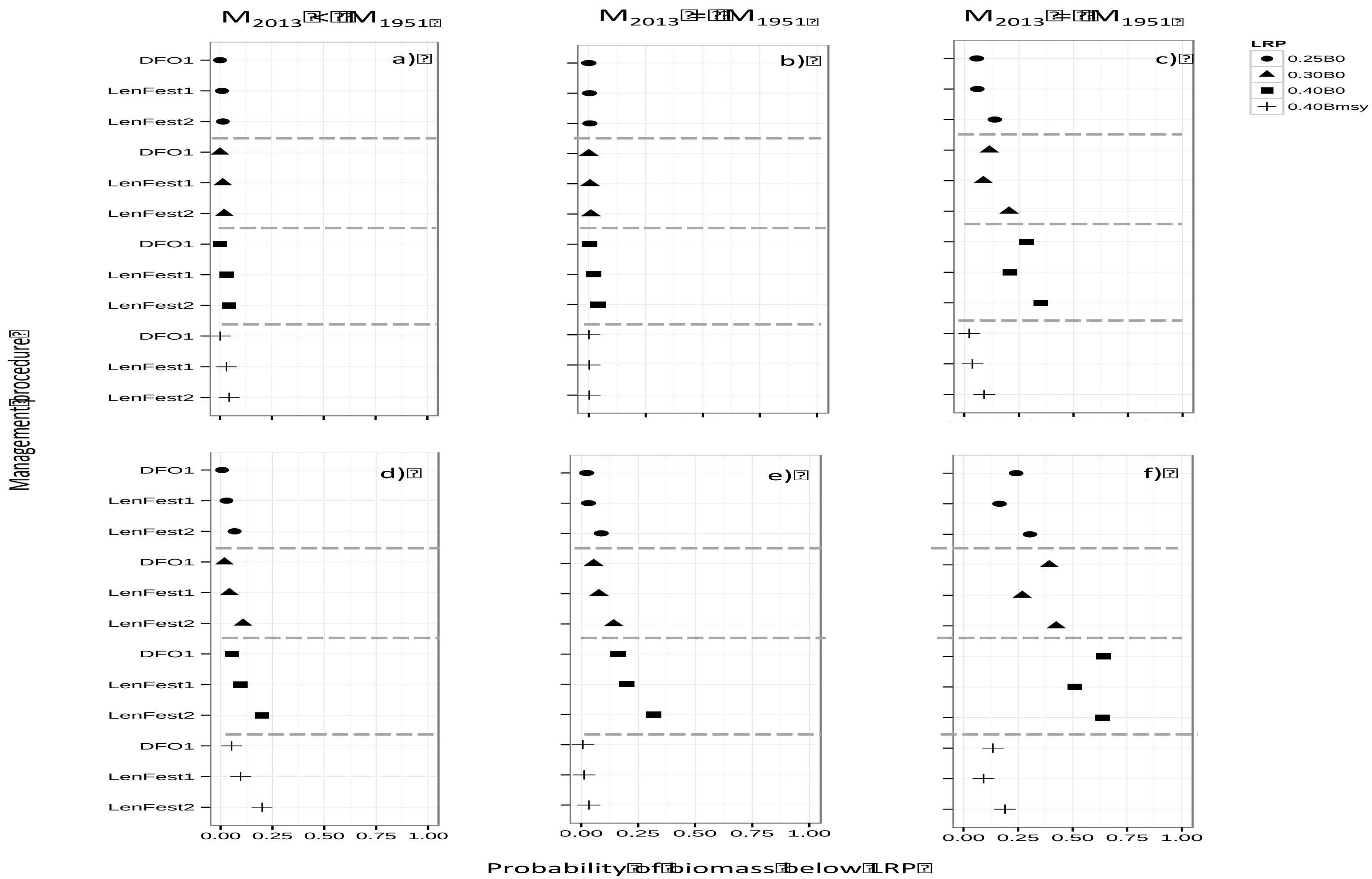

Figure 9. Management procedure performance against biomass-based candidate limit reference points (LRP) under the Constant M-Constant growth (a-c) and Increasing M – Constant growth (d-f) scenarios. Results presented for two stock ‘types’ as defined by M in the first projection year (2013) relative to M at the start of the time series (1951). The columns correspond to WCVI (a, d), SOG (b, e), and PRD (c, f).

APPENDIX A. SUPPLEMENTARY FIGURES

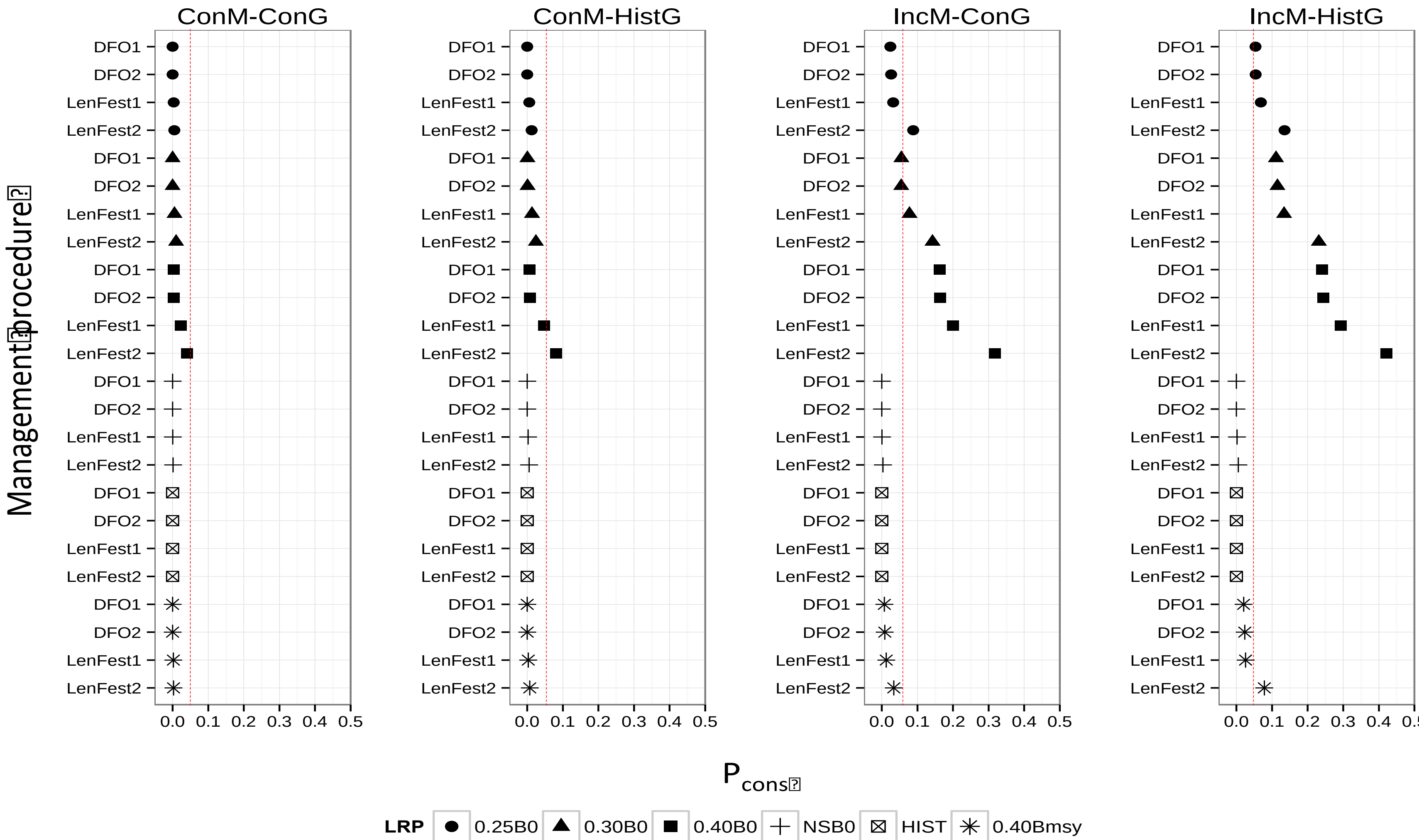

Figure A1. Management procedure performance against each candidate limit reference point (LRP) and scenario for SOG. The dashed line represents the 5% threshold recommended by Shelton and Sinclair (2008).

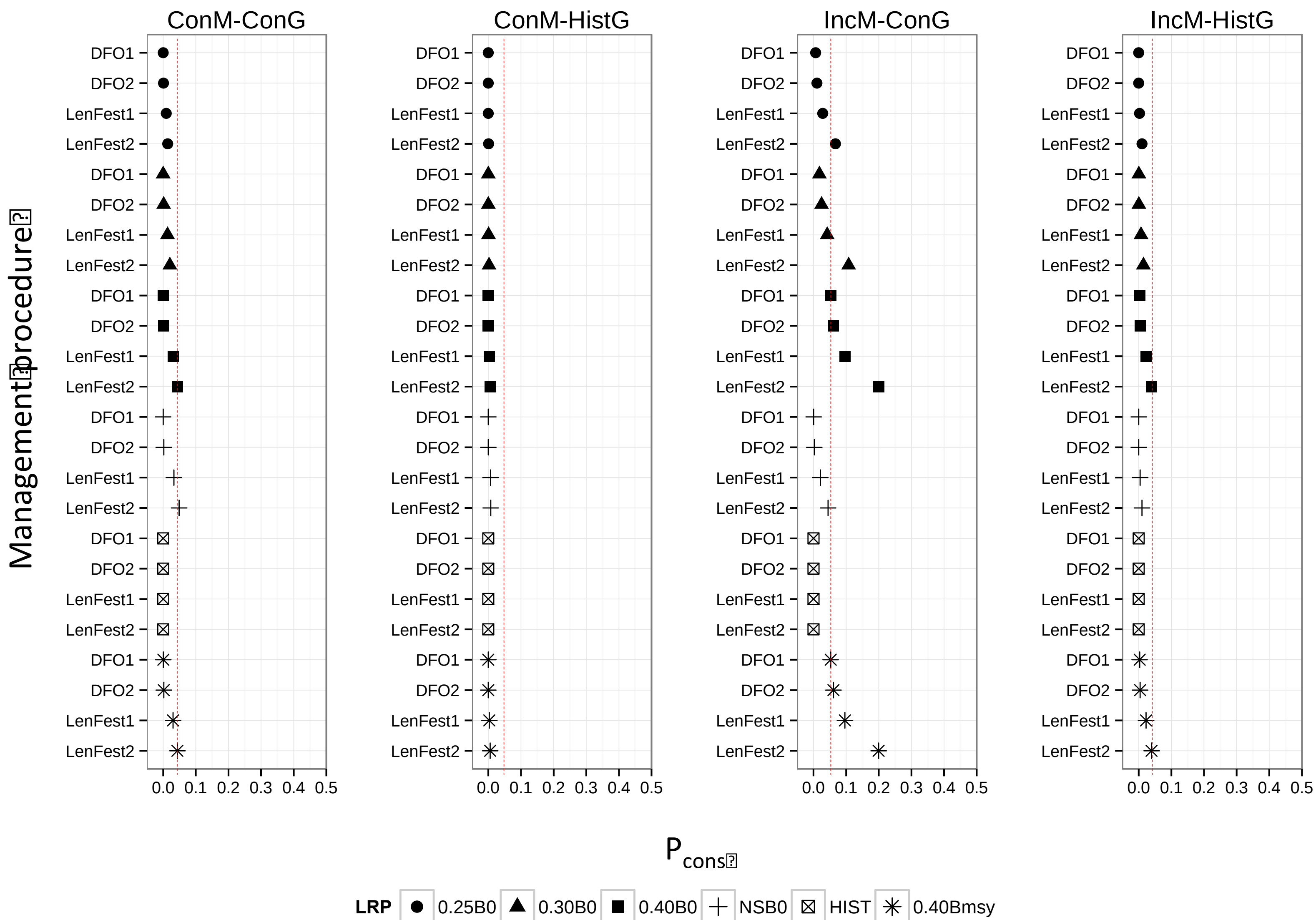

Figure A2. Management procedure performance against each candidate limit reference point (LRP) and scenario for WCVI. The dashed line represents the 5% threshold recommended by Shelton and Sinclair (2008).

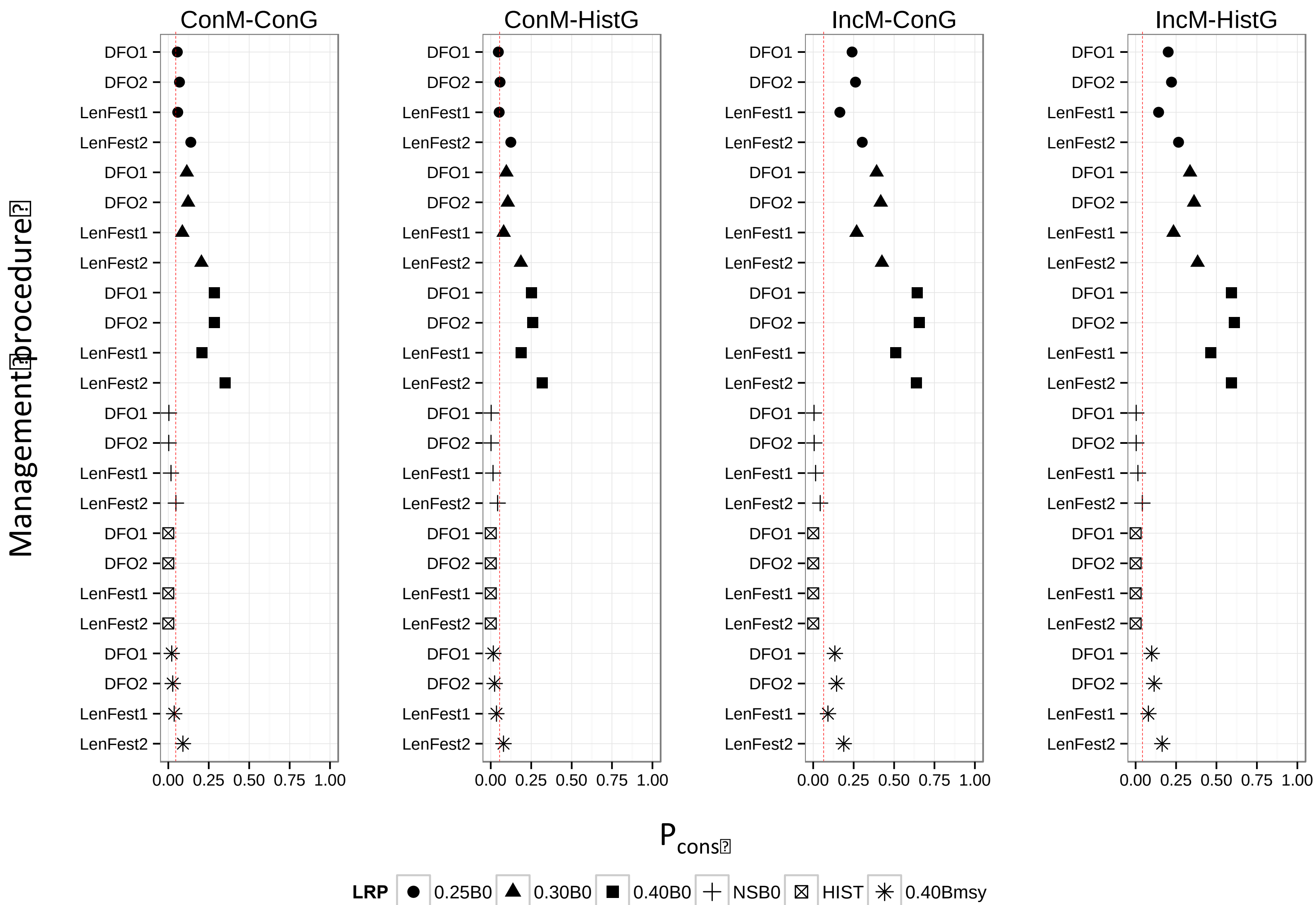

Figure A3. Management procedure performance against each candidate limit reference point (LRP) and scenario for PRD. The dashed line represents the 5% threshold recommended by Shelton and Sinclair (2008).

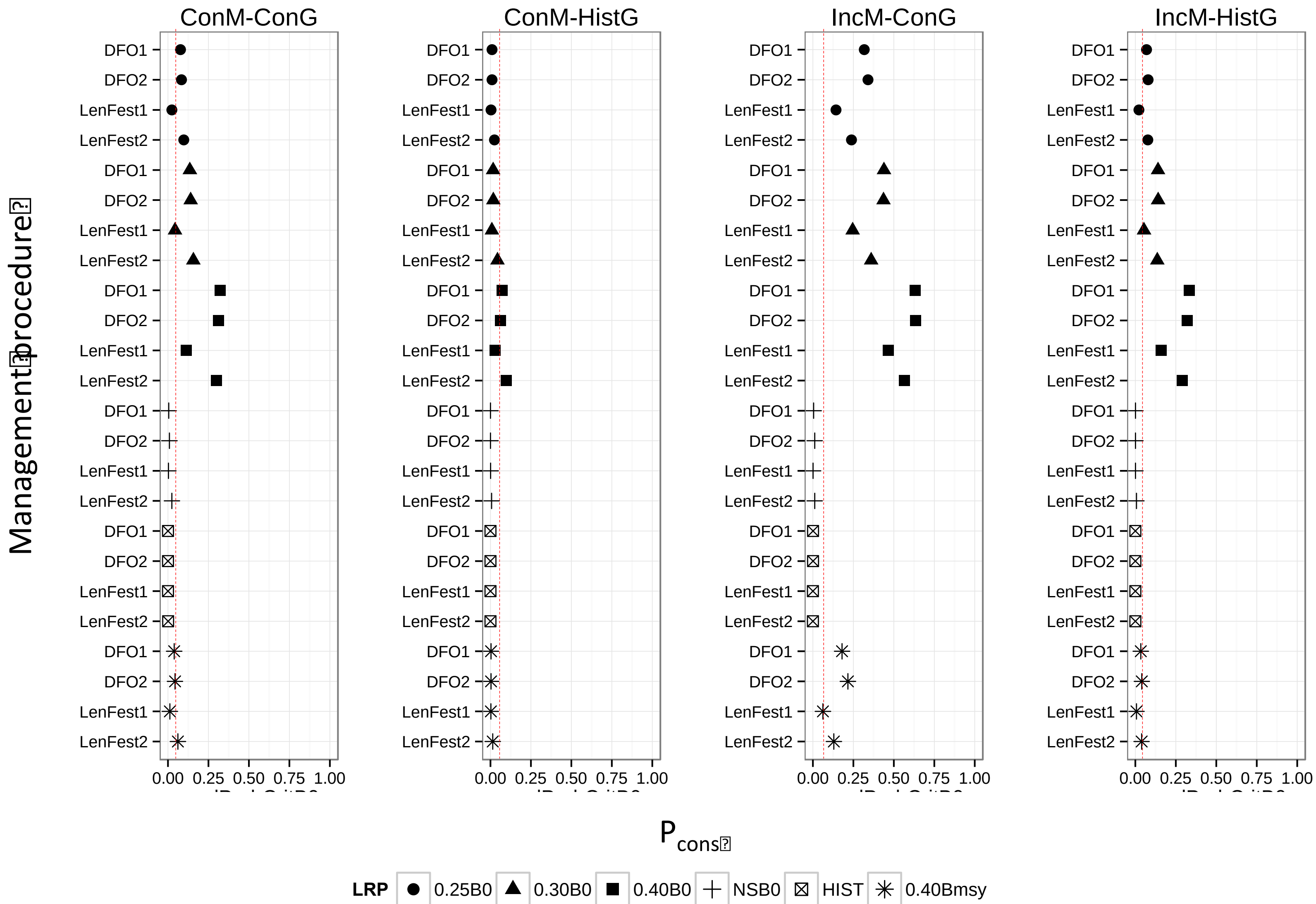

Figure A4. Management procedure performance against each candidate limit reference point (LRP) and scenario for CC. The dashed line represents the 5% threshold recommended by Shelton and Sinclair (2008).

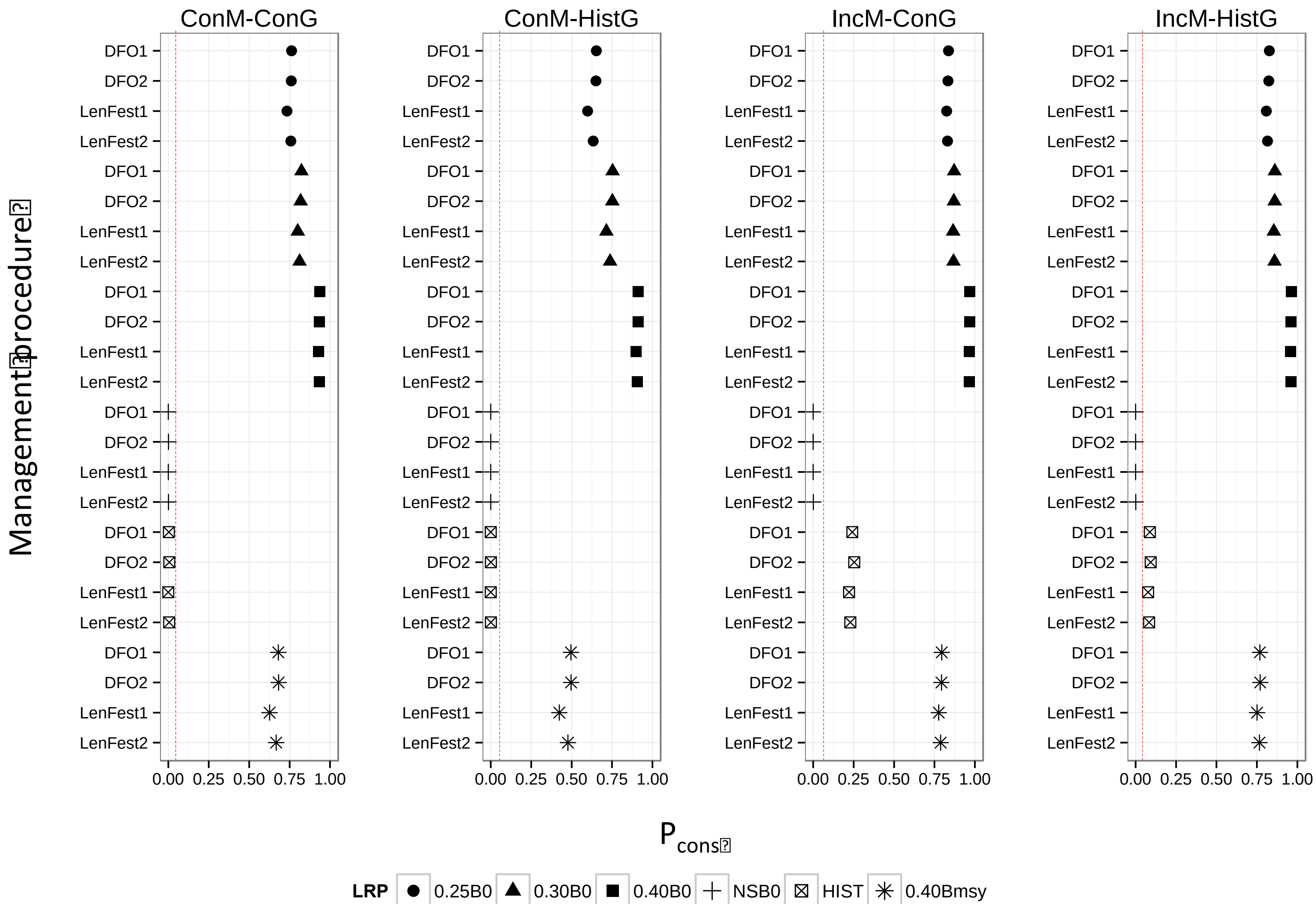

Figure A5. Management procedure performance against each candidate limit reference point (LRP) and scenario for HG. The dashed line represents the 5% threshold recommended by Shelton and Sinclair (2008).

APPENDIX B. A ‘PROOF OF CONCEPT’ APPLICATION OF THE ANALYTICAL FRAMEWORK FOR ADDRESSING UNCERTAINTY IN SPAWN SURVEY SCALING PARAMETER (Q)

Operating model		Assessment model: qPrior = 1.0	Assessment model: qPrior = 0.5
50%	q = 1.0	0.12 4.92	0.17 5.14
50%	q = 0.5	0.095 4.81	0.095 4.78
Expected $P(B < 0.25B_0)$		0.1075	0.1325
Expected Catch		4.865	4.960

Figure B1. Management outcomes for each of two possible ‘true’ states of nature (operating models) and two assessment model assumptions about the spawn survey scaling parameter, q. Performance is measured in terms of the $P(B < 0.25B_0)$ LRP (top value in each box) and average catch (bottom value in each box) over 100 simulations for the CC stock. Expected values for each performance measure represent a weighted average across operating model scenarios (in this example the scenarios are assumed to be equally likely (50:50 weighting)). Expected catch is in units of x1,000 metric tonnes (t).

Spawn survey scaling parameter, q, is an important parameter in the herring stock assessment that describes the proportion of the ‘true’ egg deposition observed by the survey. Because it cannot be measured accurately, it is necessary to make assumptions about q in the stock assessment model. Choices about the prior on q are in essence management procedure choices. Prior to 2011 q was assumed to equal 1 (i.e. the dive survey observes 100% of the true egg deposition), but it is currently estimated using an informative prior of 0.5 (i.e. the survey observes less than 100% of the true egg deposition). The assumptions made about q have important implications for both the stock assessment model (e.g. how the assessment predictions of biomass will be scaled relative to the survey) as well as performance of the larger management system. It is therefore a major source of uncertainty in Pacific Herring management.

The analytical framework can be used to explore the impact of alternative hypotheses about q and to understand the corresponding risks and tradeoffs associated with each assumption that is made. We ran 100 simulations for the CC for each of 2 possible surveys (q = 1, 0.5 in the operating model) and 2 possible assessment models (qPrior = 1, 0.5) (Fig. B1) for illustrative purposes. The operating models represent hypotheses about the ‘true’ state of nature for the survey (i.e. observes 50% or 100% of egg deposition), whereas the assessment models represent assumptions about the survey that may, or may not be consistent with the operating model. If the true q = 1, wrongly assuming a qPrior of 0.5 increases conservation risk (0.05 higher probability of breaching the LRP and a corresponding increase in catch of 220 t compared with qPrior of 1). If the true q = 0.5, there is no increase in risk for assuming the q=1: the P(B<LRP) = 0.095 for both qPrior = 1 and the catch is actually 30 t higher. This information is useful for comparing the relative change in performance between operating models and assessment model assumptions given the two performance measures considered.

Imperfect knowledge about the dynamics of the spawn survey is represented using a range of operating model scenarios (two in this example) that are weighted according to a hypothetical degree of belief in each. We arbitrarily assigned weights of 50% to each scenario. This weighting is used to illustrate an integrated performance indicator (expected probability of breaching the LRP and expected average catch) that captures the uncertainty associated with each combination of operating and assessment model. These results indicate that assuming qPrior = 1 in the assessment model provides the smallest P(B<LRP) and higher catch.

APPENDIX C. A 'PROOF OF CONCEPT' APPLICATION OF THE ANALYTICAL FRAMEWORK FOR EVALUATING EMPIRICAL MANAGEMENT PROCEDURES

The analytical framework can be used to evaluate many alternative types of MPs, including data-based or 'empirical' methods that rely only on survey estimates of biomass. One empirical MP was proposed during the May 2015 CSAS meeting for the CC and presented here for illustrative purposes only. The "ccRule" adds the observed catch and biomass from the previous year to generate a biomass forecast ($B_t = SB_{t-1} + C_{t-1}$). This step is analogous to a stock assessment model. The HCR component of the ccRule finds the lowest forecast biomass from which the stock has recovered over the previous 10-year period and sets this as the CUTOFF. If the forecast biomass is greater than the CUTOFF, the TAC = 0.1*Bt. Preliminary analyses (Figs. C1 and C2) indicate that the ccRule appears to be less conservative (results in lower depletion and higher, but more stable catches) than the DFO1, Lenfest1, and Lenfest 2 MPs. Rules of a similar type could potentially be investigated to improve on conservation performance.

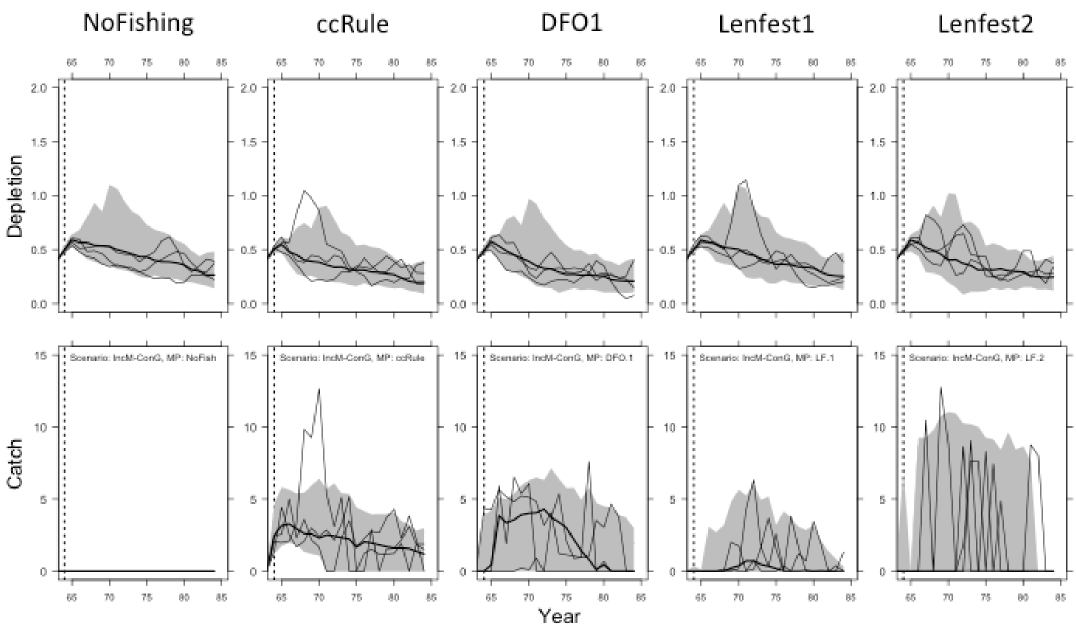

Figure C1. Spawning biomass depletion (top) and catch (bottom) envelopes for CC under the Increasing M-Constant growth scenario for no fishing and the ccRule, DFO1, Lenfest1, and Lenfest 2 management procedures. Simulation envelopes include the median (thick black line) and central 90% of depletion and catch outcomes over 100 simulations (grey shaded region), and three individual simulation replicates (thin lines) for the projection years 65-85.

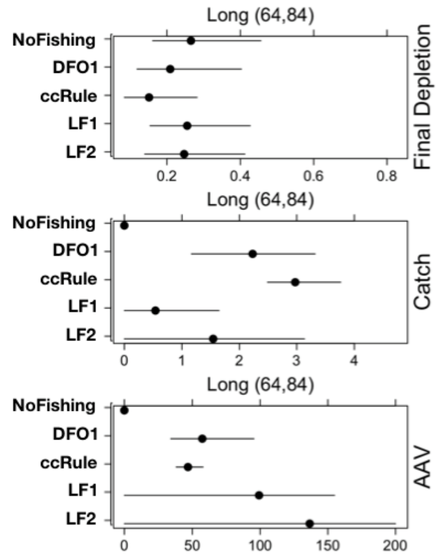

Figure C2. Summary of the median (point) and central 90% of long-term (years 64 to 84 of the projection period) spawning biomass depletion (top), catch (middle), and average annual variation in catch for CC under the Increasing M-Constant growth scenario using the No fishing, DFO1, ccRule, and Lenfest 1 and 2 management procedures.