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MANAGEMENT STRATEGY EVALUATION UPDATE AND EVALUATION OF UPPER STOCK REFERENCE POINT OPTIONS FOR PACIFIC HERRING (*CLUPEA PALLASII*) IN BRITISH COLUMBIA, CANADA

Context

Pacific Herring (*Clupea pallasii*) in British Columbia (BC) are currently managed in five major and two minor stock assessment regions (SARs), and independent catch and survey information is collected for each area in order to provide annual science advice on this scale. The major SARs are Haida Gwaii (HG), Prince Rupert District (PRD), Central Coast (CC), Strait of Georgia (SoG), and West Coast of Vancouver Island (WCVI), and the minor SARs are Area 27 and Area 2 West.

Pacific Herring have extensive annual time series of fishery-independent survey and biological sampling data extending back to 1950. With these data sources, Science, Pacific Region developed an annual stock assessment program and forecasting models, contributing to leading-edge research and development in fisheries science. Fixed harvest rates and simulation-tested harvest rules were adopted by DFO for the management of Pacific Herring in 1986, with rules prescribing an exploitation rate of 0% when predicted biomass fell below commercial cut-off levels (Hall et al. 1988). Since adopting the harvest strategy in 1986, two major herring stocks - SoG and PRD have remained above the cut-off level while major stocks in HG, CC, and WCVI experienced recent low biomass states that fell below cut-off levels. Observations such as declining biomass trends in the absence of commercial harvest, long-term declines in body size (weight-at-age), and an increasing trend in the estimated natural mortality rates spurred initiation of a management strategy evaluation (MSE) process in 2015 where the initial focus was on improving the understanding of the harvest control rule (HCR) performance against conservation objectives and identifying HCR choices that do not meet conservation objectives.

Since 2015, Science, Pacific Region has established a MSE process (DFO 2015, DFO 2019a, DFO 2020), established limit reference points (Kronlund et al. 2018) and a core set of measurable objectives (DFO 2020a), and used feedback simulation-evaluation to provide advice on stock-specific harvest rates and HCRs (DFO 2019a, DFO 2020). Additionally, the MSE framework has been used to develop a rebuilding plan for HG herring[1], demonstrating use of feedback simulation-evaluation as a foundation for developing rebuilding plans and meeting the Precautionary Approach (PA) Policy.

DFO's "A Fishery Decision-Making Framework Incorporating the Precautionary Approach" policy (DFO 2009), hereafter called the PA Policy, describes requirements for incorporating the

[1] "Haida Gwaii 'íináang | iinang Pacific Herring: An Ecosystem Overview and Ecosystem-based Rebuilding Plan."

precautionary approach for fish stocks in Canada. These requirements are summarized into four elements[2]:

- PA1. Establish limit and upper stock status reference points that delineate critical, cautious and healthy zones as well as a maximum fishing mortality rate;
- PA2. A harvest strategy and harvest control rules (HCRs, Kronlund et al. 2014a);
- PA3. Account for uncertainty and risk when developing reference points and when developing and implementing control rules (Kronlund et al. 2014a, b); and
- PA4. Evaluate the performance of the management system against the objectives specified by the harvest strategy (Kronlund et al. 2014b).

To ensure consistency with the Sustainable Fisheries Framework and implementation of the PA Policy to Pacific Herring, Fisheries and Oceans Canada (DFO) implemented a spawning biomass-based limit reference point (LRP) of $0.3SB_0$ (unfished spawning biomass) for all five major stocks beginning in 2018 (Kronlund et al. 2018, DFO 2019b). The current management framework for Pacific Herring already has many of the required elements of the PA Policy, including LRPs (PA1), management procedures (MPs) designed to avoid the LRP with high probability (PA2, PA3), and evaluation of performance via simulation-evaluation (PA4, Cleary et al. 2019). Although candidate upper stock reference (USR) points were considered by Cleary et al. (2019), implementing a USR for each major stock is required to fully align Pacific Herring with the PA Policy. Options for establishing an USR for each SAR are described here with elements PA2, PA3 and PA4 already reflected in the management strategy evaluation (MSE) process first initiated in 2015 (DFO 2015).

The new Fish Stock provisions of the revised *Fisheries Act* (R.S.C., 1985, c. F-14) passed into legislation in 2019. It introduced requirements to maintain major fish stocks at sustainable levels and to develop and implement rebuilding plans for stocks that have declined below the LRP. This legislation is relevant to the Haida Gwaii major stock area which was among the first ‘batch’ of stocks prescribed in regulation in 2022. The HG stock has persisted in a low biomass, low productivity state (Kronlund et al. 2018) from approximately 2000 to 2018, and has fluctuated at or below the LRP in most years since 2000 (DFO 2021b). As such, a draft rebuilding plan[1] for Haida Gwaii Herring has been developed through a technical working group which includes representatives from the Council of the Haida Nation, DFO, and Parks Canada. Consultations on this rebuilding plan will commence in fall 2022.

The purpose of this work is to describe the role of the USR for Pacific Herring, document and evaluate USR options, and describe criteria for selecting USRs for major SARs. Evaluation of the consequences of USR choice must be considered in the context of the entire management system. Thus, our analyses includes simulation-evaluation to examine the probability of meeting USR options under different management procedures. The simulations incorporate updates to operating model conditioning data and updated MPs for four of the major Pacific Herring SARs (PRD, CC, SoG, and WCVI). Simulation updates are not included for the Haida Gwaii major stock area because these analyses and updates are included in the rebuilding plan[2].

This Science Response Report results from the regional peer review of August 30, 2022 on the Management Strategy Evaluation Update and Evaluation of Upper Stock Reference Point Options for Pacific Herring (*Clupea pallasii*) in British Columbia, Canada.

[2] Modified from Kronlund et al. (2018).

Background

Fisheries and Oceans Canada (DFO) Fisheries Management has requested that Science Branch evaluate USR options for major herring SARs. Acknowledging that the establishment of USRs is not solely determined by biological considerations, a Science - Resource Management Working Group was convened to complete this work and to estimate the current status of these stocks relative to the recommended USRs.

Description of the fishery

At present, there are several Pacific Herring fisheries in BC. First Nations have priority access, after conservation, to fish for food, social, and ceremonial (FSC) purposes. Commercial fishing opportunities consist of four directed fisheries: food and bait, special use, spawn-on-kelp (SOK), and roe herring. There is also a small recreational fishery.

First Nations fish for whole herring, herring roe, and herring eggs for FSC purposes. Whole herring are fished by seine, gillnet, rake, dip net, and jig. Herring eggs are collected as spawn on seaweed such as kelp (i.e., SOK), or spawn on tree boughs placed in spawning locations. Indigenous harvest of herring for FSC purposes may occur coast wide where authorized by a communal license.

In addition, treaty and Aboriginal commercial fisheries may occur in some specific management regions. Four modern treaties (Nisga’a, Tsawwassen, Maa-nulth, and Tla’amin) have been ratified in British Columbia and articulate a treaty right to FSC harvest of fish. Five Nuu-chah-nulth First Nations located on the West Coast of Vancouver Island – Ahousaht, Ehattesaht, Hesquiaht, Mowachaht/Muchalaht, and Tla-o-qui-aht (the Five Nations) – have Aboriginal rights to fish for any species of fish, with the exception of Geoduck, within their Fishing Territories and to sell that fish. The implementation of the Five Nations’ right-based sale fishery is an ongoing process.

On the Central Coast, Heiltsuk First Nation have an Aboriginal right to commercially harvest Pacific Herring SOK. The Heiltsuk currently hold nine SOK licenses in this area, which they operate using open ponds. The DFO and Heiltsuk are also committed to annual development of a Joint Fisheries Management Plan for Pacific Herring in the Central Coast.

Reference points for Pacific Herring

The DFO PA Policy (DFO 2009) for fisheries management decisions requires establishing harvest strategies that identify three stock status zones (critical, cautious, and healthy) delineated by a limit reference point (LRP) and an upper stock reference (USR) point. Through an analysis of spawning biomass surplus production and identification of recent states of persistent low productivity and low biomass (LP-LB), Kronlund et al. (2018) found evidence for states of possible serious harm when spawning biomass fell to levels of $0.2SB_0$ and lower. Stocks in the HG, CC, and WCVI management areas showed recent persistent LP-LB states in which the frontier (leading edge) of the LP-LB states were estimated to be at spawning depletion levels of 0.17 (CC) to 0.28 (HG), where depletion is calculated as the estimated spawning biomass in year t over the unfished spawning biomass, SB_t/SB_0. The PA Policy is clear that LRPs must be positioned before a possible state of serious harm, that is to say, at a higher spawning biomass level, or lower fishing mortality rate, than states coincident with possible serious harm. Accordingly, Kronlund et al. (2018) recommended a biomass-based LRP of $0.3SB_0$ be adopted for the HG, CC, and WCVI stocks, and that the same LRP should also be used for PRD and SoG based on common life history and geographic proximity to the other three major SARs.

Implementation of the LRP within the MSE process occurs through the conservation objective:

> "Maintain spawning biomass above the LRP with at least 75% probability over three Pacific Herring generations (i.e., avoid a biomass limit; $P(SB_t > 0.3SB_0) \geq 0.75$)"

where performance of MPs in achieving the conservation objective is used to identify MPs that may lead to biomass falling below the LRP. Additional biomass and yield objectives have been introduced through Herring MSE (DFO 2020a, listed and discussed below), however there remains uncertainty about the relative importance of these additional objectives and ranking has not occurred.

USRs are defined by DFO as the "boundary between the healthy and cautious zones," whereby the removal rate of the fish stock is progressively reduced as it falls below this point, to avoid breaching the LRP. The USR can also be "a target reference point, determined by productivity objectives for the stock, broader biological considerations, and social and economic objectives for the fishery" (DFO 2009). Although USRs are often used as upper control point(s) in a harvest control rule (i.e., the point at which management action is taken) this is not necessarily required to avoid the LRP and support stock growth.

The recommended Herring LRP ($0.3SB_0$) is set above biomass levels for which there is evidence of possible serious harm and at a level where stock productivity is generally positive (Kronlund et al. 2018). As such, stock growth is expected to be higher above the LRP, however the interplay of production and high natural mortality rates can also lead to very low growth rates as the surplus production is essentially consumed by increasing predation (e.g., HG; DFO 2021b).

The USR can be implemented as a measurable objective within the MSE process following the same approach applied for the LRP. Measurable objectives require specifying:

1. the biomass level (e.g., USR value),
2. timeframe over which to meet the objective (e.g., three herring generations), and
3. risk tolerance for meeting the objective (minimum probability).

Simulation of MPs can then be used to inform tradeoffs in management outcomes, for example: acceptable levels of risk to maintaining the stock above the LRP, meeting the USR and allowing viable fisheries.

Analysis and Response

The Herring MSE process provides the foundation for evaluating the consequences of USR choice and determining their potential role in the herring management system. We include updates to herring operating models (OMs; Benson et al. 2023) to support this analysis. Analysis and response are presented for four of the major Pacific Herring SARs: PRD, CC, SoG and WCVI. A USR for the Haida Gwaii major SAR and the approach for defining this USR is documented within the draft rebuilding plan[1].

The following steps were used to evaluate USRs for the remaining four Pacific Herring stocks:

1. Identify USR options consistent with the PA Policy;
2. Discuss options and refine USR list for subsequent evaluation;
3. Characterize stock status relative to USR options;

4. Evaluate the consequences of USR choice using the existing stock assessment and simulation-evaluation modelling frameworks, and discuss suitability and limitations of USR options;
5. Identify sources of uncertainties in the data and methods; and
6. Propose considerations for selecting among the USR options.

USR options for Pacific Herring

USRs consistent with the PA Policy include those based on B_{MSY}, B_{MSY} proxies (defined in Annex 1b, DFO 2009), unfished biomass (SB_0), and historical trends. All options are listed below and five were selected for further evaluation.

a. 80% B_{MSY}

The PA Policy suggests a default USR of 80% B_{MSY} to delineate the cautious and healthy zones (DFO 2009); Marentette et al. (2021) describe the LRP of 40% B_{MSY} and USR of 80% B_{MSY} as 'provisional' reference points ("serving for the time being, with the possibility of change later on"). Kronlund et al. (2018) calculated theoretical equilibrium reference fishing mortality (*F*) rates based on the concept of the replacement fishing mortality as well as associated proxies based on maximum sustainable yield, spawning potential ratio and yield-per-recruit calculated equilibrium. For PRD, CC, SoG, and WCVI, F_{MSY} estimates ranged from 0.45 to 0.56 implying sustainable harvest rates, U_t, of 0.36 to 0.43, calculated as $U = 1 - e^{-F}$. These rates, which are based on the concept of replacement fishing mortality, were determined to be implausibly high for Pacific Herring stocks due in part to non-stationary conditions for natural mortality and size-at-age. The analyses therefore concluded that F_{MSY} estimates were not recommended for Pacific Herring reference points.

Recommendation: no further evaluation of 80% B_{MSY} as a USR option for Pacific Herring.

b. A B_{MSY} proxy

The DFO PA Framework Annex 1b (DFO 2009) states that in the absence of model estimates of B_{MSY} that "provisional" estimate of B_{MSY} could be taken as follows (and selecting the first feasible option):

(i) The biomass corresponding to the biomass per recruit at F0.1 multiplied by the average number of recruits, or

(ii) The average biomass (or index of biomass) over a productive period, or

(iii) The biomass corresponding to 50% of the maximum historical biomass.

Option (i) requires reliable estimates of average recruitment (used as a multiplier of F0.1). Although the Pacific Herring stock assessment model implements a Beverton-Holt stock recruitment relationship, the relationship shows recruitment for a given biomass level to be highly variable (Cleary et al. 2019). Additionally, this approach does not account for possible decreases in the number of recruits to the population which may occur as fishing pressure reduces the spawning biomass. We also do not support option (iii) based on unsuitability for SoG because the maximum biomass occurred in 2020 which is highly uncertain relative to earlier years in which age cohorts have been fully observed through sampling.

Recommendation(s): no further evaluation of option (i) or (iii), proceed with calculating B_{MSY} proxy as the average median spawning biomass over a productive period:

$$SB_{productive\ period} = (\overline{SB}_{t=t1:t2})$$

where SB_t is the median posterior value of the estimated spawning biomass from the 2021 assessment at year *t* and *t*1 and *t*2 represents the first (*t*1) and last (*t*2) years of the stock-specific productive period.

The 'productive period' B_{MSY} proxy approach requires defining a stock-specific productive period (years) over which to calculate average spawning biomass. Years *t*1:*t*2 defining the productive period were selected for each SAR using these criteria:

(i) Consecutive years of positive production: the estimated spawning biomass production (P_t) is above zero for a minimum of 75% of the selected years, where $P_t = SB_{t+1} - SB_1 + C_{t+1}$,

(ii) Minimum 10-year duration (i.e., at least two herring generations),

(iii) Median estimated spawning biomass is above the LRP (median value),

(iv) Includes a range in variability of biomass trends (i.e., not focused on strong increasing and decreasing trends), and

(v) Presence of commercial fisheries.

A 10-year productive period was proposed for PRD (1983-1992), CC (1990-1999) and WCVI (1990-1999), and a 20-year period for SoG (1987-2007). The WCVI period of 1990-1999 was first suggested by the Nuu-chah-nulth Nations as a productive period through the MSE process (DFO 2019a), and further analysis confirmed that this period also met all of the above criteria. SoG was unique in that insufficient variability could be demonstrated with a 10-year period, so a 20-year period was selected. To demonstrate the approach, Figures 1 and 2 show model outputs for WCVI and SoG stocks, each overlaid with their respective productive periods.

c. %SB_0

The recommended LRP for Pacific Herring stocks is based on a percentage of SB_0 thus several USR options based on SB_0 were considered. Cleary et al. (2019) initially introduced four candidate USRs, including 0.6SB_0, which is twice the LRP, and 0.4SB_0 which was initially suggested by the herring industry and is a common proxy for B_{MSY}.

In 2018, Marentette et al. (2021) reviewed the types of reference points that have been established for a subset of Canada's key harvested stocks or subunits. They found that LRPs and USRs based on a percentage of unfished biomass were reported for use in nine (of 102 reviewed stocks/subunits with LRP) and three (of 86 reviewed stocks/subunits with USRs).

Recommendation(s): include evaluation of USRs based on percentages of unfished spawning biomass (0.4SB_0, 0.5SB_0, and 0.6SB_0) where SB_0 is the median posterior estimate of the average unfished spawning biomass, taken from the 2021 assessment.

d. Long-term average spawning biomass

Hilborn and Stokes (2010) found that setting management targets based on levels of historical biomass were more reliable compared to theoretical calculations, such as B_0 and MSY, because they are based on past experience. Marentette et al. (2021) reported the use of historical biomass trends such as 'mean historical biomass' were reported for use in eighteen (of 102 reviewed stocks/subunits with LRP) and eight (of 86 reviewed stocks/subunits with USRs).

Recommendation(s): include evaluation of USR using historical approach calculated as

$$SB_{long-term\ average} = \overline{SB}_{t=1951:2021}$$

where the year range is extended annually.

Stock status relative to USR options

Based on the initial review above, five USR options were selected for further evaluation:

- $SB_{productive\ period}$,
- $0.4SB_0$, $0.5SB_0$, $0.6SB_0$, and
- $SB_{long-term\ average}$.

We evaluate the USR options relative to the current status of each stock using model outputs from the 2021 stock assessment (Cleary et al. 2019, DFO 2021b). Table 1 presents the 2021 estimated spawning biomass, estimated LRPs, and stock status relative to the five USR options using median posterior estimates for PRD, CC, SoG and WCVI stock areas (outputs from DFO 2021b). Figures 3 and 4 presents stock biomass trends for PRD, CC, SoG, and WCVI stock areas (DFO 2021b), overlaid with the five USR options. Each candidate USR is discussed below.

Depletion estimates for the productive period and the long-term average approaches all fall within the range of 0.4 to $0.6SB_0$ (Table 1; exception is SB_{Prod} for WCVI). Given this congruency among the five USR options, the choice of risk tolerance for achieving a USR (within the context of Herring MSE) may have more influence on the overall stock status and the management framework than the specific USR selected.

$\boldsymbol{SB_{productive\ period}}$

Criteria for selecting the productive period include a minimum of ten consecutive years. Because the year range is fixed, we categorized this approach as ‘stable and repeatable’ and suggest it may be considered more easily understood than approaches based on theoretical quantities such as unfished spawning biomass, SB_0.

When we apply the productive period criteria to the relatively healthy SoG stock, the selected years equate to the highest biomass and estimates of spawning biomass production observed in the time series (Figure 2). These high biomass years influence the upper range and magnitude of the estimated SB_0 (Table 1) and coincide with annual commercial fisheries and median effective removal rate of 15% (DFO 2021b, Figure 15). The co-occurrence of successful annual fisheries and continued positive production together suggest the selected productive period is a suitable proxy for recent estimates of B_{MSY}. For these reasons we suggest the B_{MSY} proxy approach be implemented as 80% of the average productive period spawning biomass (USR= $0.8B_{MSY\text{-}proxy}$) which corresponds to a depletion level of 0.47 (Table 1) for SoG. This metric is shown in Figure 4 (column a).

For PRD, CC and WCVI, the productive period criteria (i) to (v) yields average spawning biomass levels that are lower than the historical high biomass levels of the mid-1960s (PRD), early-1980s (CC), and mid-1970s (WCVI). The intent of a B_{MSY} approach in fisheries management is to maintain stocks at biomass levels that allow the stock to be most productive under fishing. Given these three stocks have incurred recent low productivity and low biomass states (Kronlund et al. 2018) we suggest that should a B_{MSY} proxy approach be selected for implementation for PRD, CC, and WCVI that this reflect the average productive period spawning biomass (USR= $B_{MSY\text{-}proxy}$). Using this approach, the corresponding USRs reflect average depletion levels of 0.54 for PRD, 0.59 for CC, and 0.72 for WCVI (Table 1).

Marentette et al. (2021) show implementation of USRs for Canadian stocks using both USR=$B_{MSY\text{-}proxy}$ and USR=$0.8{*}B_{MSY\text{-}proxy}$ approaches. Accordingly, Table 1 includes both versions and the recommended approach appears with an asterisk.

$\%SB_0$

Choice of USR using a percent of SB_0 implements a reference point approach congruent with the established LRP. Estimates of SB_0 for Herring are not the highest observed estimates of SB_t and in fact for some SARs, depletion (SB_t/SB_0) can be (much) greater than 1. For example, during the highest years of historical abundance for CC (early 1980s) and WCVI (mid 1970s and late 1980s) the estimated spawning biomass exceeds the unfished spawning biomass ($SB_t/SB_0>1$) which suggests USR choices such as $0.4SB_0$, $0.5SB_0$, and $0.6SB_0$ are not unrealistically high.

For the four stocks being evaluated, setting the USR equal to $0.4SB_0$ infers, based on the 2021 assessment, that all four stocks are at (WCVI) or well-above (PRD, CC, SoG) the USR (Figures 3 and 4, column b). Setting the USR equal to $0.6SB_0$ (twice the LRP) infers all stocks are to some degree currently below the USR and above the LRP (Figures 3 and 4, column d). A USR of $0.5SB_0$ provides for a mid-point option between 40% and 60% of SB_0.

$SB_{long-term\ average}$

Historical biomass trends such as ‘mean historical biomass’ have been used to define LRPs and USRs for several Canadian stocks (Marentette et al 2021). Average long-term spawning biomass estimates are within a few thousand tonnes for PRD (25.3 kt), CC (26.0 kt), and WCVI (27.7 kt) stocks, and approximately double for SoG (58.3 kt). The corresponding depletion levels are less similar and vary from 0.42 for PRD to 0.61 for WCVI (Table 1). For PRD and SoG, the long-term average approach approximates the $0.4SB_0$ option, whereas for CC and WCVI the long-term average approach approximates 0.5 and $0.6SB_0$, respectively (Table 1).

Considerations for selecting amongst USR options

To our knowledge there is no existing criteria to guide selection of USRs. For Pacific Herring, we suggest users may want to consider three criterion:

1. stability,
2. repeatability, and
3. achievability,

each discussed below.

Production

Because the Herring LRP is set above spawning biomass levels for which there is evidence of possible serious harm, spawning biomass production and growth rates will increase above the LRP and may be highest in the cautious zone, depending on where the USR is placed in relation to a population’s carrying capacity level. Therefore, it may be useful to consider recent and historical trends in production when selecting among the USR options.

For example, when examining similarities and differences in spawning biomass production and abundance among the five major SARs (over the last 30-years), Herring SARs can be grouped as:

a. Stock(s) in or near the critical zone (e.g., HG),
b. Stock(s) exhibiting positive and negative production with recent periods of low biomass relative to historic levels (e.g., PRD, CC, WCVI), and

c. Stock(s) where production is largely positive leading to recent historic high biomass levels (e.g., SoG).

We characterize the productive period approach as “stable” and “repeatable" in application: year-to-year differences in productive period spawning biomass are unlikely to change with the addition of new survey and fishery data.

SB_0 and estimated long-term average spawning biomass are also relatively constant over years (e.g., recent 10-years). Model diagnostics arising from 10-year retrospective analyses conducted through the annual stock assessment process show assessment model estimates of SB_0 to be relatively consistent from year to year (DFO 2021b, figures not included). However, situations with large increases or decreases in model estimates of the instantaneous natural mortality rate will have an impact on estimates of SB_0 and may decrease stability of this USR approach when applied in the context of an annual assessment process. The impacts of this phenomenon to the annual assessment process in terms of MP performance could be further explored through simulations, for example to investigate ‘Does a directional change in SB_0 impact MP performance against a biomass objective?’.

Simulation evaluations to inform selection of USRs

DFO Science Branch uses a closed-loop simulation approach to evaluate the relative performance of candidate MPs against biomass and fishery objectives for all major Pacific Herring SARs (Cox et al. 2019, Benson et al. 2023), using the following ‘proposed’ core objectives (DFO 2015):

1. Maintain spawning biomass above the LRP with at least 75% probability over three Pacific Herring generations (i.e., avoid a biomass limit; P(SBt > 0.3SB0) ≥ 0.75),
2. Maintain spawning biomass at or above the USR with at least 50% probability over three Pacific Herring generations (i.e., achieve a target biomass; e.g., P(SBt ≥ 0.6 SB0) ≥ 0.5),
3. Maintain average annual variability (AAV) in catch below 25% over three Pacific Herring generations (i.e., objective relating to low catch variability; AAV < 0.25), and
4. Maximize average annual catch over three Pacific Herring generations (i.e., objective relating to maximizing catch biomass).

In order to implement USR objectives within this framework, the current herring operating model (Benson et al. 2023) was updated to include stock and fishery monitoring data from 1951-2021. MP evaluations for PRD, CC, SoG, and WCVI were also updated and include performance metrics for each of the five USR options, as well as conservation and yield objectives (Tables 2-5).

As expected based on past performance, probabilities for meeting the LRP-based conservation objective differ from those reported in previous assessments (e.g., DFO 2019a, DFO 2020, DFO 2021a, DFO 2021b). The addition of new data to the terminal year of the historical time series can be heavily influenced by the last three to five years of stock status and natural mortality trends used to condition the OM. The magnitude of the influence depends on how much the updated trend differs from the last three to five years, with directional changes in the estimated natural mortality rate having the largest influence. That said, performance evaluation of MPs against the LRP and the five USR biomass objectives provides an approach to compare and understand relative performance of MPs and to highlight similarities and differences in USR options.

MPs listed in Tables 2 to 5 are ranked based on conservation performance (probability of avoiding the LRP) and report the probability the objective will be obtained over the course of a

15 year simulation (three herring generations) given the trajectory of the stock in the terminal three to five years and the hypothesized natural mortality scenario. Currently there is no subsequent ranking of objectives beyond the conservation priority however performance metrics associated with the biomass and yield objectives can inform trade-offs between objectives.

Interpretation of the simulation results should focus on the performance of MPs relative to objectives. For example, implementing the conservation objective (Obj. 1) exactly as it is stated would eliminate those MPs that do not meet the Obj.1 with a minimum 75% probability. However, when evaluating performance against multiple objectives one needs to consider trade-offs between objectives, including risk tolerance (probability) and time period (number of projection years) for meeting each objective.

Each of Tables 2-5 include a “no fishing MP” (NoFish_FSC) which represents the best state that the stock can achieve given the simulated hypotheses describing future natural mortality and stock growth, as described by the OMs. MP performance under the density dependent model (DDM) OM scenario shows higher conservation performance relative to the density independent model (DIM) OM scenario. This result is observed across all four SARs, with the greatest difference in performance between scenarios for WCVI (Table 5).

Application of the NoFish_FSC MP demonstrates the probability of achieving a USR objective in the absence of commercial harvest, where acceptable probability is chosen based on risk tolerance and uncertainty. Obj. 2 *provisionally* defines the USR as a target reference point with a 50% probability, implying the biomass is expected to be above and below the target 50% of the time.

In some cases the simulations show there is less than a 50% probability (P<0.5) of the biomass being above a USR option after several generations without fishing, for example with the DDM scenarios for SoG, where USR=0.6SB_0, and for WCVI (also DDM), where this condition is not met for USR=SB_{Prod}, 0.6SB_0 and $\overline{SB}$. In such situations, one could consider whether the risk tolerance for meeting the USR objective is unrealistically high, or alternatively one may decide that given the target was never “achieved” in simulation under no fishing, that the USR option is unsuitable. In some situations Obj. 2 simply cannot be achieved for some MPs and OM combinations (not without reducing the risk tolerance).

In other instances, when simulations show that under no fishing the stock has an acceptable probability of being above the USR, it would next be useful to examine performance of MPs that include some level of commercial harvest (perhaps reflecting recently applied harvest rates) which would allow consideration of trade-offs between biomass and yield objectives.

Finally, for a stock that has experienced positive spawn biomass production and stock growth under relatively low annual exploitation rates, e.g., SoG, one could identify from the simulations the USR options that can be met with a 50% probability (or other risk tolerance) for the MP that most closely matches the realized harvest rate. For SoG, with a median effective removal rate of 15% (DFO 2021b, Figure 15), we see the minimum escapement rule with 15% harvest rate (minE0.3B0_HR15) meets the USRs of 0.6SB_0 and $\overline{SB}$ with a minimum 50% probability and with a 45% probability for 0.8SB_{Prod}.

Social and economic considerations

When spawning biomass is estimated to be above the LRP there presents an opportunity to weigh social and economic considerations against biological objectives. Since herring stocks are more responsive to changes in natural mortality than to fishing mortality at moderate levels, socioeconomic objectives, such as consistency in yield, predictability in management approach, and moderate harvest opportunity during stock growth periods may be weighed against the time period or probability of meeting biomass objectives (such as the USR). In conjunction with selecting a MP, the selection of a USR could have significant economic implications. For example, if a hockey-stick shaped rule (e.g., HS30-60_HR.10) is implemented the removal rate would decline through (or throughout) some portion of the cautious zone, whereas with a minimum escapement rule (minE-0.3SB_0_HR.1) the removal rate would remain constant throughout most of the cautious zone. For the SoG, simulations show that for 10%, 15% and 20% maximum target harvest rates, the minimum escapement rule is more consistent with economic objectives than the hockey-stick rule, as evidenced by a lower average annual variability (AAV) in catch (DDM and DIM; Table 4). However, for PRD, the same comparison using a 10% maximum target harvest rate shows the converse, with the hockey-stick shaped rule yielding lower AAV when compared with the minimum escapement rule (DDM only) and near-identical performance for DIM (Table 2). In all cases, higher average catches are achieved with the minimum escapement rule. These comparisons draw attention to the value of the MSE process for eliminating 'poor choice' MPs, e.g., those for which the risk of breaching the LRP is undesirably high, but as well for highlighting important trade-offs between types of MPs.

Social considerations such as spawn distribution, fishery access and priority may also be considered in the establishment of USRs; however, these objectives have not yet been implemented through the MSE process.

Implementation of USRs within the Herring management framework

This paper discusses implementation of USRs for Pacific Herring as target reference points and includes an evaluation of USR options to support on-going consultations and final selection of USRs for PRD, CC, SoG and WCVI SARs. Full implementation of USRs within a biomass objective for each Herring SAR will also require choice of risk tolerance (minimum probability for meeting the objective) and time period (duration over which the objective is met).

Selection of USRs and implementation in the management framework will take place within the integrated fisheries management plan (IFMP) process. As such, the 2023 harvest options tables presented in the Pacific Herring stock assessment Canadian Science Advisory Secretariat (CSAS) science response, 'Stock status update with application of management procedures for Pacific Herring (*Clupea pallasii*) in British Columbia: status in 2022 and forecast for 2023' will include performance metrics for all five USR options. When considering risk tolerance for meeting the USR objective, this too should be considered for each SAR independently. Close consideration of the "no fishing MP" may be useful for informing risk tolerances for each SAR because this MP represents the best state that the stock can achieve given the hypothesized conditions and provides a starting point to see 'with what probability' can the USR be achieved under simulated conditions.

Finally, once USRs have been selected, additional metrics such as stock status relative to USRs can be calculated for inclusion in the IFMP.

Exceptional circumstances

We recommend reevaluation of USRs under the following circumstances:

a. Changes in the spatial definition of a stock,
b. Addition of new operating model structure or scenarios, for example, addition of new ecosystem considerations such as predation or productivity regimes, and

c. In circumstances where the observed survey biomass falls outside the simulated range of predicted survey biomass, or there is new information to suggest that the realized trajectory of the stock is not represented in the simulations.

Sources of uncertainties

Estimated stock status and USRs are derived from a statistical catch at age model that uses Bayesian methods to incorporate prior information and integrate over parameter uncertainty to provide results that can be probabilistically interpreted (Cleary et al. 2019). The assessment model integrates over the substantial uncertainty associated with several important model parameters including: spawn survey catchability (q), the productivity of the stock (via the steepness parameter, h, of the stock recruitment relationship), the rate of natural mortality (M), and recruitment deviations. That said, the true uncertainty in current stock status and future projections is likely to be underestimated because the assessment model cannot account for alternative structural models for Pacific Herring population dynamics. We address many of the key uncertainties through the MSE process by using feedback simulations to evaluate MP performance under alternative scenarios about future rates of natural mortality where the operating model is also incorporating prior information and integrates over parameter uncertainty in each time step. The use of simulations provides a basis for evaluating whether unexpected outcomes are occurring in the realized performance. Herring MPs are shown to be responsive to stock declines by reducing harvest rates and closing commercial fisheries in order to avoid breaching the LRP. Finally, annual surveys and stock assessment provide “eyes” on herring stocks each year allowing for detection of exceptional circumstances.

Future work is focussed on increasing ecological realism in OMs for Pacific Herring, including uncertainty in stock structure and interacting ecological processes such as time varying natural mortality informed by predator consumption rates.

Conclusions

This work explores five USR options for four of the major Pacific Herring SARs (PRD, CC, SoG and WCVI):

- The productive period USR defined as the average spawning biomass for a predefined productive period, or in the case of SoG, 80% of the average productive period
- USRs based on a percentage of the unfished spawning biomass (40%, 50% and 60% of SB_0)
- USRs based on long-term average spawning biomass

We present a case for considering USRs as biomass objectives for Pacific Herring, where the probability of meeting the objective is evaluated using existing Herring operating models through the MSE process. USR options are also evaluated in the context of the historical time series using assessment model output from the 2021 stock assessment.

We advise that risk tolerances for meeting USR objectives need to consider the unique productivity of each stock and trade-offs between objectives, and suggest that the “no fishing MP” be used as a starting point to see ‘with what probability’ each USR option can be achieved under simulated conditions. We continue to recommend that MP options for each SAR be identified through the MSE process (whereby poor choices are eliminated), and support continued inclusion of both minimum escapement and segmented (hockey-stick) harvest control rules because simulations have shown that setting the upper control point at the USR is not necessarily required in order achieve desired management outcomes such as avoiding the LRP and supporting stock growth from depleted levels.

Final selection of USRs and implementation in the management framework will take place within the integrated fisheries management plan (IFMP) process.

Tables

Table 1. Model estimates for PRD, CC, SoG and WCVI Pacific Herring stock assessment regions (SARs) derived from the latest stock assessment (DFO 2021b), following the modelling approach of Cleary et al. (2019). The recommended approach for implementing the productive period option for each SAR appears with an asterisk. Depletion estimates are calculated as SB_{2021}/SB_0.

SAR	Median posterior estimates from the 2021 stock assessment									
	SB_0 (kt)	LRP (kt) (depletion)	Current stock depletion	Proposed productive period (years)	USR= average SB_{Prod} (kt) (depletion)	USR= 80% of average SB_{Prod} (kt) (depletion)	USR= 40%SB_0 (kt) (depletion)	USR= 50%SB_0 (kt) (depletion)	USR= 60%SB_0 (kt) (depletion)	USR= $SB_{long\text{-}term}$ (kt) (depletion)
PRD	60.4	18.1 (0.30)	0.49	1983-1992	32.5* (0.54)	26.0 (0.43)	24.2 (0.40)	30.2 (0.50)	36.2 (0.60)	25.3 (0.42)
CC	52.8	15.9 (0.30)	0.56	1990-1999	31.1* (0.59)	24.9 (0.47)	21.1 (0.40)	26.4 (0.50)	31.7 (0.60)	26.0 (0.49)
SoG	137.1	41.1 (0.30)	0.58	1988-2007	79.7 (0.58)	63.8* (0.47)	54.8 (0.40)	68.6 (0.50)	82.3 (0.60)	58.3 (0.43)
WCVI	45.6	13.7 (0.30)	0.51	1990-1999	32.9* (0.72)	26.3 (0.58)	18.2 (0.40)	22.8 (0.50)	27.4 (0.60)	27.7 (0.61)

Table 2. Updated management procedure evaluations for PRD herring. Performance metrics are given for two operating model (OM) scenarios: density-dependent natural mortality (DDM) and density-independent natural mortality (DIM); the constant natural mortality (conM) scenario has been removed from the evaluation. Performance criteria are calculated over three Pacific Herring generations (i.e., 15 years) from the start of the projection period for all objectives (Obj). MPs are ordered within each scenario by performance of achieving Objective 1. Legend: limit reference point (LRP); spawning biomass in year t (SB_t); estimated unfished spawning biomass (SB_0); average spawning biomass in the productive period ($\overline{SB}_{Prod}$), average annual variability (AAV; kt); and average catch ($\bar{C}$; kt). MPs are defined in DFO (2019a) and DFO (2020).

Scenario		Conservation Obj 1 (LRP)	USR Options					Yield	
								Obj 3	Obj 4
OM	**MP**	$SB_t > .3SB_0$	$\geq \overline{SB}_{Prod}$	$\geq .4SB_0$	$\geq .5SB_0$	$\geq .6SB_0$	$\geq \overline{SB}$	**AAV**	$\bar{C}$
DDM	NoFish_FSC	98%	86%	93%	89%	81%	95%	0	0.14
DDM	HS50-60_HR20_cap2.5	97%	80%	92%	83%	73%	92%	36.62	2.13
DDM	HS30-60_HR05	97%	82%	92%	84%	75%	92%	45.71	2.33
DDM	HS30-60_HR10_cap2.5	96%	79%	91%	83%	73%	91%	26.53	2.25
DDM	minE0.5B0_HR10	96%	79%	89%	63%	77%	87%	39.83	4.21
DDM	minE0.3B0_HR10	94%	67%	86%	74%	61%	84%	30.73	4.48
DDM	minE0.5B0_HR20	93%	55%	81%	64%	48%	78%	50.09	6.43
DIM	NoFish_FSC	94%	71%	87%	76%	65%	87%	0	0.14
DIM	HS50-60_HR20_cap2.5	93%	65%	83%	71%	57%	82%	51.69	1.82
DIM	HS30-60_HR05	92%	63%	82%	69%	56%	80%	42.60	1.96
DIM	HS30-60_HR10_cap2.5	91%	61%	80%	68%	55%	78%	35.58	2.07
DIM	minE0.5B0_HR10	89%	56%	78%	63%	49%	74%	52.38	3.35
DIM	minE0.3B0_HR10	87%	52%	74%	59%	47%	70%	33.96	3.77
DIM	minE0.5B0_HR20	85%	31%	68%	38%	51%	64%	63.44	5.10

Table 3. Updated management procedure evaluations for CC herring. Performance metrics are given for two operating model (OM) scenarios: density-dependent natural mortality (DDM) and density-independent natural mortality (DIM); the constant natural mortality (conM) scenario has been removed from the evaluation. Performance criteria are calculated over three Pacific Herring generations (i.e., 15 years) from the start of the projection period for all objectives (Obj). MPs are ordered within each scenario by performance of achieving Objective 1. Legend: limit reference point (LRP); spawning biomass in year t (SB_t); estimated unfished spawning biomass (SB_0); average spawning biomass in the productive period ($\overline{SB}_{Prod}$), average annual variability (AAV; kt); and average catch ($\bar{C}$; kt). MPs are defined in DFO (2019a) and DFO (2020).

Scenario		Conservation Obj 1 (LRP)	USR Options					Yield	
								Obj 3	Obj 4
OM	**MP**	$SB_t > .3SB_0$	$\geq \overline{SB}_{Prod}$	$\geq .4SB_0$	$\geq .5SB_0$	$\geq .6SB_0$	$\geq \overline{SB}$	**AAV**	$\bar{C}$
DDM	NoFish_FSC	92%	69%	83%	76%	68%	78%	0	0.14
DDM	HS30-60_HR05	91%	64%	82%	73%	62%	74%	40.76	1.74
DDM	minE0.5B0_HR10	90%	58%	81%	69%	56%	70%	53.22	2.92
DDM	HS30-60_HR10_cap5	90%	58%	80%	68%	56%	69%	38.83	2.92
DIM	NoFish_FSC	85%	54%	74%	64%	51%	65%	0	0.14
DIM	HS30-60_HR05	83%	48%	71%	58%	44%	59%	50.38	1.38
DIM	minE0.5B0_HR10	82%	43%	68%	52%	40%	54%	70.82	2.21
DIM	HS30-60_HR10_cap5	81%	43%	67%	52%	40%	54%	52.19	2.45

Table 4. Updated management procedure evaluations for SoG herring. Performance metrics are given for two operating model (OM) scenarios: density-dependent natural mortality (DDM) and density-independent natural mortality (DIM); the constant natural mortality (conM) scenario has been removed from the evaluation. Performance criteria are calculated over three Pacific Herring generations (i.e., 15 years) from the start of the projection period for all objectives (Obj). MPs are ordered within each scenario by performance of achieving Objective 1. Legend: limit reference point (LRP); spawning biomass in year t (SB_t); estimated unfished spawning biomass (SB_0); average spawning biomass in the productive period ($\overline{SB}_{Prod}$), average annual variability (AAV; kt); and average catch ($\bar{C}$; kt). MPs are defined in DFO (2019a) and DFO (2020).

Scenario		Conservation Obj 1 (LRP)	USR Options					Yield	
								Obj 3	Obj 4
OM	**MP**	$SB_t > .3SB_0$	$\geq .8\overline{SB}_{Prod}$	$\geq .4SB_0$	$\geq .5SB_0$	$\geq .6SB_0$	$\geq \overline{SB}$	**AAV**	$\bar{C}$
DDM	NoFish_FSC	80%	60%	68%	54%	41%	65%	0	0.14
DDM	HS30-60_HR10	77%	53%	63%	46%	33%	59%	69.87	4.92
DDM	minE0.3B0_HR10	76%	50%	60%	44%	31%	57%	47.88	6.15
DDM	HS30-60_HR15	76%	49%	59%	42%	27%	56%	64.75	6.97
DDM	HS30-60_HR20	74%	44%	54%	23%	37%	52%	65.70	8.80
DDM	minE0.3B0_HR15	73%	45%	54%	39%	25%	53%	45.96	8.59
DDM	minE0.3B0_HR20	70%	39%	50%	33%	20%	48%	49.45	10.79
DIM	NoFish_FSC	78%	57%	65%	51%	41%	63%	0	0.14
DIM	HS30-60_HR10	75%	51%	59%	45%	33%	58%	71.39	4.58
DIM	minE0.3B0_HR10	74%	51%	59%	45%	33%	58%	67.87	4.36
DIM	HS30-60_HR15	73%	48%	56%	41%	28%	55%	68.93	6.48
DIM	HS30-60_HR20	72%	43%	52%	37%	23%	51%	67.81	8.18
DIM	minE0.3B0_HR15	70%	45%	53%	38%	26%	52%	50.49	7.88
DIM	minE0.3B0_HR20	67%	40%	49%	34%	21%	47%	48.10	10.04

Table 5. Updated management procedure evaluations for WCVI herring. Performance metrics are given for two operating model (OM) scenarios: density-dependent natural mortality (DDM) and density-independent natural mortality (DIM); the constant natural mortality (conM) scenario has been removed from the evaluation. Performance criteria are calculated over three Pacific Herring generations (i.e., 15 years) from the start of the projection period for all objectives (Obj). MPs are ordered within each scenario by performance of achieving Objective 1. Legend: limit reference point (LRP); spawning biomass in year t (SB_t); estimated unfished spawning biomass (SB_0); average spawning biomass in the productive period ($\overline{SB}_{Prod}$), average annual variability (AAV; kt); and average catch ($\bar{C}$; kt). MPs are defined in DFO (2019a) and DFO (2020).

Scenario		Conservation Obj 1 (LRP)	USR Options					Yield	
								Obj 3	Obj 4
OM	MP	$SB_t > .3SB_0$	$\geq \overline{SB}_{Prod}$	$\geq .4SB_0$	$\geq .5SB_0$	$\geq .6SB_0$	$\geq \overline{SB}$	AAV	$\bar{C}$
DDM	NoFish_FSC	84%	33%	71%	57%	45%	43%	0	0.14
DDM	minE0.3B0_HR.05	82%	27%	68%	54%	41%	39%	59.45	1.01
DDM	HS30-60_HR10_cap2.0	82%	27%	67%	53%	40%	38%	60.72	1.15
DDM	HS50-60_HR10	82%	25%	67%	52%	37%	36%	89.73	1.28
DDM	HS30-60_HR15_cap2.0	81%	27%	67%	53%	40%	39%	57.13	1.30
DDM	HS50-60_HR15	81%	23%	64%	48%	33%	32%	82.56	2.08
DDM	minE0.3B0_HR10	80%	24%	65%	50%	35%	34%	75.21	1.87
DIM	NoFish_FSC	65%	17%	51%	36%	25%	25%	0	0.14
DIM	HS30-60_HR10_cap2.0	63%	15%	48%	32%	21%	22%	71.81	0.79
DIM	minE0.3B0_HR.05	63%	15%	48%	32%	22%	22%	70.09	0.76
DIM	HS30-60_HR15_cap2.0	62%	15%	47%	31%	21%	22%	80.94	0.83
DIM	HS50-60_HR10	62%	14%	46%	30%	20%	20%	96.54	0.72
DIM	HS50-60_HR15	61%	12%	44%	28%	18%	19%	107.55	1.00
DIM	minE0.3B0_HR10	61%	13%	43%	29%	19%	20%	83.98	1.26

Figures

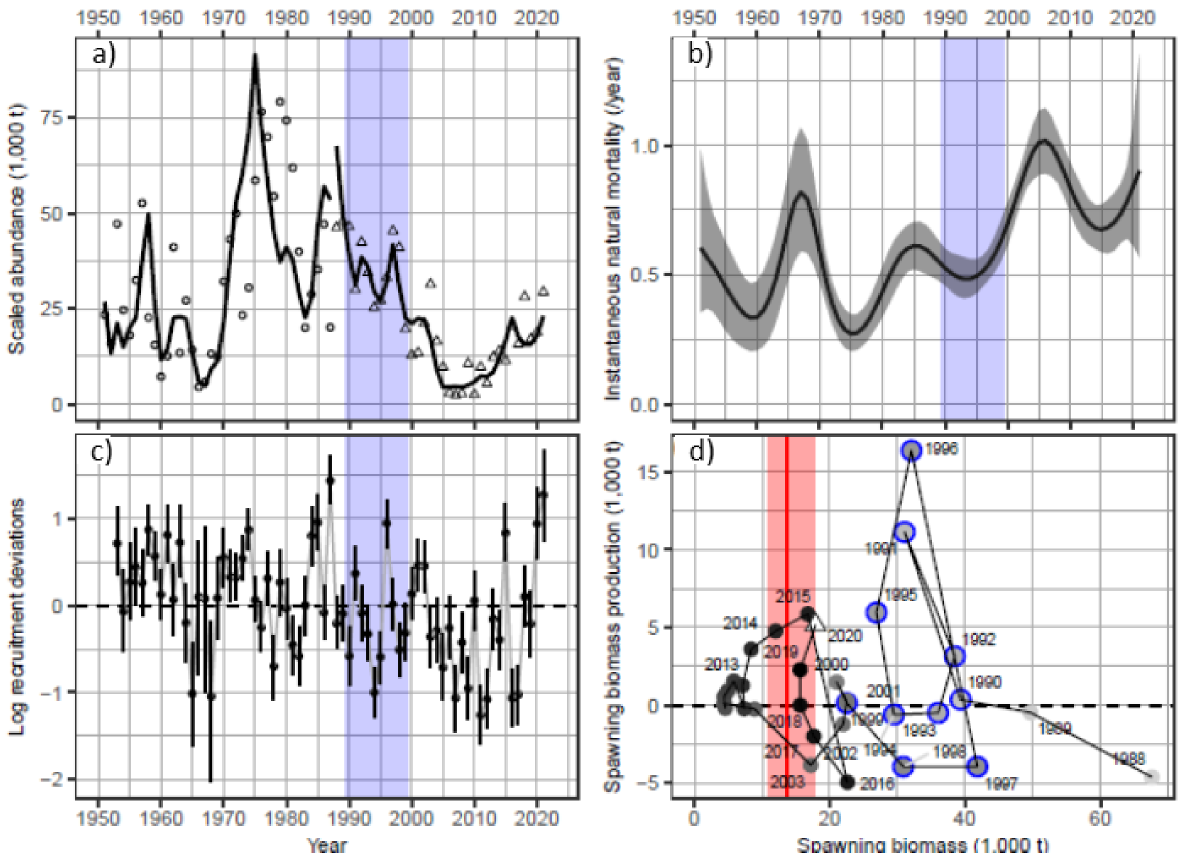

Figure 1. Statistical catch-age model outputs for WCVI herring from 1951-2021 (DFO 2021b). Panel (a): Model fit (lines) to scaled abundance. Spawn index is scaled to abundance by the spawn index scaling parameter q. Panel (b): Instantaneous natural mortality rate (year−1). Panel (c): Log recruitment deviations from 1953 to 2021. Panel (d): Phase plot of spawning biomass production for the dive survey period (1988 to 2020). Points are chronologically shaded light to dark; triangle indicates 2020. Legend: biomass and catch are in thousands of tonnes (t), points and time-series lines are median posterior estimates, bands and error bars are 90% credible intervals, dashed horizontal lines indicate zero, and red lines indicate the median limit reference point $0.3SB_0$, where SB_0 is the estimated unfished spawning biomass. Vertical blue shading and blue circles (Panel d) show productive period years proposed for WCVI, 1990-1999.

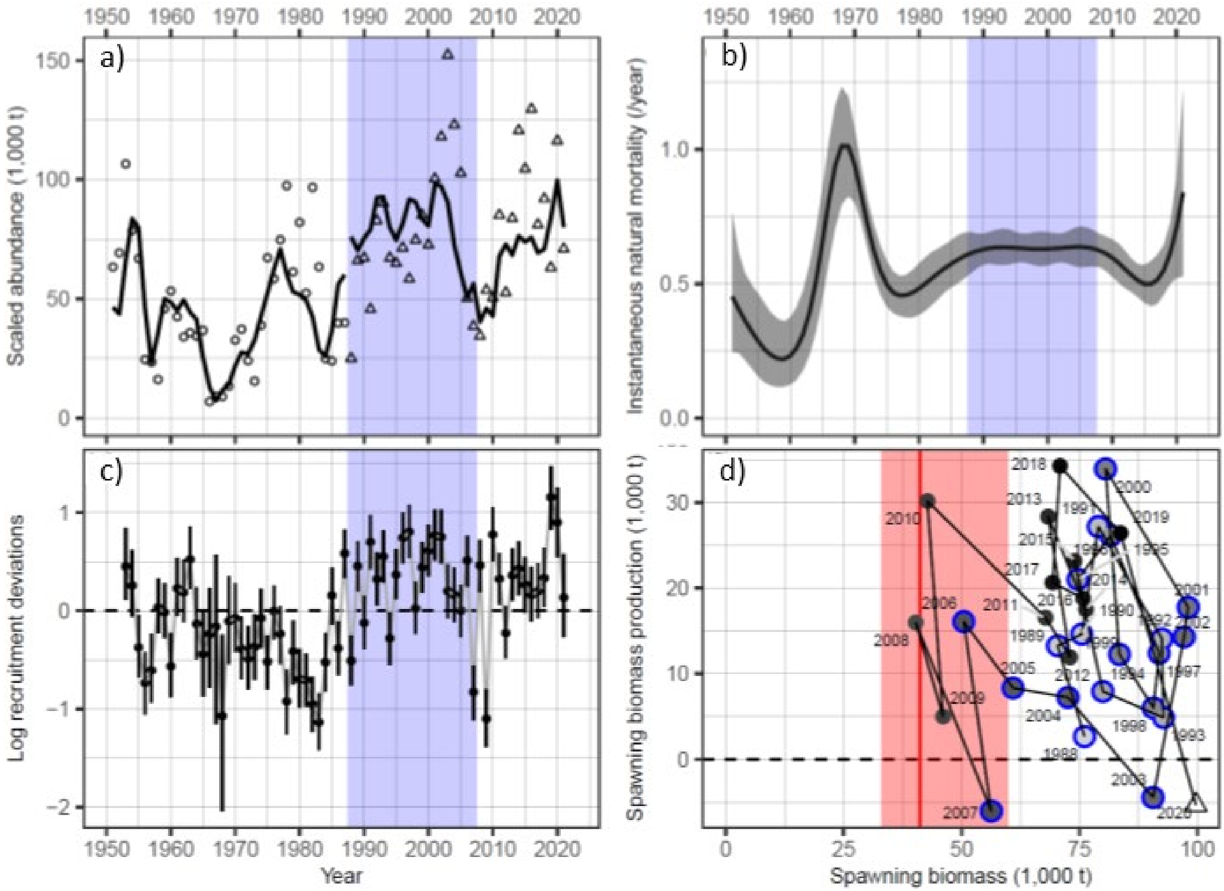

Figure 2. Statistical catch-age model outputs for SoG herring from 1951-2021 (DFO 2021b). Panel (a): Model fit (lines) to scaled abundance. Spawn index is scaled to abundance by the spawn index scaling parameter q. Panel (b): Instantaneous natural mortality rate (year−1). Panel (c): Log recruitment deviations from 1953 to 2021. Panel (d): Phase plot of spawning biomass production for the dive survey period (1988 to 2020). Points are chronologically shaded light to dark; triangle indicates 2020. Legend: biomass and catch are in thousands of tonnes (t), points and time-series lines are median posterior estimates, bands and error bars are 90% credible intervals, dashed horizontal lines indicate zero, and red lines indicate the median limit reference point 0.3SB$_0$, where SB$_0$ is the estimated unfished spawning biomass. Vertical blue shading and blue circles (Panel d) show productive period years proposed for SoG, 1988-2017.

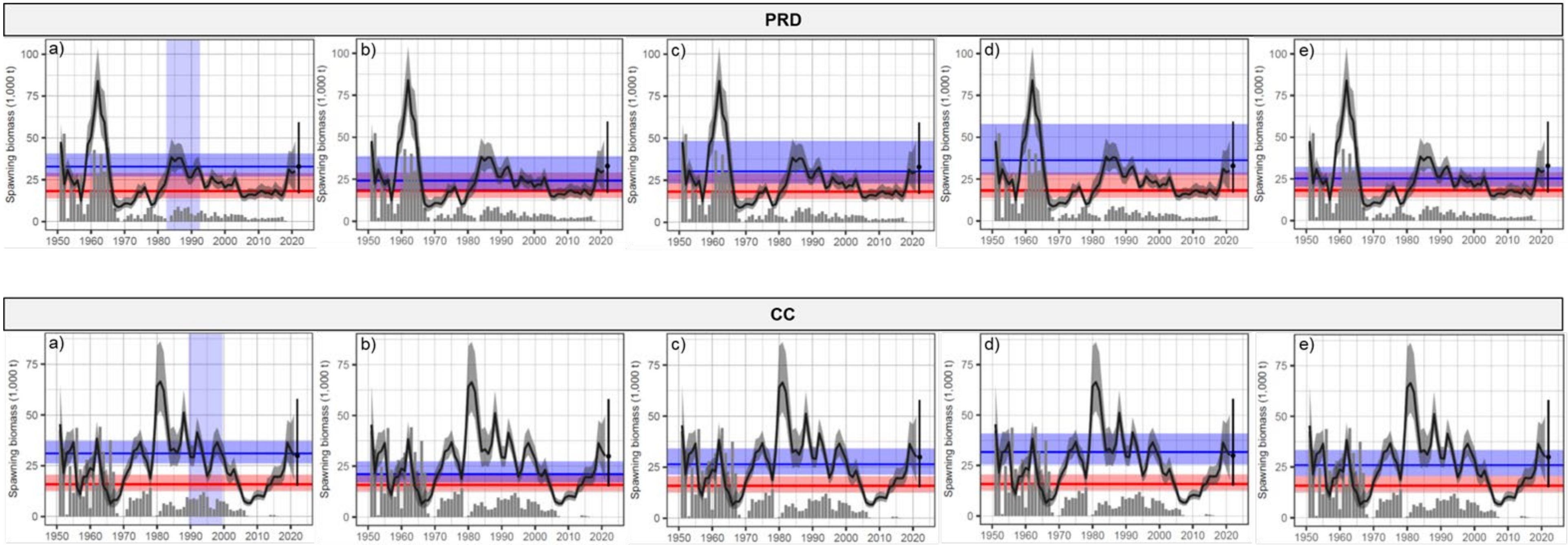

Figure 3. Spawning biomass trends for PRD and CC taken from statistical catch-age model outputs from 1951-2021 (DFO 2021b). Legend: spawning biomass and catch are in thousands of tonnes (t) with 90% credible intervals, horizontal red shading denotes the LRP and horizontal blue shading denotes each USR option: $SB_{productive\ period}$ *where vertical blue shading denotes productive period years proposed for each SAR (years listed in Table 1), (b)* $0.4SB_0$*, (c)* $0.5SB_0$*, (d)* $0.6SB_0$*, and (e)* $SB_{long-term\ average}$*.*

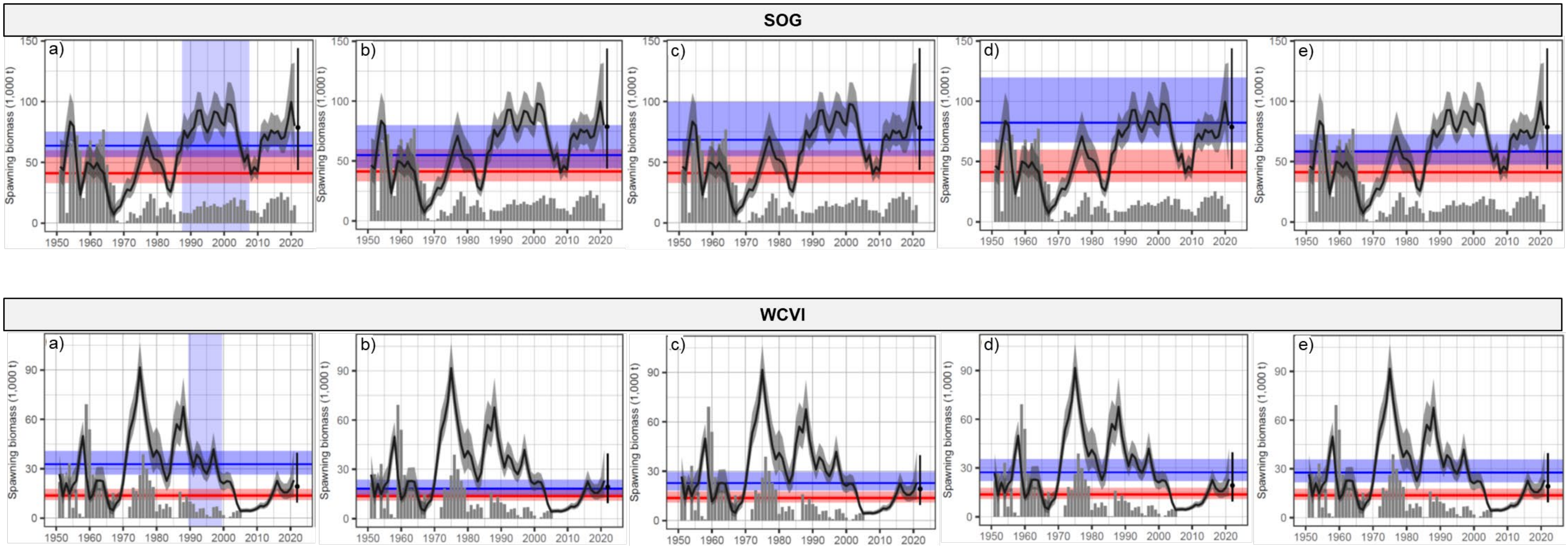

Figure 4. Spawning biomass trends for SoG and WCVI taken from statistical catch-age model outputs from 1951-2021 (DFO 2021b). Legend: spawning biomass and catch are in thousands of tonnes (t) with 90% credible intervals, horizontal red shading denotes the LRP and horizontal blue shading denotes each USR option: $SB_{productive\ period}$ *where vertical blue shading denotes productive period years proposed for each SAR (years listed in Table 1), (b) 0.4*SB_0*, (c) 0.5*SB_0*, (d) 0.6*SB_0*, and (e)* $SB_{long-term\ average}$.

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