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STOCK STATUS UPDATE WITH APPLICATION OF MANAGEMENT PROCEDURES FOR PACIFIC HERRING (*CLUPEA PALLASII*) IN BRITISH COLUMBIA: STATUS IN 2020 AND FORECAST FOR 2021

Context

Pacific Herring abundance in British Columbia (BC) is assessed using a statistical catch-age (SCA) model. In 2017, the Pacific Herring stock assessment included updates to the model (integrated statistical catch-age model; Martell et al. 2012), and a bridging analysis to support these changes (Cleary et al. 2019). Also introduced in the 2017 assessment was the estimation of stock productivity and current stock status relative to the new limit reference point (LRP) of $0.3SB_0$ (Kronlund et al. 2017), where SB_0 is estimated unfished spawning biomass. The structure of the 2017 model was not changed for the 2018, 2019, or 2020 stock assessments.

In 2016, DFO committed to renewing the current management framework to address a range of challenges facing Pacific Herring stocks and fisheries in BC. Renewal of the management framework includes engaging in a management strategy evaluation (MSE) process to evaluate the performance of candidate management procedures against a range of hypotheses about future stock and fishery dynamics. As part of the MSE process, a CSAS regional peer review occurred July 25 and 26, 2018, where performance of Pacific Herring management procedures (MPs) were assessed against conservation objectives for Strait of Georgia (SoG) and West Coast of Vancouver Island (WCVI) stock assessment regions (DFO 2019a). Steps included operating model (OM) development, fitting the OM to Pacific Herring stock and fishery monitoring data (OM conditioning), and closed-loop simulations of MP performance for alternative future natural mortality scenarios. In the spring of 2019, the MSE process was initiated for the northern stock regions: Haida Gwaii (HG), Prince Rupert District (PRD), and Central Coast (CC) (DFO 2020a). In the summer of 2020, updates were made to the MSE simulations for the WCVI and SoG management areas. These updates included conditioning the OM with more recent stock and fishery data and evaluating the performance of additional candidate MPs for these management areas.

Since initiation of the Pacific Herring MSE process, results have been included in the annual stock assessment as follows:

1. The 2018 stock assessment included updated MP recommendations for SoG and WCVI stock assessment regions for 2019 (DFO 2019b).
2. The 2019 stock assessment included MP recommendations for SoG and WCVI stock assessment regions as per 2018, and updated MP recommendations for HG, PRD, and CC (DFO 2020b).

3. The 2020 stock assessment includes updated MP recommendations for SoG and WCVI stock assessment regions, and MP recommendations for HG, PRD, and CC as per 2019 (DFO 2020b).

Fisheries and Oceans Canada (DFO) Pacific Fisheries Management Branch requested that DFO Pacific Science Branch assess the status of British Columbia (BC) Pacific Herring stocks in 2020 and recommend harvest advice for 2021 as simulation-tested MPs to inform the development of the 2020/2021 Integrated Fisheries Management Plan, where appropriate. Estimated stock trajectories, current status of stocks for 2020, management procedure options and harvest advice recommendations from those MPs for 2021 reflect methods of Cleary et al. (2019) and, where applicable, recommendations from the aforementioned 2018, 2019 and 2020 MSE analyses. These recommendations are described in the Section 'Application of MPs and harvest options for 2021.'

This Science Response results from the Science Response Process of September 30, 2020 on the Stock status update with application of management procedures for BC Pacific Herring: 2020 status and 2021 forecast.

Background

Pacific Herring in BC are managed as five major and two minor stock assessment regions (SARs; Figure 1). 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). The minor SARs are Area 27 (A27) and Area 2 West (A2W). We conduct formal analyses of stock trend information for the Pacific Herring major SARs. For the minor SARs, we present catch data, biological data, and spawn survey data (Appendix).

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 (FB), special use (SU), spawn-on-kelp (SOK) products, 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, or spawn on set tree boughs. 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. On the West Coast of Vancouver Island, five Nuu-chah-nulth First Nations – Ahousaht, Ehattesaht, Hesquiaht, Mowachaht/Muchalaht, and Tla-o-qui-aht (the T'aaq-wiihak First 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 Department has developed a 2020/21 Five Nations Multi-species Fishery Management Plan (FMP) in consultation with the Five Nations. Feedback provided by the Five Nations during consultations was considered and incorporated into the 2020/21 FMP by DFO where possible. The FMP includes specific details about the fishery, such as allocation/access, licensing and designations, fishing area, harvesting opportunities, as well as fishery monitoring and catch reporting. For further information see the FMP.

On the Central Coast, Heiltsuk First Nation have an Aboriginal right to commercially fish herring SOK. The Heiltsuk currently hold nine SOK licenses in this area, and SOK is harvested using the preferred means of the Heiltsuk, which is open ponding. The DFO and Heiltsuk are also committed to annual development of a Joint Fisheries Management Plan for Pacific Herring in the Central Coast.

In 2019/2020, the primary Pacific Herring fisheries were seine roe and gillnet roe fisheries, with a combined coast wide catch of 8,246 tonnes (t). The FB seine fishery had a coast wide catch of 2,193 t. The roe, FB and SU fisheries operated in SoG only in 2019/2020. Three commercial SOK licences were operational in CC in 2019/2020. There were no commercial SOK fisheries in PRD in 2019/2020.

A complete dockside monitoring program exists for all Pacific Herring commercial fisheries and the resulting validated catch data are included in the annual stock assessment process for all fisheries, except SOK.

The exclusion of SOK fishery data from the annual stock assessment process was identified as a key uncertainty in the most recent CSAS review of the stock assessment framework (Cleary et al. 2019). Recommendations for addressing this uncertainty will require quantifying ponding mortality and removals (eggs) associated with SOK fisheries. Although this work is underway, results are not yet available for informing the stock assessment.

Description of the stock assessment process

The SCA model is fitted to commercial catch data, fishery and survey proportion-at-age data, and a fishery-independent spawning biomass index to estimate total and spawning biomass, natural mortality, and recruitment. Observed annual weight-at-age is estimated external to the model, and maturity-at-age is a fixed input parameter. In 2017, an updated version of the SCA model was applied to assess each of the five major Pacific Herring SARs (Cleary et al. 2019). The main change from the SCA model used from 2011 to 2016 was the partitioning of variance between observation and process error to improve the estimation of the variance structure (Cleary et al. 2019). A bridging analysis was used to validate the updated model: this showed parameter estimates and biomass trajectories associated with the structural adjustments to be nearly identical to results from previous versions of the model, supporting the adoption of the revised structure (Cleary et al. 2019).

A Bayesian framework was used to estimate time series of spawning biomass, instantaneous natural mortality, and age-2 recruitment from 1951 to 2020. Advice to managers for the major SARs includes posterior estimates of current stock status (SB_{2020}), stock status relative to the LRP of $0.3SB_0$, and spawning biomass in 2021 assuming no catch (SB_{2021}). The projected spawning biomass is based on the current year's recruitment deviations from average predicted by the Beverton-Holt stock-recruit model and estimated natural mortality and weight-at-age, both averaged over the most recent 5-years. The Markov chain Monte Carlo (MCMC) sampling procedure follows the same method implemented by Cleary et al. (2019).

Cleary et al. (2019) reported results from two SCA model fits that differed in assumptions about dive survey catchability q_2 (from 1988 to 2020): assessment model 1 (AM1) where q_2 is estimated with a prior distribution assumed; and assessment model 2 (AM2) where $q_2 = 1$. The assumptions that the dive survey spawn index represents all the spawn deposited and that no eggs are lost to predation are strong. However, there is little information in the stock assessment data to inform an estimate of q_2; examination of the Bayes posterior shows the prior is not updated for the HG, CC, SoG, and WCVI SARs, and the estimated value reflects the prior mean (Cleary et al. 2019, Appendix D). Assuming $q_2 = 1$ produces a “minimum” biomass estimate buffering any other assessment and management implementation errors (see Martell et al. (2012) and DFO (2012)). Application of AM1 would remove such safeguards despite recent simulation evaluation showing that large (positive) assessment errors are produced by the current assessment model even with $q_2 = 1$ (DFO 2019a). Scaling the assessment with values of $q_2 < 1$ is likely to result in larger absolute assessment errors than those estimated when $q_2 = 1$ (DFO 2019a). For these reasons, advice presented here is based on the AM2 parameterization, supported also by comparisons presented in DFO (2016, Table A1), and Cleary et al. (2019, Appendix D).

Analysis and response

COVID-19 pandemic

The COVID-19 pandemic impacted our ability to collect and analyse Pacific Herring data in 2020. The pandemic and associated provincial response changed rapidly during the Pacific Herring field program season. Despite these challenges, surveyors assessed all major observed spawns in the five major SARs. The pandemic impacted our ability to assess Pacific Herring spawn in SARs with later spawns more than SARs with earlier spawns. For example, spawns were surveyed by surface surveys instead of underwater dive surveys in PRD and HG.

Although Pacific Herring biological samples were collected as usual, the pandemic delayed the analysis and availability of biological data for all SARs. The DFO sclerochronology lab at the Pacific Biological Station closed from March 16th to July 6th, which resulted in delayed age data for Pacific Herring samples collected in 2020. However, the lab was able to process the full collection of 2020 samples during the summer of 2020 to support the Pacific Herring assessment program.

Additional impacts of the pandemic include: delayed timing in final data summary reports, reduced availability of Science staff in the spring and summer for area specific discussions on Pacific Herring data, and delayed delivery of stock assessment advice.

Management strategy evaluation

Fisheries and Oceans Canada (DFO) has committed to renewing the current management framework to address a range of challenges facing Pacific Herring stocks and fisheries in British Columbia. Renewal of the management framework for Pacific Herring uses MSE to evaluate the performance of candidate MPs against hypotheses about past and future stock and fishery dynamics. The purpose of the MSE process is to identify MPs that provide acceptable outcomes related to conservation and fishery management objectives. The identification of a preferred management procedure requires a fully specified set of measurable objectives that include reference points (typically categorized as limits and targets) and to the extent possible, specification of objectives related to catch, catch variability, and socio-cultural goals. MSE is an iterative and ongoing process conducted with the participation of First Nations, the fishing industry, as well as government and non-government organizations.

The first MSE cycles for the SoG and WCVI management areas were completed in 2018 (DFO 2019a). Steps included OM development, fitting the OMs to Pacific Herring stock and fishery monitoring data from 1951 to 2017, and closed-loop simulations of MP performance for alternative future natural mortality scenarios (DFO 2019a). In the spring of 2019, the MSE process was extended to the HG, PRD, and CC management areas with stock and fishery monitoring data updated to include 2018 and performance evaluation of area specific MPs (DFO 2020a). In the summer of 2020 the second MSE cycle was initiated for the WCVI and SoG management areas. This included conditioning the OMs with more recent stock and fishery data, and evaluating the performance of additional candidate MPs for these management areas.

A core set of fisheries management objectives (DFO 2020a) have been applied to each major SAR:

1. Maintain spawning biomass above the LRP with at least 75% probability over three Pacific Herring generations (i.e., avoid a biomass limit; $P(SB_t > 0.3SB_0) \geq 0.75$),
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; $P(SB_t \geq 0.6SB_0) \geq 0.5$),
3. Maintain average annual variability (AAV) in catch below 25% over three Pacific Herring generations (goal reflecting catch variability; AAV < 0.25), and
4. Maximize average annual catch over three Pacific Herring generations (goal reflecting catch biomass).

However, a fully specified set of objectives has not yet been developed for each management area. DFO will continue to collaborate with coastal First Nations to develop area-specific objectives specific to Food, Social and Ceremonial fisheries as well as spawn-on-kelp (SOK) fisheries. In addition, DFO will continue to engage with the herring industry, government, and non-government organizations to describe broader objectives related to conservation, economics, and access.

The MPs for each SAR differ in the form of the HCR and choices of catch cap, but use the same type of monitoring data and assessment model (e.g., Cleary et al. 2019). The current stock assessment model assumes natural mortality is time-varying and this is reflected in the MSE as three hypotheses about future Pacific Herring natural mortality M:

1. M is a time-varying, density-dependent process (DDM),
2. M is a time-varying, density-independent process (DIM), and
3. M is constant over time (conM).

These three hypotheses are captured as three operating model (OM) scenarios in DFO (2019a). The DDM scenario was identified as the Reference OM scenario based on discussion at the July 2018 CSAS review process (DFO 2020a), while the DIM and conM scenarios were identified as Robustness OM scenarios. There is however currently no scientifically supported method for predicting the natural mortality and thus all three scenarios are included.

Several lessons were learned from the MSE analyses conducted so far:

1. The catch-at-age stock assessment model can produce large (positive) assessment errors. Such assessment errors cause over-estimation of spawning biomass and result in recommended catch limits such that the realized harvest rate exceeds the intended target specified by a HCR (e.g., over-harvest).

2. Reduction in harvest rate from 20% to 10% was the most effective means of mitigating stock assessment errors by reducing the absolute size of the catch. The use of a catch cap, implemented as a maximum annual catch level, was an effective model-free way to further mitigate assessment errors at very high biomass levels. Simulation analyses additionally showed that outcomes are insensitive to the choice of operational control points (OCPs) in the HCR when a low harvest rate (HR) and catch cap are applied. This occurs because low biomass levels (associated with the lower OCP) are avoided for these MPs.

3. Differences in specification of Pacific Herring MPs, including the HCR components, are expected a priori among SARs. The reasons relate to differences in objectives deemed important by resource users, differences in historical and current stock and fishery dynamics, and differences in the magnitude and direction of assessment model errors in each SAR. Conservation objectives such as those based on avoiding a threshold to serious harm (i.e., a limit reference point) in alignment with the DFO PA Framework (DFO 2009) are held constant among SARs based on the analyses of Kronlund et al. (2017).

4. There are many possible ways to incorporate MP performance in robustness trials into decision-making but, there is currently no accepted scientific way of combining results from multiple operating models.

5. In situations where multiple MPs meet the agreed upon objectives, further criteria, such as ranking secondary objectives, is needed in order to provide decision-makers with a tractable set of trade-off choices.

6. Outcomes of MP evaluations appear to be influenced by the last three to five years of stock status and natural mortality trends used to condition the OM. If simulations were run over a greater number of years (ie. 50 years) performance would start to approach equilibrium and be unaffected by most recent trends in OM conditioning data.

Input data

There are three types of input data used for the Pacific Herring stock assessment: catch data, biological data, and abundance data. These data sets are described in the following sections, and summarized in Table 1. Relative to the previous assessment, the only change made to input data was to update all data time series to include data from the 2019/2020 herring season (July 1 to June 30). Note that we refer to ‘year’ instead of ‘herring season’ in this report; therefore 2020 refers to the 2019/2020 Pacific Herring season.

Catch data

For the purposes of stock assessment, catch data are summarized by gear type as described in Table 1 and presented in Figure 2. As in previous years, catch input to the stock assessment model does not include mortality from the commercial SOK fishery, nor any recreational fisheries or food, social, and ceremonial (FSC) harvest. The FSC and recreational harvest are considered minor relative to commercial harvest. The commercial SOK fishery is licensed based on pounds of validated SOK product (i.e., eggs adhered to kelp), not tonnes of fish used or spawned. Currently there is no basis for validating mortality imposed on the population by this fishery, however methods for estimating SOK mortality are being developed.

Combined commercial removals from 2011 to 2020 from the roe, food and bait, and special use fisheries appear in Table 2. The proportion of coast-wide catch that comes from the SoG was 22% in 1990, and 100% in 2020. Total SOK harvest (pounds of validated product) for the major SARs from 2011 to 2020 is presented in Table 3.

Biological data

Biological samples are collected as described in Cleary et al. (2019) and Table 1. Biological data inputs to the stock assessment are annual weight-at-age (Figure 3) and annual numbers-at-age, shown as proportions-at-age (Figure 4).

Significant declines in weight-at-age are evident for all major herring stocks, from the mid-1980s to 2010. Declining weight-at-age may be attributed to any number of factors, including fishing effects (i.e., gear selectivity), environmental effects (e.g., changes in ocean productivity), or changes in sampling protocols (e.g., shorter time frame over which samples are collected). There has been an increasing trend in weight-at-age for all major stocks from 2012 to 2020, although to a lesser degree for PRD.

Abundance data

The spawn index survey collects information on spawn length (parallel to shore), spawn width (perpendicular to shore), number of egg layers by vegetation type, and other data. There are two spawn survey periods defined by the predominant survey method: surface period from 1951 to 1987, and dive period from 1988 to 2020. Data from these surveys are used to calculate egg densities per spawn. Ultimately, the estimated weight of mature spawners required to produce the egg deposition is calculated and referred to as the ‘spawn index’. Execution of the 2020 spawn survey followed standard dive survey protocols for SoG, CC, and WCVI SARs as described in Cleary et al. (2019), and a surface survey protocol was used for HG and PRD SARs due to COVID-19. Time series of spawn index by major stock assessment region, from 1951 to 2020 are summarized in Figure 5. In 2020, there was a notable increase in survey biomass (index values) for HG and SoG SARs (Figure 5 and Tables 4 & 7), a small increase in survey biomass for WCVI (Figure 5 and Table 8), and a small decrease in survey biomass for PRD and CC (Figure 5 and Tables 5 & 6).

Spatial spawn distribution

Tables 4 through 8 summarize the spatial distribution of survey spawn biomass (i.e., the spawn index) by proportion over the most recent 10 years for the major SARs. HG and SoG are summarized by Group, while PRD, CC, and WCVI are summarized by Statistical Area; the choice of spatial grouping reflects spawning behaviour and biology for each SAR based on the survey data and working group discussions with local First Nations.

First Nations observations

The onset of the COVID-19 pandemic impacted First Nations participation in herring survey activities as well as participation in FSC harvest. Impacts also extended to DFO Science staff in terms of reduced capacity for external engagement. As such, assembling local observations was not possible for the 2020 season. However, discussions with local Nations will proceed with

Science and Fisheries Management throughout the consultation period. All efforts will be made to include this information next season.

Stock status update

Analyses of stock trend information for AM2 are presented following methods of Cleary et al. (2019) for the Pacific Herring major stock assessment regions. Perceptions of stock status based on outputs from the SCA model (AM2) are summarized for each stock in a multi-panel figure (e.g., Figure 6). The panels show:

a. Time series of model fit to scaled spawn survey data,

b. Time series of instantaneous natural mortality rate M estimates,

c. Time series reconstruction of number of age-2 recruits,

d. Time series of estimated spawning biomass SB_t and total catch C_t in year t, with reference lines at model estimates of $0.3SB_0$,

e. Time series of (log) deviations from the estimated Beverton-Holt recruitment function, and

f. Phase plot of spawning biomass production ($\frac{SB_{t+1}-SB_t+C_{t+1}}{SB_t}$) for the dive survey period, with reference lines at model estimates of $0.3SB_0$.

Note that spawn survey data (i.e., spawn index) is scaled to abundance in panel (a) by the spawn survey scaling parameter q. The spawn index has two distinct periods defined by the dominant survey method: surface surveys (1951 to 1987), and dive surveys (1988 to 2020). Thus, two q parameters are implemented in the estimation procedure: q_1 (1951 to 1987) with an uninformative prior, and q_2 (1988 to 2020) with an informative prior approximating 1.0.

The surface survey methodology has been used on occasion from 1988 to 2020. Generally this occurs in instances when herring spawn is observed in locations where a dive survey team is not available, or when spawning occurs very early (January or February) or late (May) in the season. In these instances, spawner biomass estimates obtained from surface surveys for a given stock area and year are added to biomass estimates from dive surveys, and $q_2 = 1$ is assumed for the combined index. In 2020, a full surface survey was conducted for the HG and PRD SARs; in this assessment the resulting survey biomass is assumed continuous with the dive survey time series.

Reference points

A biological limit reference point (LRP) is defined for the major Pacific Herring SARs at $0.3SB_0$ (Kronlund et al. 2017). Candidate upper stock references (USR) were introduced in Cleary et al. (2019) and implemented as biomass objectives in the simulation analyses for WCVI and SoG in 2018 (DFO 2019a) and then for HG, PRD, and CC in 2019 (DFO 2020a). Candidate USRs are:

1. $0.4SB_0$,

2. $0.6SB_0$,

3. Average spawning biomass from 1951 to 2020, SB_{ave}, and

4. Average spawning biomass during a productive period (Cleary et al. 2019), $SB_{ave-prod}$.

Simulation results showed similar properties between USRs $0.6SB_0$ and SB_{ave} both within and among SARs, while the USR based on the average biomass in a productive period, $SB_{ave-prod}$, was found to be most variable among SARs. The simulation-evaluations did not select a single USR, however a USR of $0.6SB_0$ is included in this stock status update because this candidate is sufficiently above the LRP (2*LRP) and it is a repeatable calculation across all SARs. Stock status relative to the assessment model estimates $0.3SB_0$ (LRP) and $0.6SB_0$ (one candidate USR) are presented for each SAR in Tables 24 through 28.

The LRP and USR relate stock status to the DFO PA Framework (DFO 2009), and in the assessment of Pacific Herring the same calculations are applied for each SAR. There is an important distinction between reference points (e.g., LRP, USR) and the operational control points of the harvest control rule (HCR) or the management procedure used to set catch limits. Specifically, operational control points (OCPs) define the inflection points of a HCR, and identify biomass levels where management action is taken. For example, the harvest rate is set to zero and fishing ceases when biomass falls below the lower OCP.

Haida Gwaii

Estimated spawning biomass declined to near historic lows in the mid-1990s and briefly increased through the late 1990s before falling to persistent historic lows from 2000 to 2010 (Figure 6d). A modest increase in estimated spawning biomass occurred during the early 2010s before falling once again to near historic lows from 2016 to 2018. The modest increase can be attributed to increases in the spawn index in 2013 and 2015 (Figure 6a) that were supported by above average recruitment of age-2 fish in 2012 (Figure 6c, d). An increasing trend in the estimated natural mortality rate since 1980 (Figure 6b) largely absorbed surplus production attributable to above average recruitment events (e.g., 1997 and 2012; Figure 6c, d). Estimated natural mortality has increased sharply since the early 2010s following a decline from a peak rate in the early 2000s. Since 2000, the HG stock has been in a low biomass state, with many of these years also showing low productivity which has precluded stock growth (Figure 6f). There is an increase in survey biomass in 2019 and 2020, and above-average recruitment of age-2s in 2019, however there is insufficient information to verify an increasing trend. The most recent year, between 2019 and 2020, there is evidence of positive productivity, however biomass remains low relative to historical patterns and natural mortality rates remain at historic high levels. The effective harvest rate U_t since 2000 has been at or near zero (Figure 12), with the last commercial roe fishery in 2002, and the last commercial SOK fishery in 2004.

Estimated spawning biomass in 2020 is 14,846 t (SB_{2020}, median posterior value) or 65.0% of SB_0, an increase from last year (Tables 19 & 24). Spawning biomass in 2020 is estimated to above the LRP of $0.3SB_0$ with a 97.5% probability (Table 24).

Prince Rupert District

Estimated spawning biomass recovered by the mid-1980s from historic low depletion levels following the collapse of the 1960s, to about 50% of the historic high biomass estimated in the early 1960s (Figure 7d). However, after the mid-1980s, estimated spawning biomass steadily declined before stabilizing at a relatively low level (but above historic lows) by the mid-2000s. The estimated stock biomass has shown little trend from 2005 to 2018, with a modest increase in 2019. Survey biomass in 2020 is near-identical to that of 2019. Fluctuations in the trend in spawning biomass appear to be less than those observed in other SARs, possibly because some spawn index points are being under- or over-fit (e.g., 2001 to 2004, and 2010 to 2013) as shown in Figure 7a. Estimated natural mortality reached historic highs in the late 1960s, before declining through the late 1970s. Beginning in about 1980, estimated natural mortality increased through to 2005, roughly doubling from 0.25 to 0.5 yr^{-1} (Figure 7b). Estimated natural mortality stabilized from 2005 to 2020 at a median rate of 0.45. This trend in natural mortality coincides with the decline in spawning biomass (Figure 7d); recruitment deviations have fluctuated around 0 without any strong positive or negative trends (Figure 7e). An above average age-2+ recruitment in 2014, 2017 to 2018, and an increase in the spawn index in the last two years appears to be sufficient to lead to an increased biomass in 2019 and 2020 relative to 2018 (Figure 7f). Commercial catches from 2007 to 2018 have remained low (below 2,000 t) and there was no commercial catch in 2019 and 2020. The estimated natural mortality appears to be unchanged from last year, resulting in what appears to be a small increase in production between 2018 and 2019, sustaining the 2019 biomass increase through 2020.

The model estimates spawning biomass in 2020, SB_{2020}, at 27,552 t (posterior median), equal to 45.2% of SB_0 (Tables 20 & 25). Commercial fisheries have occurred annually in PRD since the mid-1980s, with the exception of 2019 and 2020, during which the effective harvest rate U_t was estimated to be at or below 20% (Figure 12) in all years except 1989. Spawning biomass in 2020 is estimated to be greater than the LRP of $0.3SB_0$ with a 86.9% probability (Table 25).

Central Coast

Estimated spawning biomass fluctuated around a strongly declining trend from a historic high around 1980 before reaching a historic low level in the late 2000s (Figure 8d). An increase in spawning stock biomass was estimated through the mid-2010s but remained below levels estimated prior to 2000, with survey biomass declining in 2017 and 2018. In 2019 there was an increase in estimated spawning biomass, with a similar level estimated for 2020. The estimated biomass trend largely reflects the trend in the spawn index (Figure 8a), where fluctuations correspond opposite to the fluctuations in estimated natural mortality (Figure 8b). For example, the decline in spawn index (and estimated spawning biomass) to the historic lows of the late 2000s followed a strongly increasing trend in estimated natural mortality through the same period. Estimated natural mortality moderated by the late 2000s, which was followed by the increase in spawn index (and estimated spawning biomass) until 2017 whereupon natural mortality ceased declining. Recruitment deviations were slightly negative (lower than predicted by the stock-recruitment function) on average from about 1990 to 2017, and are above average in 2019 and 2020 (Figure 8e). The model estimates very similar spawning biomass in 2019 and 2020, and the analysis of surplus production shows there is evidence of strong production in the year between 2016-2017 and between 2018-2019, similar to the 1990 to 1999 period (Figure 8f). Surplus production in the year between 2019-2020 is negative.

An examination of spawn biomass by Herring Section shows the increase in herring spawn to have largely occurred in Spiller Channel (Sections 072 and 078) and Kitasu Bay (Section 067). The appearance of herring spawn in Thompson/Stryker (Section 074) is the first significant spawn in many years (Figure 9).

A fixed cutoff HCR was implemented in 1986, and from 1986 to 2007 the effective harvest rate U_t is estimated to fluctuate above and below the 20% target rate, with median estimates exceeding 20% frequently (Figure 12). Occurrences of U_t exceeding the 20% target harvest rate are due in part to positive assessment model errors, and lags in detecting a directional change in the trend.

Following a commercial fishery closure from 2007 to 2013, the CC stock reopened to commercial fisheries in 2014, and small commercial roe fisheries occurred in 2014, 2015, and 2016. A commercial SOK fishery operated yearly from 2014 to 2020, however these removals are not included in the estimation of U_t. Commercial SOK fishery did not occur in Area 07 in 2020 due to COVID-19.

The model estimates spawning biomass in 2020, SB_{2020}, at 37,592 t (posterior median), equal to 69.9% of SB_0 (Tables 21 & 26). Spawning biomass in 2020 is estimated to be greater than the LRP of $0.3SB_0$ with a 99.4% probability (Table 26).

Strait of Georgia

The estimated spawning biomass for the SoG stock increased in 2020 and the uncertainty associated with the last few years of spawning biomass along with the forecast biomass SB_{2020}, is quite large (Figure 10d). There was an increasing trend in estimated spawning biomass from about 2010 to 2016 which coincided with a decline in estimated natural mortality that began in the late 2000s (Figure 10b). The model estimates natural mortality has been increasing since 2016, and has now reached a level last estimated in the early 1970s. This coincides with large shifts in survey biomass in recent 5 years, with the index declining from 2016 to 2017 and 2018 to 2019. The large uncertainty in both spawning biomass and natural mortality estimates in 2020 may be in part a function of the declining trend in the spawn index starting in 2017 following the increasing trend that began in 2010 (Figure 10a). The model fits an averaged trajectory through the spawn index values of the 2010s and has, to date, insufficient information to determine whether the decline from 2016 to 2019 represents a true decline in estimated spawning biomass. The model estimates above average recruitment in most years from 2010 to 2020 (Figure 10c) with the recruitment deviations showing especially large recruitment of age-2 fish in 2019 and 2020 (Figure 10e). The large uncertainty around estimated age-2 recruitment in the terminal year of the time series is a common observation because these age-2 fish are only partially recruited to the fishing gear. Analysis of surplus production shows that for the year between 2019 and 2020, the SoG SAR is estimated to be in a high production, high biomass state (Figure 10f).

Commercial fisheries have occurred annually in SoG since the early-1970s (following the stock collapse of the late 1960s). Since implementing the fixed cutoff HCR in 1986, the effective harvest rate U_t is estimated to fluctuate above and below the 20% target rate, with median estimates above 20% in 2005, 2006, and from 2016 to 2018 (Figure 12). The model estimates spawning biomass in 2020, SB_{2020}, at 89,869 t (posterior median), equal to 63.7% of SB_0 (Tables 22 & 27). Spawning biomass in 2020 is estimated to be greater than the LRP of $0.3SB_0$ with a 98.2% probability (Table 27).

West Coast of Vancouver Island

The time series of estimated spawning biomass shows a decline from the late 1980s through to a historic low in the 2000s (Figure 11d). The low estimated spawning biomass persisted through the 2006 to 2012 period and has since slowly increased to a level similar to that estimated for 2000. The model reconstruction of spawning biomass closely follows the trajectory of spawn index values (Figure 11a). Historically high natural mortality rates occur in the late 2000s and these rates have since declined (Figure 11b). Recruitment deviations have been negative (lower than predicted by the stock-recruit function) on average since about 2003 (Figure 11e), however the reduction in estimated natural mortality and absence of removals from a commercial fishery appears to be sufficient to offset this below average recruitment of age-2 fish to support biomass growth. The absence of a commercial fishery since 2005 means the realized harvest rate has been near zero for the last 15 years (Figure 12). In recent years there has been modest evidence for an increase in biomass. The production estimates in the 2019-2020 year are at zero (Figure 11f).

The model estimates spawning biomass in 2020, SB_{2020}, at 18,254 t (posterior median), equal to 39.5% of SB_0 (Tables 23 & 28). Spawning biomass in 2020 is estimated to be greater than the LRP of $0.3SB_0$ with a 77.2% probability (Table 28).

Management performance

Management procedure performance can be investigated using time series of effective harvest rate. The estimated effective harvest rate U in each year t, calculated as $U_t = C_t/(C_t + SB_t)$, where C_t is catch in year t, and SB_t is estimated spawning biomass in year t. Times series of U_t relative to target harvest rate of 20% are presented in Figure 12.

Application of MPs and harvest options for 2021

Harvest options for 2021 reflect application of simulation-tested MPs for each major SAR. The description of MP evaluations for HG, PRD and CC appearing below reflects the 2019 assessment (DFO 2020b). MPs included for SoG and WCVI combines information from the first MSE cycle (DFO 2020b) with updated MP evaluations conducted in September 2020 (DFO 2020c, *In prep.*[1]). Finally, science advice in 2018 recommended discontinuing the use of the historical fixed cutoff HCR (DFO 2019a), as such this MP has been removed from further consideration for all Pacific Herring SARs.

Haida Gwaii

The HG stock persisted in a low biomass, low productivity state from approximately 2000 to 2018. The stock was below the LRP for much of that period and shows little evidence of sustained stock growth despite the absence of commercial fisheries since 2002 (2004 for the SOK fishery). Survey biomass increased in 2019 and 2020, however biomass estimates are highly uncertain given persistent high natural mortality rates. In the absence of fishing, spawning biomass in 2021 is forecast at 11,285 t (posterior median). Results of the simulation-evaluations found that none of the proposed MPs, including the historical and no fishing MPs, performed satisfactorily against the conservation objective of maintaining spawning biomass above the LRP with high probability (at least 75%).[2]

The projected spawning biomass in 2021 is forecast to be below $0.3SB_0$ with 14.0% probability in the absence of fishing (Table 24 and Figure 13).

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[1] DFO. 2020c. Updated evaluation of management procedures for Pacific Herring (*Clupea pallasii*) in the Strait of Georgia and the West Coast of Vancouver Island management areas of British Columbia. DFO Can. Sci. Advis. Sec. Sci. Resp. In prep.

[2] "High" probability is defined as 75 to 95% by the DFO Decision-making framework (DFO 2009).

DFO has committed to developing and implementing a rebuilding plan for Haida Gwaii Pacific Herring by the end of fiscal year 2020/21.[3] Work is underway through a technical working group comprised of members of the Council of Haida Nation, DFO, and Parks Canada. Guidance for the Development of Rebuilding Plans under the Precautionary Approach Framework: Growing Stocks out of the Critical Zone (DFO 2013) states that the primary objective of any rebuilding plan is to promote stock growth out of the Critical Zone (i.e., to grow the stock above the status-based LRP) by ensuring removals from all fishing sources are kept to the lowest possible level until the stock has cleared this zone with high probability. Stock rebuilding does not end having met this goal, however, and one of the goals of the rebuilding plan will be to identify candidate threshold biomass levels greater than the LRP that are consistent with a rebuilt state.

DFO supports commercial herring fishery closures for the HG major stock region until April 2021. As such, the harvest recommendation for the HG stock in 2021 is 0 t.

Prince Rupert District

The PRD estimated stock biomass has shown little trend from 2005 to 2018, with a modest increase in 2019. Survey biomass in 2020 is almost identical to 2019. For PRD the best performing MPs generally had 10% or lower harvest rates, although two MPs with a 20% harvest rate did meet the conservation objective because they use a higher lower OCP (see Section 'Reference points') of $0.5SB_0$. These MPs also result in more frequent fishery closures because spawning biomass declines below the lower control point more frequently. While several MPs are able to meet core conservation objective of maintaining spawning biomass above the LRP with high probability (at least 75%)[2], they also imply different trade-offs among biomass (e.g., ecosystem) and yield outcomes. For management regions where multiple MPs meet the conservation objective, further ranking of the remaining objectives is needed in order to provide decision makers with a tractable set of trade-off choices. However this was not undertaken with the first MSE cycle because a fully specified set of objectives has not yet been developed for each management area.

Effective harvest rates for the past 10 years (with positive catches) average ~12% (Figure 12), during which the stock showed no sign of growth before 2018 and is estimated to fluctuate at or near $0.3SB_0$ (Figure 7d). Spawning biomass depletion increased above $0.3SB_0$ in 2019 and 2020. Although there is not evidence of a low biomass and low productivity state for PRD in the past 30-years, the adjacent SARs (HG and CC) show evidence of recent prolonged periods of low biomass and low productivity: states that were entered rapidly and were preceded by high biomass levels (Kronlund et al. 2017).

In the absence of fishing, spawning biomass in 2021 is forecast to an estimated 29,698 t (posterior medians), almost identical to the median estimate for 2020. The forecast spawning biomass in 2021 is estimated to be below the LRP of $0.3SB_0$ with 11.4% probability in the absence of fishing (Table 25).

[3] In response to recommendations in the Commissioner of the Environment and Sustainable Development (CESD) October 2016 Report 2 - Sustaining Canada's Major Fish Stocks - Fisheries and Oceans Canada, the Department will develop rebuilding plans for major fish stocks that are in the precautionary approach critical zone, including Haida Gwaii Pacific Herring by the end of fiscal year 2020/21.

Harvest options for 2021, resulting from simulation-tested MPs, are presented in Table 29. Management procedures and performance metrics appear in identical format to that of September 2019 (DFO 2020b). These options reflect application of MPs to the 2021 forecast biomass for PRD, whereby each MP meets the conservation objective with a minimum 75% probability under the Reference OM (DDM) scenario. Harvest options under the two Robustness OM scenarios are also included. For ease of comparison with MSE results (DFO 2020a), all MPs and scenarios listed in Table 29 include performance metrics for the four core objectives.

Central Coast

The CC stock persisted in a low biomass, low productivity state from approximately 2005 to 2014. An increasing trend has been observed in recent years, and overall the stock shows more volatility (large increases/ decreases) than was observed prior to 2005. For the CC, MPs performing best against the conservation objective have a 10% or lower harvest rate and include a range of operational control point choices. Similar to PRD, the simulation results for CC indicate there are multiple MPs that meet the conservation objective of maintaining spawning biomass above the LRP with high probability (at least 75%)[2]. For management regions where multiple MPs meet the conservation objective, further ranking of the remaining objectives is needed in order to provide decision makers with a tractable set of trade-off choices. However this was not undertaken with the first MSE cycle because a fully specified set of objectives has not yet been developed for each management area.

In the absence of fishing, spawning biomass in 2021 is forecast at 35,770 t (posterior median), decreasing from 37,592 t in 2020 (Table 26). The 2021 spawning biomass is forecast to be below the LRP of $0.3SB_0$ with 1.9% probability in the absence of fishing.

Harvest options for 2021, resulting from simulation-tested MPs, are presented in Table 30. Management procedures and performance metrics appear in identical format to that of September 2019 (DFO 2020b). These options reflect application of MPs to the 2021 forecast biomass for CC, whereby each MP meets the conservation objective with a minimum 75% probability under the Reference OM (DDM) scenario. Harvest options under the two Robustness OM scenarios are also included. For ease of comparison with MSE results (DFO 2020a), all MPs and scenarios listed in Table 30 include performance metrics for the four core objectives.

Additionally, DFO acknowledges commitment to the Heiltsuk Nation for the development of a Joint Fisheries Management Plan for Pacific Herring in the Central Coast in 2021. Results presented here may inform this on going commitment.

Strait of Georgia

In 2018, closed-loop feedback simulations for the SoG showed that all tested MPs could maintain the spawning biomass above the LRP with 91% probability or higher across all OM scenarios.

Additional simulation-evaluations were conducted in 2019 to further explore the role of catch caps in mitigating assessment errors (DFO 2020a). A comparison of catch caps from 30,000 t to 5,000 t showed no discernible gain in conservation performance under all 3 OM scenarios. Results also showed MPs with catch caps of 20,000 t or less rarely exceed the 20% harvest rate for any given projection year (over the 15 year projections).

In September 2020, the SoG OM was updated to include spawn survey data from 2018 to 2020 and biological data for 2018 and 2019 (DFO 2020c[1]). The updated closed-loop feedback simulations for the SoG show that MPs with harvest rates at 10, 15, and 20% maintain the spawning biomass above the LRP with 75 to 85% probability over all 3 OM scenarios (Table 31). MPs with harvest rate of 30% did not meet the conservation objective (p=69% for the Reference OM).

In the absence of fishing, spawning biomass in 2021 is forecast at 81,873 t (posterior median) and is forecast to be below the LRP of $0.3SB_0$ with 4.3% probability in the absence of fishing.

Harvest options for 2021, resulting from simulation-tested MPs, are presented in Table 31. These options reflect application of MPs to the 2021 forecast biomass for SoG, whereby each MP meets the conservation objective with a minimum 75% probability under the Reference OM (DDM) scenario. Harvest options under the two Robustness OM scenarios are also included. All MPs and scenarios listed in Table 31 include updated performance metrics for the four core objectives under all 3 scenarios(DFO 2020c[1]).

West Coast of Vancouver Island

The WCVI stock persisted in a low biomass, low productivity state from approximately 2004 to 2014. An increasing trend has been observed in recent years, with biomass remaining low relative to historical levels, trending around the LRP of $0.3SB_0$.

In 2018, closed-loop feedback simulations for the WCVI showed the conservation objective could be met under the Reference OM scenario with between 75 and 87%, but that these MPs failed to meet the conservation objective under the DIM Robustness OM scenario, where natural mortality rates are most similar to the last 10 years ($p = 56$ to 74%).

In September 2020, the WCVI OM was updated to include spawn survey data and biological data from 2018 to 2019 (DFO 2020c[1]). The updated closed-loop feedback simulations for the WCVI show that MPs with harvest rates of 5, 10, and 15% maintained the spawning biomass above the LRP with between 81 and 93% probability over all 3 OM scenarios (Table 32).

Improved MP performance in the 2020 update for WCVI, relative to the first WCVI MSE cycle, is due to increased spawn index in 2018 and 2019 and increased status relative to SB_0. Performance improvement is observed under all 3 scenarios.

In the absence of fishing, spawning biomass in 2021 is forecast at 16,005 t (posterior median) and is forecast to be below the LRP of $0.3SB_0$ with 37.0% probability in the absence of fishing.

Harvest options for 2021, resulting from simulation-tested MPs, are presented in Table 32. These options reflect application of MPs to the 2021 forecast biomass for WCVI, whereby each MP meets the conservation objective with a minimum 75% probability under the Reference OM (DDM) scenario. Harvest options under the two Robustness OM scenarios are also included. All MPs and scenarios listed in Table 32 include updated performance metrics for the four core objectives under all 3 scenarios (DFO 2020c[1]).

Conclusions

The 2020 Science Response includes a formal analyses of stock trend information for the Pacific Herring major SARs using the stock assessment framework reviewed in 2017 (Cleary et al. 2019) with the data time series updated to 2020

In the first MSE cycle for HG, none of the MPs tested could meet the conservation objective with at least 75% probability (DFO 2020a), thus harvest options are not provided for 2021. DFO has committed to developing and implementing a rebuilding plan for Haida Gwaii Herring by the end of fiscal year 2020/21, and supports commercial herring fishery closures for the HG major stock region until April 2021.

The MSE process identifies a range of MPs that meet the conservation objective with at least 75% probability for PRD, CC, SoG, and WCVI management areas for the Reference OM scenario (DFO (2020a); DFO 2020c[1]). As such, harvest options or MP calculations for 2021 for these SARs are provided using MPs that meet the minimum conservation criteria under the Reference OM scenario. Tables also include MP performance under the DIM and conM Robustness OM scenarios (Tables 29 to 32).

Science advice for the minor SARs is limited to presentation of catch data, biological data, and spawn survey data (Appendix).

Tables

Table 1. Input data for the 2020 Pacific Herring statistical catch-age model. The spawn index has two distinct periods defined by the dominant survey method: surface surveys (1951 to 1987), and dive surveys (1988 to 2020). Note: the 'spawn index' is not scaled by the spawn survey scaling parameter q.

Source	Data	Years
Roe gillnet fishery	Catch	1972 to 2020
Roe seine fishery	Catch	1972 to 2020
Other fisheries	Catch	1951 to 2020
Test fishery (Seine)	Biological: number-at-age	1975 to 2020
Test fishery (Seine)	Biological: weight-at-age	1975 to 2020
Roe seine fishery	Biological: number-at-age	1972 to 2020
Roe seine fishery	Biological: weight-at-age	1972 to 2020
Roe gillnet fishery	Biological: number-at-age	1972 to 2020
Other fisheries	Biological: number-at-age	1951 to 2020
Other fisheries	Biological: weight-at-age	1951 to 2020
Surface survey	Abundance: spawn index	1951 to 1987
Dive survey	Abundance: spawn index	1988 to 2020

Table 2. Total landed Pacific Herring catch in tonnes from 2011 to 2020 in the major stock assessment regions (SARs). Legend: Haida Gwaii (HG), Prince Rupert District (PRD), Central Coast (CC), Strait of Georgia (SoG), and West Coast of Vancouver Island (WCVI). Note: 'WP' indicates that data are withheld due to privacy concerns.

	SAR				
Year	HG	PRD	CC	SoG	WCVI
2011	0	2,147	0	5,128	0
2012	0	1,383	0	11,339	0
2013	0	2,027	0	16,547	0
2014	0	2,003	687	20,310	0
2015	0	2,163	626	19,968	0
2016	0	2,425	213	21,310	0
2017	0	2,849	0	25,279	0
2018	0	417	0	19,067	0
2019	0	0	0	21,419	0
2020	0	0	0	10,439	0

Table 3. Total Pacific Herring spawn-on-kelp harvest, reported as pounds of eggs on kelp, from 2011 to 2020 in the major stock assessment regions (SARs). Legend: Haida Gwaii (HG), Prince Rupert District (PRD), Central Coast (CC), Strait of Georgia (SoG), and West Coast of Vancouver Island (WCVI). Note: 'WP' indicates that data are withheld due to privacy concerns.

	SAR				
Year	**HG**	**PRD**	**CC**	**SoG**	**WCVI**
2011	0	123,626	0	0	0
2012	0	87,494	0	0	0
2013	0	72,895	0	0	0
2014	0	113,269	239,861	0	0
2015	0	84,066	169,470	0	0
2016	0	WP	351,953	0	0
2017	0	82,597	392,747	0	0
2018	0	20,832	286,109	0	0
2019	0	WP	356,042	0	0
2020	0	0	44,857	0	0

Table 4. Pacific Herring spawn index in tonnes, and proportion of the spawn index by Group from 2011 to 2020 in the Haida Gwaii major stock assessment region. Legend: 'Cumshewa' is Section 023; 'Juan Perez/Skincuttle' is Sections 021 and 025; 'Louscoone' is Section 006; and 'Selwyn' is Section 024. Note: the 'spawn index' is not scaled by the spawn survey scaling parameter q.

		Proportion		
Year	**Spawn index**	**006**	**021&025**	**023&024**
2011	7,554	0.026	0.749	0.226
2012	9,720	0.020	0.821	0.158
2013	16,025	0.079	0.864	0.057
2014	10,566	0.000	0.932	0.068
2015	13,102	0.000	0.940	0.060
2016	6,888	0.000	0.947	0.053
2017	3,016	0.000	0.982	0.018
2018	4,588	0.000	0.766	0.234
2019	11,624	0.016	0.919	0.065
2020	20,423	0.000	0.923	0.077

Table 5. Pacific Herring spawn index in tonnes, and proportion of the spawn index by Statistical Area from 2011 to 2020 in the Prince Rupert District major stock assessment region. See Table 4 for description.

		Proportion		
Year	**Spawn index**	**03**	**04**	**05**
2011	21,097	0.022	0.757	0.220
2012	22,716	0.038	0.774	0.188
2013	25,755	0.026	0.750	0.224
2014	17,125	0.148	0.595	0.257
2015	17,407	0.056	0.756	0.188
2016	18,985	0.007	0.808	0.185
2017	19,235	0.052	0.632	0.317
2018	14,155	0.057	0.667	0.277
2019	27,190	0.010	0.452	0.538
2020	25,845	0.026	0.542	0.432

Table 6. Pacific Herring spawn index in tonnes, and proportion of the spawn index by Statistical Area from 2011 to 2020 in the Central Coast major stock assessment region. See Table 4 for description.

		Proportion		
Year	**Spawn index**	**06**	**07**	**08**
2011	10,534	0.241	0.645	0.114
2012	7,592	0.216	0.575	0.209
2013	20,369	0.217	0.777	0.006
2014	13,309	0.287	0.673	0.040
2015	32,146	0.223	0.706	0.072
2016	32,508	0.245	0.726	0.028
2017	23,517	0.359	0.584	0.057
2018	12,264	0.322	0.626	0.052
2019	46,255	0.323	0.641	0.036
2020	42,713	0.417	0.550	0.033

Table 7. Pacific Herring spawn index in tonnes, and proportion of the spawn index by Group from 2011 to 2020 in the Strait of Georgia major stock assessment region. Legend: '14&17' is Statistical Areas 14 and 17 (excluding Section 173); 'ESoG' is eastern Strait of Georgia; 'Lazo' is above Cape Lazo; and 'SDodd' is South of Dodd Narrows. See Table 4 for description.

		Proportion			
Year	**Spawn index**	**14&17**	**ESoG**	**Lazo**	**SDodd**
2011	85,001	0.984	0.000	0.000	0.016
2012	52,636	0.855	0.009	0.084	0.052
2013	83,693	0.928	0.000	0.055	0.016
2014	120,468	0.758	0.020	0.212	0.010
2015	104,481	0.525	0.014	0.354	0.106
2016	129,502	0.902	0.000	0.090	0.009
2017	81,064	0.806	0.000	0.194	0.000
2018	91,939	0.984	0.001	0.014	0.000
2019	63,038	0.985	0.001	0.014	0.000
2020	116,151	0.758	0.109	0.126	0.007

Table 8. Pacific Herring spawn index in tonnes, and proportion of the spawn index by Statistical Area from 2011 to 2020 in the West Coast of Vancouver Island major stock assessment region. See Table 4 for description.

		Proportion		
Year	**Spawn index**	**23**	**24**	**25**
2011	9,663	0.267	0.299	0.434
2012	5,407	0.069	0.368	0.563
2013	12,258	0.337	0.061	0.602
2014	13,937	0.631	0.093	0.276
2015	11,323	0.372	0.185	0.442
2016	20,528	0.577	0.266	0.157
2017	15,734	0.335	0.097	0.568
2018	28,107	0.331	0.194	0.475
2019	17,030	0.228	0.163	0.610
2020	18,761	0.562	0.288	0.150

Table 9. Posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates of key parameters for the Pacific Herring statistical catch-age model in the Haida Gwaii major stock assessment region. Legend: R_0 is unfished age-2 recruitment; h is steepness of the stock-recruitment relationship; M is instantaneous natural mortality rate; $\overline{R}$ is average age-2 recruitment from 1951 to 2020; $\overline{R}_{init}$ is average age-2 recruitment in 1950; ρ is the fraction of total variance associated with observation error; ϑ is the precision of total error; q is catchability for surface (1951 to 1987; q_1) and dive (1988 to 2020; q_2) survey periods; τ is the standard deviation of process error (i.e., recruitment); and σ is the standard deviation of observation error (i.e., survey index). Note: τ and σ are calculated values.

Parameter	5%	50%	95%	MPD
R_0	211.586	278.472	383.792	286.585
h	0.659	0.788	0.894	0.806
M	0.230	0.406	0.683	0.377
$\overline{R}$	143.534	174.155	210.607	185.278
$\overline{R}_{init}$	9.229	31.002	166.202	33.405
ρ	0.215	0.274	0.344	0.262
ϑ	0.782	0.945	1.142	1.021
q_1	0.332	0.408	0.498	0.394
q_2	0.982	0.999	1.016	0.999
τ	0.779	0.874	0.978	0.851
σ	0.470	0.538	0.613	0.506

Table 10. Posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates of key parameters for the Pacific Herring statistical catch-age model in the Prince Rupert District major stock assessment region. See Table 9 for description.

Parameter	5%	50%	95%	MPD
R_0	240.901	316.701	482.373	306.528
h	0.529	0.687	0.842	0.716
M	0.249	0.450	0.774	0.426
$\overline{R}$	163.528	190.820	223.119	198.618
$\overline{R}_{init}$	63.841	212.149	1,146.095	247.714
ρ	0.214	0.283	0.365	0.279
ϑ	0.957	1.179	1.426	1.260
q_1	0.481	0.563	0.659	0.552
q_2	0.985	1.001	1.018	1.001
τ	0.691	0.778	0.882	0.756
σ	0.423	0.489	0.570	0.471

Table 11. Posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates of key parameters for the Pacific Herring statistical catch-age model in the Central Coast major stock assessment region. See Table 9 for description.

Parameter	5%	50%	95%	MPD
R_0	313.897	395.644	517.709	384.444
h	0.675	0.804	0.903	0.824
M	0.278	0.485	0.802	0.446
$\overline{R}$	233.170	262.312	297.587	263.012
$\overline{R}_{init}$	56.231	205.911	1,168.956	257.919
ρ	0.179	0.242	0.316	0.222
ϑ	1.004	1.211	1.451	1.287
q_1	0.282	0.326	0.373	0.330
q_2	0.983	0.999	1.016	0.999
τ	0.706	0.790	0.884	0.778
σ	0.384	0.446	0.519	0.415

Table 12. Posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates of key parameters for the Pacific Herring statistical catch-age model in the Strait of Georgia major stock assessment region. See Table 9 for description.

Parameter	5%	50%	95%	MPD
R_0	1,372.197	1,701.495	2,239.026	1,626.890
h	0.582	0.731	0.867	0.763
M	0.265	0.470	0.804	0.450
$\overline{R}$	975.035	1,113.005	1,284.721	1,132.280
$\overline{R}_{init}$	44.925	168.308	1,073.714	269.926
ρ	0.214	0.283	0.366	0.273
ϑ	1.214	1.490	1.798	1.587
q_1	0.850	1.014	1.183	1.011
q_2	0.984	0.999	1.016	0.999
τ	0.614	0.691	0.786	0.677
σ	0.376	0.436	0.503	0.414

Table 13. Posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates of key parameters for the Pacific Herring statistical catch-age model in the West Coast of Vancouver Island major stock assessment region. See Table 9 for description.

Parameter	5%	50%	95%	MPD
R_0	443.919	565.524	760.813	555.285
h	0.604	0.731	0.852	0.741
M	0.343	0.607	0.994	0.582
$\overline{R}$	325.828	372.458	432.218	376.430
$\overline{R}_{init}$	33.231	164.769	1,227.907	260.607
ρ	0.238	0.309	0.390	0.298
ϑ	1.061	1.286	1.552	1.388
q_1	0.699	0.837	0.989	0.848
q_2	0.982	0.999	1.016	0.999
τ	0.646	0.732	0.826	0.711
σ	0.425	0.489	0.562	0.463

Table 14. Posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates of age-2 recruitment (millions) from 2011 to 2020 for the Pacific Herring statistical catch-age model in the Haida Gwaii major stock assessment region.

Year	5%	50%	95%	MPD
2011	104.669	152.721	219.935	158.291
2012	436.988	613.458	853.497	635.131
2013	56.318	83.611	124.036	86.487
2014	87.913	131.920	196.117	136.594
2015	61.407	90.978	133.390	94.328
2016	126.689	184.652	271.499	193.075
2017	177.709	262.786	388.369	273.599
2018	32.366	59.685	106.286	59.189
2019	544.017	922.670	1,494.497	977.149
2020	43.256	166.815	573.342	176.281

Table 15. Posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates of age-2 recruitment (millions) from 2011 to 2020 for the Pacific Herring statistical catch-age model in the Prince Rupert District major stock assessment region.

Year	5%	50%	95%	MPD
2011	110.798	154.742	218.567	160.834
2012	165.922	229.947	318.514	238.742
2013	57.216	82.709	119.026	86.221
2014	302.245	430.393	601.589	449.167
2015	136.717	198.125	283.896	207.054
2016	65.179	102.917	157.713	106.653
2017	219.362	325.992	493.125	337.644
2018	440.542	661.917	993.308	676.723
2019	31.979	73.975	150.677	75.344
2020	47.802	139.242	361.309	141.884

Table 16. Posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates of age-2 recruitment (millions) from 2011 to 2020 for the Pacific Herring statistical catch-age model in the Central Coast major stock assessment region.

Year	5%	50%	95%	MPD
2011	97.274	127.378	166.594	129.918
2012	293.856	382.053	505.332	387.153
2013	120.392	160.211	214.410	162.373
2014	347.632	462.612	612.253	474.001
2015	114.316	154.100	207.884	157.210
2016	129.821	174.182	232.840	179.042
2017	171.301	230.614	312.942	236.288
2018	759.860	1,045.035	1,427.240	1,068.110
2019	58.150	91.726	143.975	90.665
2020	263.515	431.406	704.108	422.849

Table 17. Posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates of age-2 recruitment (millions) from 2011 to 2020 for the Pacific Herring statistical catch-age model in the Strait of Georgia major stock assessment region.

Year	5%	50%	95%	MPD
2011	1,211.714	1,536.305	1,936.326	1,550.830
2012	676.302	864.974	1,115.089	877.757
2013	1,200.713	1,545.335	1,957.615	1,561.860
2014	1,276.667	1,638.010	2,115.678	1,656.510
2015	1,085.312	1,412.005	1,828.821	1,431.830
2016	972.751	1,287.365	1,689.215	1,319.250
2017	1,000.934	1,354.150	1,813.165	1,394.130
2018	1,077.779	1,482.605	2,008.077	1,519.520
2019	2,726.630	3,753.780	5,279.273	3,843.830
2020	1,941.690	2,974.110	4,476.720	2,965.210

Table 18. Posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates of age-2 recruitment (millions) from 2011 to 2020 for the Pacific Herring statistical catch-age model in the West Coast of Vancouver Island major stock assessment region.

Year	5%	50%	95%	MPD
2011	77.953	108.226	149.399	108.145
2012	91.942	126.676	176.227	127.107
2013	226.815	312.196	429.304	315.743
2014	175.668	244.244	331.787	247.089
2015	626.544	839.246	1,107.183	855.444
2016	94.362	129.824	176.231	132.411
2017	98.074	138.529	194.366	141.307
2018	308.892	438.751	630.524	448.650
2019	226.712	339.115	496.404	345.391
2020	633.904	1,029.105	1,661.937	1,037.650

Table 19. Posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates of spawning biomass in thousands of tonnes and depletion (i.e., relative spawning biomass SB_t/SB_0, where SB_t is spawning biomass in year t, and SB_0 is estimated unfished spawning biomass) from 2011 to 2020 for the Pacific Herring statistical catch-age model in the Haida Gwaii major stock assessment region.

	Spawning biomass				Depletion			
Year	5%	50%	95%	MPD	5%	50%	95%	MPD
2011	5.682	7.514	9.662	7.534	0.222	0.328	0.468	0.341
2012	7.973	10.595	13.803	10.682	0.313	0.463	0.664	0.484
2013	10.930	14.688	19.714	14.906	0.430	0.644	0.936	0.675
2014	7.833	10.453	13.908	10.543	0.308	0.457	0.662	0.477
2015	5.058	6.815	9.031	6.822	0.202	0.300	0.430	0.309
2016	3.525	4.837	6.464	4.795	0.142	0.212	0.303	0.217
2017	3.943	5.528	7.502	5.450	0.159	0.241	0.353	0.247
2018	3.500	5.141	7.359	4.959	0.144	0.224	0.337	0.225
2019	5.660	8.755	13.183	8.638	0.239	0.383	0.601	0.391
2020	7.852	14.846	26.952	14.418	0.344	0.650	1.204	0.653

Table 20. Posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates of spawning biomass in thousands of tonnes and depletion from 2011 to 2020 for the Pacific Herring statistical catch-age model in the Prince Rupert District major stock assessment region. See Table 19 for description.

	Spawning biomass				Depletion			
Year	**5%**	**50%**	**95%**	**MPD**	**5%**	**50%**	**95%**	**MPD**
2011	14.530	18.157	22.934	18.506	0.187	0.305	0.445	0.335
2012	13.409	16.798	21.140	17.153	0.170	0.281	0.411	0.311
2013	13.545	16.869	21.300	17.279	0.172	0.284	0.417	0.313
2014	12.936	16.040	20.063	16.392	0.165	0.270	0.386	0.297
2015	15.300	19.239	24.140	19.608	0.196	0.323	0.463	0.355
2016	13.587	17.327	22.204	17.410	0.178	0.289	0.422	0.316
2017	12.207	16.255	21.545	15.938	0.163	0.271	0.402	0.289
2018	15.120	20.546	27.880	19.706	0.212	0.341	0.503	0.357
2019	20.767	30.241	43.896	28.516	0.307	0.502	0.761	0.517
2020	15.767	27.552	45.625	25.223	0.243	0.452	0.777	0.457

Table 21. Posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates of spawning biomass in thousands of tonnes and depletion from 2011 to 2020 for the Pacific Herring statistical catch-age model in the Central Coast major stock assessment region. See Table 19 for description.

	Spawning biomass				Depletion			
Year	**5%**	**50%**	**95%**	**MPD**	**5%**	**50%**	**95%**	**MPD**
2011	8.051	10.085	12.731	10.177	0.135	0.189	0.260	0.198
2012	7.517	9.455	11.918	9.572	0.126	0.176	0.244	0.186
2013	11.418	14.396	18.144	14.604	0.190	0.270	0.372	0.284
2014	11.985	15.151	19.053	15.420	0.199	0.284	0.391	0.300
2015	14.922	19.069	24.013	19.404	0.250	0.356	0.489	0.377
2016	15.199	19.474	24.572	19.700	0.256	0.364	0.501	0.383
2017	15.708	20.325	25.698	20.370	0.267	0.379	0.525	0.396
2018	18.783	24.408	31.419	24.159	0.324	0.455	0.625	0.470
2019	28.546	39.281	53.401	38.237	0.505	0.730	1.048	0.744
2020	22.392	37.592	59.937	35.679	0.413	0.699	1.130	0.694

Table 22. Posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates of spawning biomass in thousands of tonnes and depletion from 2011 to 2020 for the Pacific Herring statistical catch-age model in the Strait of Georgia major stock assessment region. See Table 19 for description.

	Spawning biomass				Depletion			
Year	5%	50%	95%	MPD	5%	50%	95%	MPD
2011	57.232	68.001	80.891	67.984	0.333	0.494	0.659	0.520
2012	60.798	72.172	85.486	72.055	0.354	0.523	0.695	0.551
2013	56.658	67.532	80.556	67.535	0.331	0.491	0.656	0.516
2014	63.737	75.917	90.457	76.307	0.369	0.551	0.736	0.584
2015	62.825	74.374	88.103	75.008	0.362	0.540	0.718	0.574
2016	64.617	76.962	91.905	77.942	0.379	0.558	0.746	0.596
2017	57.488	70.092	86.232	71.288	0.344	0.507	0.692	0.545
2018	56.146	69.596	87.843	70.368	0.343	0.502	0.688	0.538
2019	59.411	79.294	106.420	78.374	0.380	0.573	0.809	0.599
2020	51.926	89.869	149.254	85.414	0.352	0.637	1.097	0.653

Table 23. Posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates of spawning biomass in thousands of tonnes and depletion from 2011 to 2020 for the Pacific Herring statistical catch-age model in the West Coast of Vancouver Island major stock assessment region. See Table 19 for description.

	Spawning biomass				Depletion			
Year	5%	50%	95%	MPD	5%	50%	95%	MPD
2011	5.526	7.140	9.338	7.138	0.107	0.156	0.223	0.161
2012	5.193	6.755	8.863	6.777	0.101	0.148	0.212	0.153
2013	6.116	7.963	10.284	7.963	0.119	0.173	0.245	0.179
2014	8.829	11.463	14.715	11.558	0.172	0.249	0.353	0.260
2015	12.656	16.327	20.822	16.552	0.246	0.355	0.499	0.373
2016	17.322	22.698	29.694	23.079	0.341	0.498	0.702	0.520
2017	13.788	18.299	24.493	18.491	0.274	0.402	0.567	0.416
2018	12.450	16.650	22.227	16.535	0.250	0.363	0.511	0.372
2019	11.794	16.612	23.429	16.245	0.242	0.362	0.525	0.366
2020	10.002	18.254	32.644	17.543	0.216	0.395	0.709	0.395

Table 24. Posterior (5th, 50th, and 95th percentile) estimates of proposed reference points for the Pacific Herring statistical catch-age model in the Haida Gwaii major stock assessment region. All biomass numbers are in thousands of tonnes. Legend: SB_0 is estimated unfished spawning biomass; SB_t is spawning biomass in year t; and SB_{2021} is projected spawning biomass in 2021 assuming no fishing.

Reference point	5%	50%	95%
SB_0	18.290	22.759	29.632
$0.3SB_0$	5.487	6.828	8.889
SB_{2020}	7.852	14.846	26.952
SB_{2020}/SB_0	0.344	0.650	1.204
$SB_{2020}/0.3SB_0$	1.148	2.166	4.012
$P(SB_{2020} < 0.3SB_0)$	–	0.025	–
SB_{2021}	5.311	11.285	24.951
SB_{2021}/SB_0	0.233	0.492	1.072
$SB_{2021}/0.3SB_0$	0.775	1.638	3.572
$P(SB_{2021} < 0.3SB_0)$	–	0.140	–
$P(SB_{2021} < 0.6SB_0)$	–	0.663	–
Proportion aged 3	0.05	0.19	0.53
Proportion aged 4-10	0.36	0.66	0.87

Table 25. Posterior (5th, 50th, and 95th percentile) estimates of proposed reference points for the Pacific Herring statistical catch-age model in the Prince Rupert District major stock assessment region. See Table 24 for description.

Reference point	5%	50%	95%
SB_0	45.629	59.182	90.486
$0.3SB_0$	13.689	17.755	27.146
SB_{2020}	15.767	27.552	45.625
SB_{2020}/SB_0	0.243	0.452	0.777
$SB_{2020}/0.3SB_0$	0.810	1.507	2.591
$P(SB_{2020} < 0.3SB_0)$	–	0.131	–
SB_{2021}	15.620	29.698	54.712
SB_{2021}/SB_0	0.254	0.486	0.912
$SB_{2021}/0.3SB_0$	0.846	1.621	3.039
$P(SB_{2021} < 0.3SB_0)$	–	0.114	–
$P(SB_{2021} < 0.6SB_0)$	–	0.708	–
Proportion aged 3	0.05	0.18	0.48
Proportion aged 4-10	0.46	0.74	0.90

Table 26. Posterior (5th, 50th, and 95th percentile) estimates of proposed reference points for the Pacific Herring statistical catch-age model in the Central Coast major stock assessment region. See Table 24 for description.

Reference point	5%	50%	95%
SB_0	43.002	53.471	68.383
$0.3SB_0$	12.901	16.041	20.515
SB_{2020}	22.392	37.592	59.937
SB_{2020}/SB_0	0.413	0.699	1.130
$SB_{2020}/0.3SB_0$	1.376	2.330	3.768
$P(SB_{2020} < 0.3SB_0)$	–	0.006	–
SB_{2021}	19.209	35.770	65.349
SB_{2021}/SB_0	0.360	0.668	1.199
$SB_{2021}/0.3SB_0$	1.200	2.227	3.997
$P(SB_{2021} < 0.3SB_0)$	–	0.019	–
$P(SB_{2021} < 0.6SB_0)$	–	0.385	–
Proportion aged 3	0.06	0.20	0.51
Proportion aged 4-10	0.43	0.71	0.88

Table 27. Posterior (5th, 50th, and 95th percentile) estimates of proposed reference points for the Pacific Herring statistical catch-age model in the Strait of Georgia major stock assessment region. See Table 24 for description.

Reference point	5%	50%	95%
SB_0	110.309	137.447	193.386
$0.3SB_0$	33.093	41.234	58.016
SB_{2020}	51.926	89.869	149.254
SB_{2020}/SB_0	0.352	0.637	1.097
$SB_{2020}/0.3SB_0$	1.173	2.123	3.658
$P(SB_{2020} < 0.3SB_0)$	–	0.018	–
SB_{2021}	44.526	81.873	155.580
SB_{2021}/SB_0	0.308	0.591	1.109
$SB_{2021}/0.3SB_0$	1.028	1.970	3.696
$P(SB_{2021} < 0.3SB_0)$	–	0.043	–
$P(SB_{2021} < 0.6SB_0)$	–	0.517	–
Proportion aged 3	0.08	0.23	0.50
Proportion aged 4-10	0.39	0.64	0.82

Table 28. Posterior (5th, 50th, and 95th percentile) estimates of proposed reference points for the Pacific Herring statistical catch-age model in the West Coast of Vancouver Island major stock assessment region. See Table 24 for description.

Reference point	5%	50%	95%
SB_0	36.907	45.784	58.776
$0.3SB_0$	11.072	13.735	17.633
SB_{2020}	10.002	18.254	32.644
SB_{2020}/SB_0	0.216	0.395	0.709
$SB_{2020}/0.3SB_0$	0.719	1.318	2.364
$P(SB_{2020} < 0.3SB_0)$	–	0.228	–
SB_{2021}	7.651	16.005	34.031
SB_{2021}/SB_0	0.167	0.344	0.731
$SB_{2021}/0.3SB_0$	0.557	1.148	2.435
$P(SB_{2021} < 0.3SB_0)$	–	0.370	–
$P(SB_{2021} < 0.6SB_0)$	–	0.884	–
Proportion aged 3	0.12	0.34	0.65
Proportion aged 4-10	0.21	0.43	0.68

Table 29. Management procedure (MP) performance for the Pacific Herring statistical catch-age model in the Prince Rupert District major stock assessment region under three operating model (OM) scenarios: density-dependent natural mortality (DDM), density-independent natural mortality (DIM), and constant natural mortality (conM). 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. The recommended total allowable catch (TAC) in thousands of tonnes (t) and associated harvest rate (HR) are reported for each MP. Legend: limit reference point (LRP); P is probability; maximum (max); SB_t is spawning biomass in year t; SB_0 is estimated unfished spawning biomass; average annual variability (AAV); and $\overline{C}$ is average catch. MPs are defined in DFO (2019a) and DFO (2020a). Performance criteria $SB_t >= 0.4SB_0$ is proposed by the Herring Industry Advisory Board (HIAB) as a biomass target at $P >= 50\%$ level. Note: dashes indicate that TAC and HR do not apply, either because the MP specifies no fishing at current projected biomass level, or because the MP fails to meet Objective 1.

Scenario		Conservation	Biomass		Yield			
		Obj 1 (LRP)	HIAB	Obj 2	Obj 3	Obj 4		
		$P \geq 75\%$	$P \geq 50\%$	$P \geq 50\%$	$< 25\%$	max	**2021**	
OM	**MP**	$SB_t > 0.3SB_0$	$\geq 0.4SB_0$	$\geq 0.6SB_0$	AAV	$\overline{C}$	**TAC**	**HR**
DDM	NoFish_FSC	78%	67%	42%	0.00	0.14	–	–
DDM	HS30-60_HR0.05	78%	64%	40%	36.50	1.28	0.91	0.03
DDM	HS50-60_HR0.2_cap2.5	78%	64%	40%	39.43	1.43	0.00	0.00
DDM	minE0.5B0_HR0.1	78%	63%	37%	51.86	1.85	0.00	0.00
DDM	HS30-60_HR0.1_cap2.5	77%	62%	38%	33.35	1.64	1.81	0.06
DDM	minE0.5B0_HR0.2	76%	59%	28%	67.14	2.71	0.00	0.00
DIM	HS30-60_HR.05	66%	49%	27%	41.91	0.97	–	–
DIM	HS50-60_HR.2_cap2.5	66%	50%	27%	41.89	0.94	–	–
DIM	minE.5B0_HR.1	66%	48%	24%	57.00	1.20	–	–
DIM	NoFish_FSC	65%	52%	32%	0.00	0.14	–	–
DIM	HS30-60_HR.1_cap2.5	65%	47%	26%	41.46	1.43	–	–
DIM	minE.5B0_HR.2	63%	43%	18%	75.94	1.56	–	–
conM	NoFish_FSC	100%	97%	72%	0.00	0.14	–	–
conM	HS50-60_HR.2_cap2.5	100%	94%	66%	40.10	1.76	0.00	0.00
conM	HS30-60_HR.05	100%	94%	65%	37.00	2.02	0.91	0.03
conM	HS30-60_HR.1_cap2.5	99%	94%	63%	24.63	2.12	1.81	0.06
conM	minE.5B0_HR.1	98%	92%	58%	52.45	3.11	0.00	0.00
conM	minE.5B0_HR.2	96%	84%	43%	62.26	5.17	0.00	0.00

Table 30. Management procedure performance for the Pacific Herring statistical catch-age model in the Central Coast major stock assessment region. See Table 29 for description.

		Conservation	**Biomass**		**Yield**			
	Scenario	**Obj 1 (LRP)**	**HIAB**	**Obj 2**	**Obj 3**	**Obj 4**		
		$P \geq 75\%$	$P \geq 50\%$	$P \geq 50\%$	$< 25\%$	max	**2021**	
OM	**MP**	$SB_t > 0.3SB_0$	$\geq 0.4SB_0$	$\geq 0.6SB_0$	AAV	$\overline{C}$	**TAC**	**HR**
DDM	NoFish_FSC	77%	62%	39%	0.00	0.14	–	–
DDM	HS30-60_HR0.05	77%	63%	37%	39.92	1.09	1.76	0.05
DDM	minE0.5B0_HR0.1	76%	62%	33%	52.30	1.54	3.55	0.10
DDM	HS30-60_HR0.1_cap5.0	75%	61%	32%	46.10	1.81	3.52	0.10
DIM	NoFish_FSC	57%	42%	19%	0.00	0.14	–	–
DIM	HS30-60_HR.05	55%	38%	17%	40.94	0.66	–	–
DIM	minE.5B0_HR.1	55%	36%	15%	44.30	0.78	–	–
DIM	HS30-60_HR.1_cap5.0	52%	35%	14%	53.32	1.00	–	–
conM	NoFish_FSC	100%	99%	84%	0.00	0.14	–	–
conM	HS30-60_HR.05	99%	97%	75%	39.69	2.68	1.76	0.05
conM	HS30-60_HR.1_cap5.0	99%	94%	69%	26.62	3.93	3.52	0.10
conM	minE.5B0_HR.1	98%	94%	67%	45.77	4.62	3.55	0.10

Table 31. Management procedure performance for the Pacific Herring statistical catch-age model in the Strait of Georgia major stock assessment region. See Table 29 for description.

		Conservation	Biomass		Yield			
	Scenario	**Obj 1 (LRP)**	**HIAB**	**Obj 2**	**Obj 3**	**Obj 4**		
		$P \geq 75\%$	$P \geq 50\%$	$P \geq 50\%$	$< 25\%$	max	**2021**	
OM	**MP**	$SB_t > 0.3SB_0$	$\geq 0.4SB_0$	$\geq 0.6SB_0$	AAV	$\overline{C}$	**TAC**	**HR**
DDM	NoFish_FSC	88%	78%	53%	0.00	0.14	–	–
DDM	HS30-60_HR.1	85%	71%	45%	50.73	6.16	7.54	0.10
DDM	minE-LRP_HR.1	83%	69%	43%	38.21	7.24	8.18	0.10
DDM	HS30-60_HR.15	83%	68%	39%	48.59	8.51	11.31	0.15
DDM	HS30-60_HR0.2	82%	64%	33%	49.67	10.62	15.08	0.19
DDM	minE-LRP_HR.2	77%	60%	30%	43.51	12.60	16.33	0.20
DIM	NoFish_FSC	85%	74%	55%	0.00	0.14	–	–
DIM	HS30-60_HR.1	82%	70%	46%	50.16	6.14	7.54	0.10
DIM	minE-LRP_HR.1	81%	69%	45%	39.53	7.06	8.18	0.10
DIM	HS30-60_HR.15	80%	67%	40%	48.34	8.54	11.31	0.15
DIM	HS30-60_HR0.2	78%	64%	35%	50.93	10.65	15.08	0.19
DIM	minE-LRP_HR.2	75%	61%	33%	42.84	12.38	16.33	0.20
conM	NoFish_FSC	100%	100%	93%	0.00	0.14	–	–
conM	HS30-60_HR.1	100%	99%	82%	36.74	10.76	7.54	0.10
conM	minE-LRP_HR.1	100%	98%	81%	30.37	11.25	8.18	0.10
conM	HS30-60_HR.15	100%	97%	75%	37.62	15.30	11.31	0.15
conM	HS30-60_HR0.2	99%	94%	66%	38.95	19.42	15.08	0.19
conM	minE-LRP_HR.2	98%	93%	63%	32.79	20.31	16.33	0.20

Table 32. Management procedure performance for the Pacific Herring statistical catch-age model in the West Coast of Vancouver Island major stock assessment region. See Table 29 for description. In addition, SB_{AVE} is average spawning biomass from 1990 to 1999, calculated over two Pacific Herring generations. Performance criteria $SB_t >= 0.65SB_0$, $SB_t >= 0.75SB_0$, and $SB_t >= SB_{\text{AVE}}$ are proposed by the Nuu-chah-nulth Nations (NCN) as biomass targets at $P >= 50\%$ and $P >= 75\%$ levels.

Scenario		Conservation	Biomass					Yield			
		Obj 1 (LRP)	HIAB	Obj 2	NCN			Obj 3	Obj 4		
		$P \geq 75\%$	$P \geq 50\%$	$P \geq 50\%$	$P \geq 50\%$	$P \geq 50\%$	$P \geq 75\%$	$< 25\%$	max	2021	
OM	**MP**	$SB_t > 0.3SB_0$	$\geq 0.4SB_0$	$\geq 0.6SB_0$	$\geq 0.65SB_0$	$\geq 0.75SB_0$	$\geq SB_{\text{AVE}}$	AAV	$\overline{C}$	**TAC**	**HR**
DDM	NoFish_FSC	92%	86%	67%	63%	52%	64%	0.00	0.14	–	–
DDM	minE-LRP_HR.05	92%	82%	61%	56%	45%	56%	43.83	1.59	0.77	0.05
DDM	HS50-60_HR.1	92%	83%	58%	52%	40%	48%	55.74	2.47	0.00	0.00
DDM	HS30-60_HR.10_cap2.0	91%	83%	62%	55%	45%	55%	34.71	1.60	0.23	0.01
DDM	HS30-60_HR.15_cap2.0	91%	83%	61%	55%	45%	55%	26.38	1.74	0.35	0.02
DDM	HS50-60_HR.15	91%	81%	53%	47%	34%	42%	60.80	3.38	0.00	0.00
DDM	consTAC1.0	90%	83%	63%	57%	47%	58%	6.77	1.26	0.00	0.00
DIM	NoFish_FSC	85%	74%	52%	47%	36%	35%	0.00	0.14	–	–
DIM	minE-LRP_HR.05	83%	71%	47%	41%	32%	29%	48.76	1.39	0.77	0.05
DIM	HS30-60_HR.10_cap2.0	83%	70%	46%	41%	31%	29%	46.91	1.46	0.23	0.01
DIM	HS50-60_HR.1	83%	70%	45%	39%	28%	26%	64.52	1.83	0.00	0.00
DIM	HS30-60_HR.15_cap2.0	82%	70%	47%	41%	32%	29%	44.24	1.40	0.35	0.02
DIM	HS50-60_HR.15	82%	69%	40%	35%	23%	21%	67.62	2.54	0.00	0.00
DIM	consTAC1.0	81%	70%	48%	42%	32%	31%	6.98	1.25	0.00	0.00
conM	NoFish_FSC	94%	84%	58%	53%	41%	98%	0.00	0.14	–	–
conM	consTAC1.0	93%	81%	56%	49%	39%	96%	6.67	1.26	0.00	0.00
conM	HS30-60_HR.10_cap2.0	93%	81%	54%	48%	38%	95%	24.51	1.85	0.23	0.01
conM	HS30-60_HR.15_cap2.0	93%	80%	54%	48%	38%	95%	21.03	1.92	0.35	0.02
conM	minE-LRP_HR.05	93%	80%	53%	46%	37%	95%	45.12	2.76	0.77	0.05
conM	HS50-60_HR.1	91%	77%	47%	40%	31%	92%	49.69	5.01	0.00	0.00
conM	HS50-60_HR.15	89%	74%	41%	36%	26%	89%	51.66	7.29	0.00	0.00

Figures

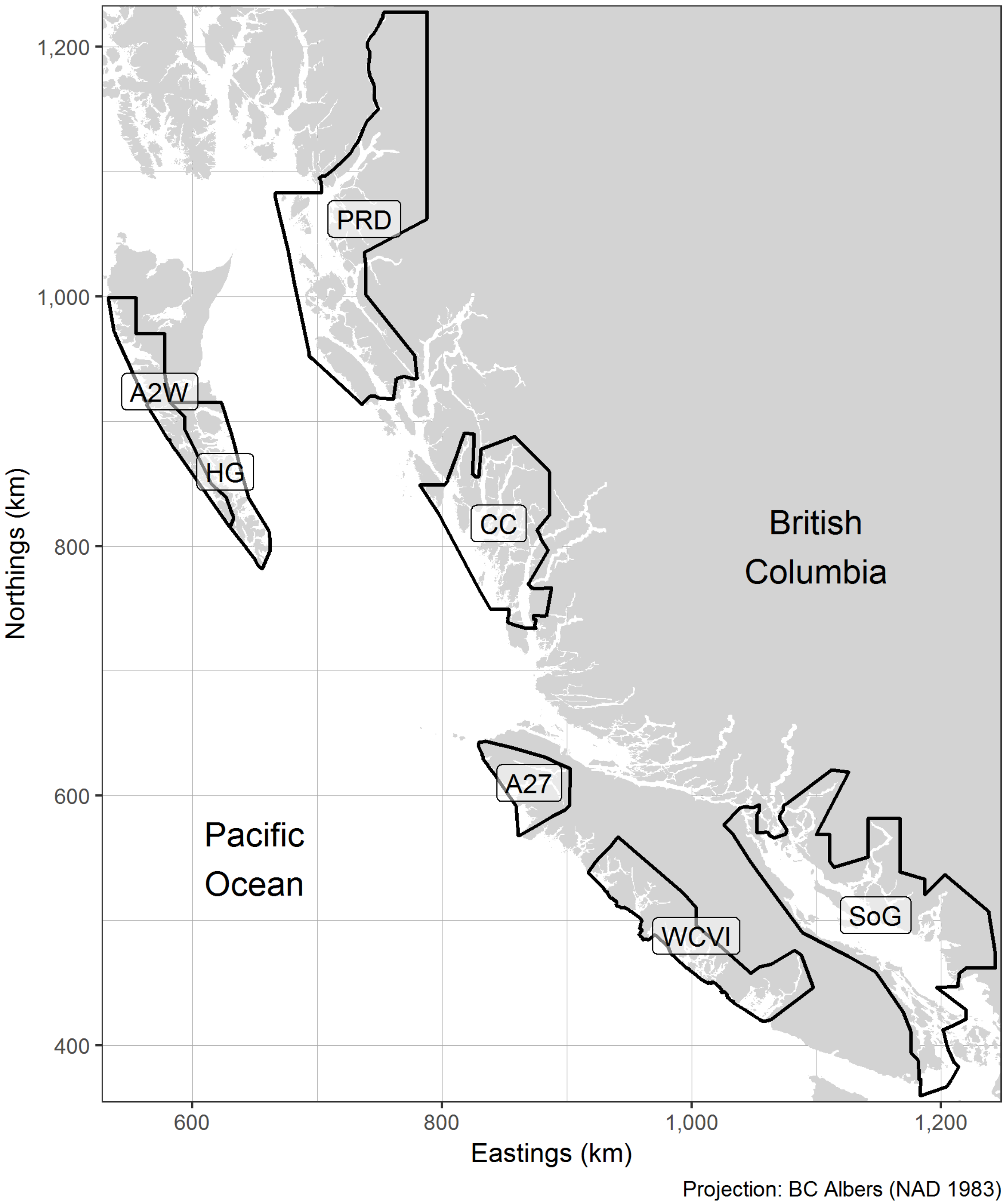

Figure 1. Boundaries for the Pacific Herring stock assessment regions (SARs) in British Columbia. The major SARs are Haida Gwaii (HG), Prince Rupert District (PRD), Central Coast (CC), Strait of Georgia (SoG), and West Coast of Vancouver Island (WCVI). The minor SARs are Area 27 (A27) and Area 2 West (A2W). Units: kilometres (km).

Figure 2. Time series of total landed Pacific Herring catch in thousands of tonnes (t) from 1972 to 2020 in the major stock assessment regions. See Figures 6 to 11 for catches during the reduction period (1951 to 1971). Legend: 'Other' represents the reduction, the food and bait, as well as the special use fishery; 'RoeGN' represents the roe gillnet fishery; and 'RoeSN' represents the roe seine fishery.

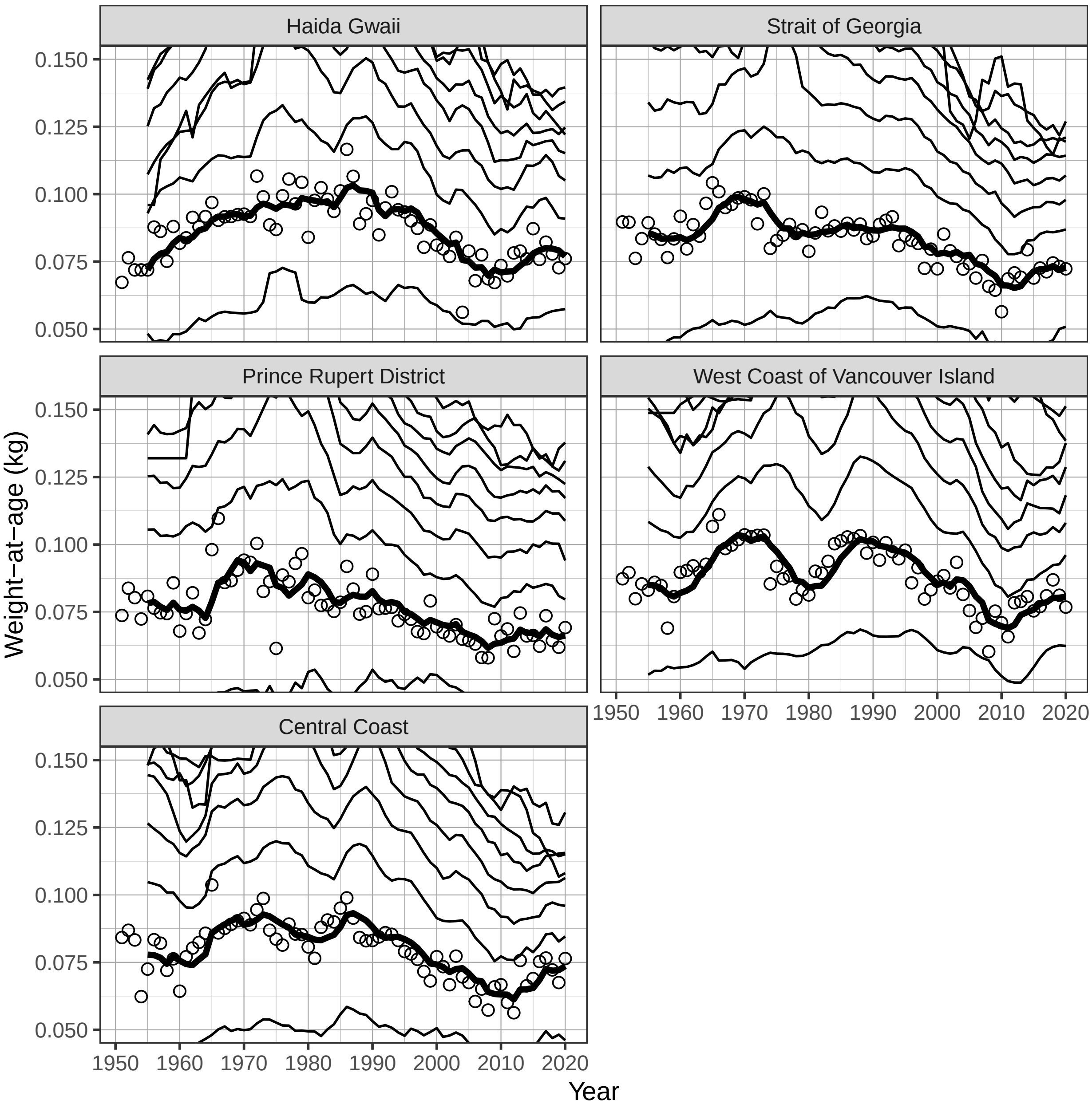

Figure 3. Time series of Pacific Herring weight-at-age in kilograms (kg) for age-3 (circles) and 5-year running mean weight-at-age (lines) from 1951 to 2020 in the major stock assessment regions. Lines show 5-year running means for age-2 to age-10 herring (incrementing up from bottom line); the thick black line highlights age-3 herring. Missing weight-at-age values (i.e., years where there are no biological samples) are imputed using one of two methods: values at the beginning of the time series are imputed by extending the first non-missing value backwards; other values are imputed as the mean of the previous 5 years. Biological summaries only include samples collected using seine nets (commercial and test) due to size-selectivity of other gear types such as gillnet. The age-10 class is a 'plus group' which includes fish ages 10 and older. Note: vertical axes are cropped at 0.05 and 0.15 kg.

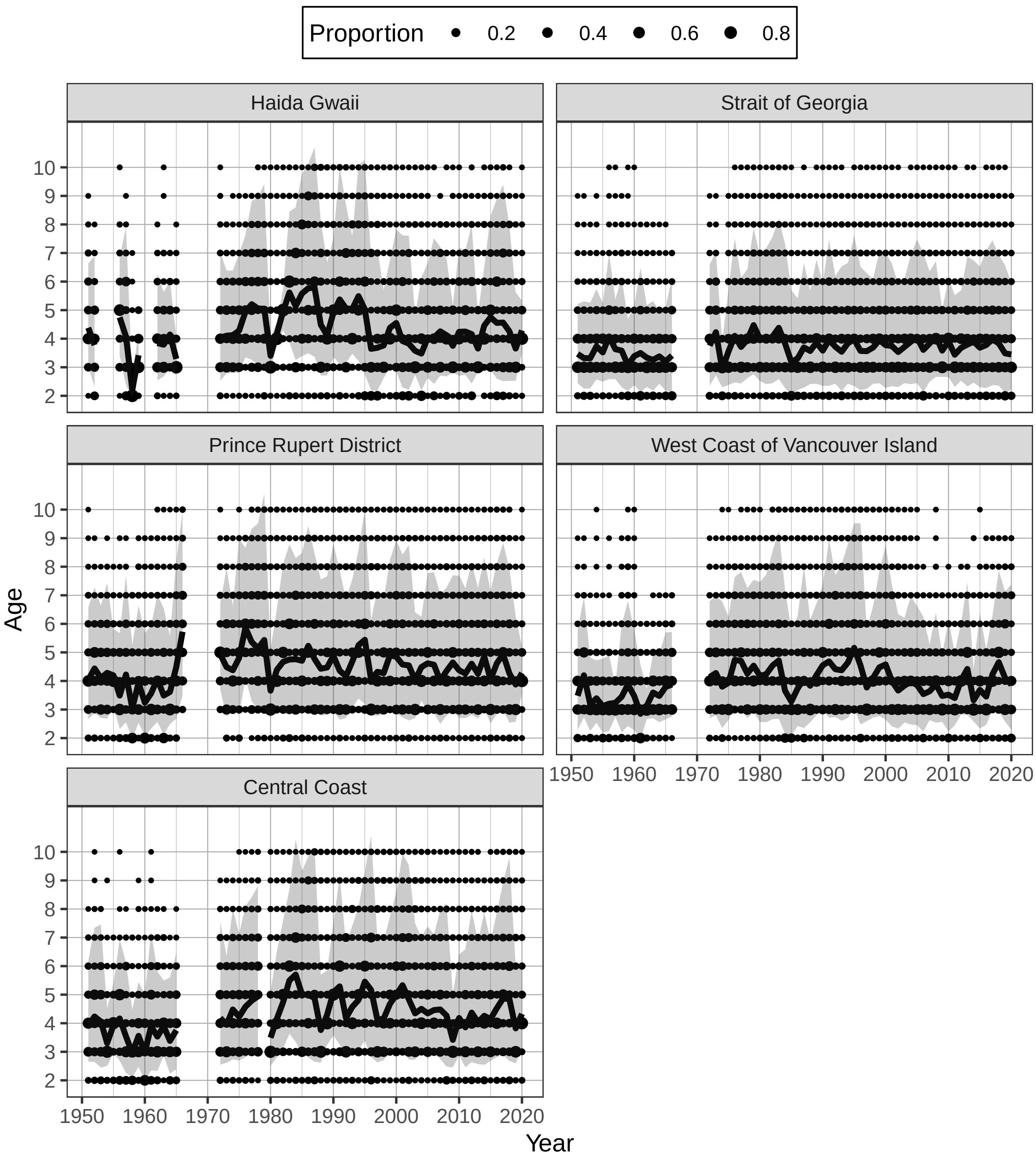

Figure 4. Time series of Pacific Herring proportion-at-age from 1951 to 2020 in the major stock assessment regions. The black line is the mean age, and the shaded area is the approximate 90% distribution. Biological summaries only include samples collected using seine nets (commercial and test) due to size-selectivity of other gear types such as gillnet. The age-10 class is a 'plus group' which includes fish ages 10 and older.

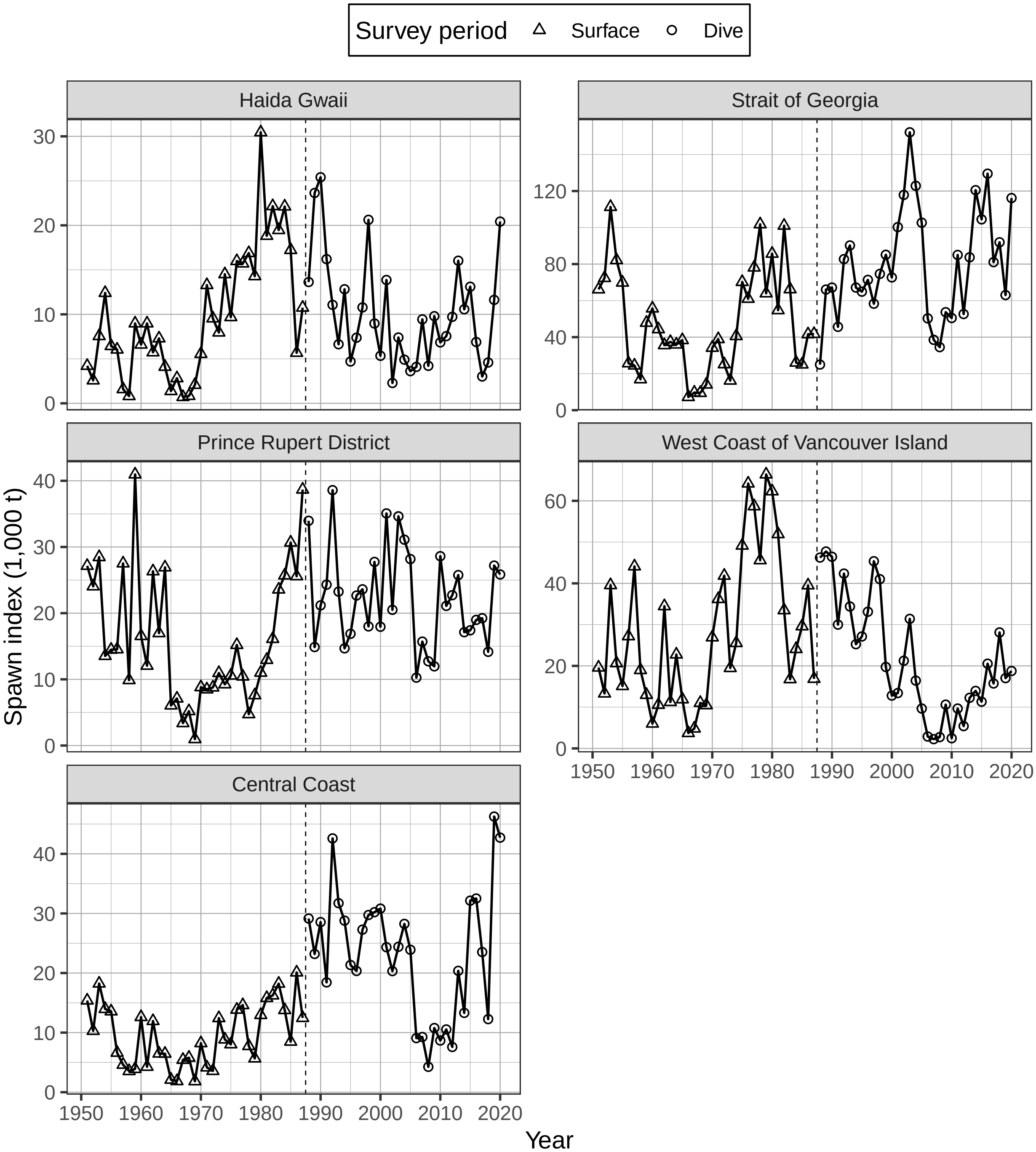

Figure 5. Time series of Pacific Herring spawn index in thousands of tonnes (t) from 1951 to 2020 in the major stock assessment regions. The spawn index has two distinct periods defined by the dominant survey method: surface surveys (1951 to 1987), and dive surveys (1988 to 2020). The dashed vertical line is the boundary between these two periods. Note: the 'spawn index' is not scaled by the spawn survey scaling parameter q.

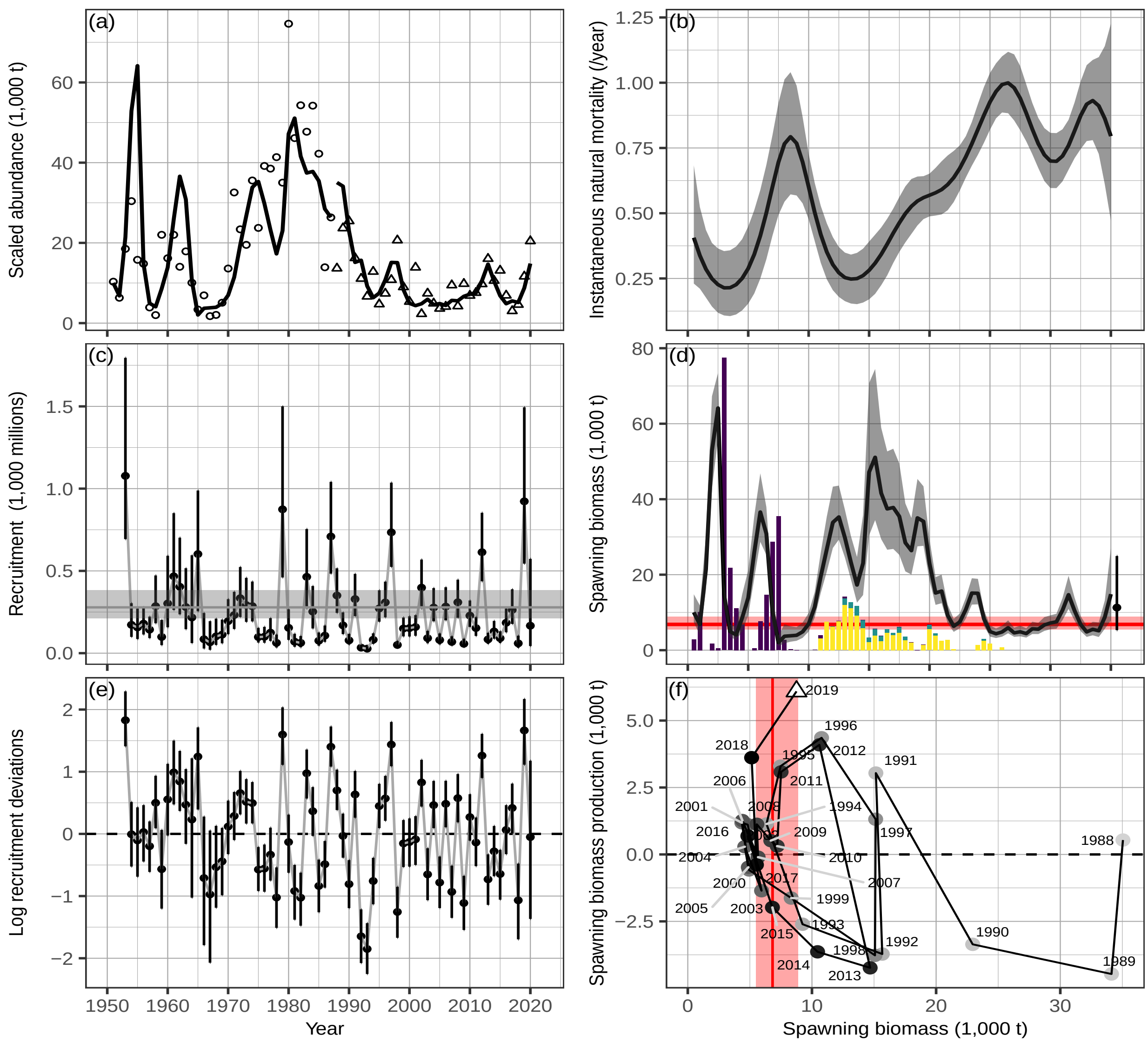

Figure 6. Time series of model output for the Pacific Herring statistical catch-age model from 1951 to 2020 in the Haida Gwaii major stock assessment region. Panel (a): model fit (median posterior estimate; lines) to scaled spawn survey data (points). Spawn survey data (i.e., spawn index) is scaled to abundance by the spawn survey scaling parameter q (median posterior estimate). Panel (b): posterior estimates of instantaneous natural mortality rate (year^{-1}). Panel (c): reconstructed number of age-2 recruits in thousands of millions. Horizontal line and shaded area indicate median and 90% credible interval for unfished age-2 recruitment R_0, respectively. Panel (d): posterior estimate of spawning biomass. Circle and vertical line indicate the median and 90% credible interval, respectively, of forecast spawning biomass in 2021 in the absence of fishing. Vertical bars indicate commercial catch, excluding spawn-on-kelp (see Figure 2 for legend). Panels (b & d): lines and shaded areas indicate medians and 90% credible intervals, respectively. Panel (e): log recruitment deviations. Panels (c & e): time series start in 1953; circles and vertical lines indicate medians and 90% credible intervals, respectively. Panel (f): phase plot of spawning biomass production for the dive survey period (1988 to 2019; median posterior estimates). Grey shading becomes darker in chronological order; the triangle indicates 2019. Panels (d & f): red lines and shading indicate medians and 90% confidence intervals, respectively, for the limit reference point $0.3SB_0$, where SB_0 is estimated unfished spawning biomass. Panels (e & f): horizontal dashed lines indicate zero. Note: biomass and catch are in thousands of tonnes (t).

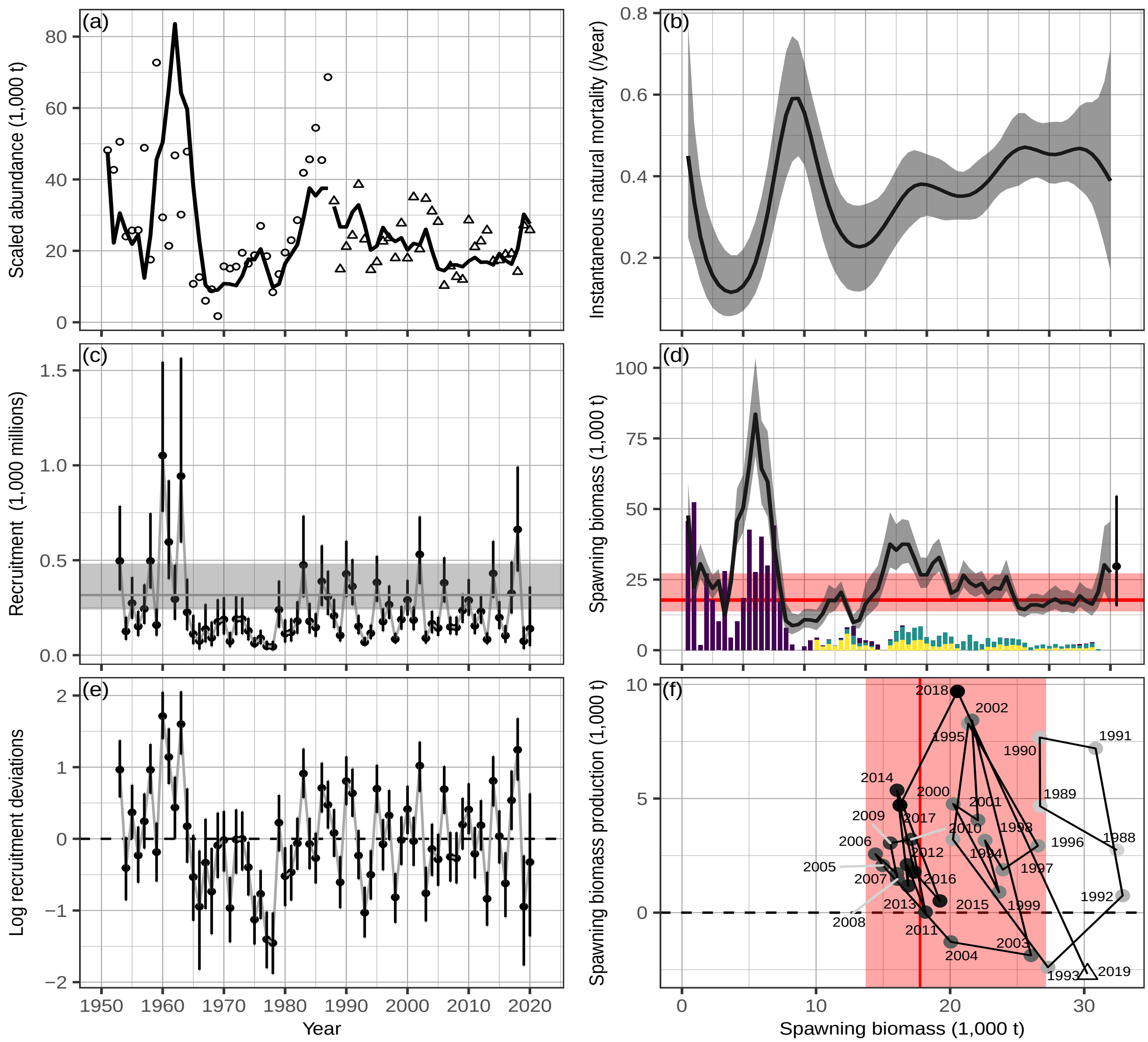

Figure 7. Time series of model output for the Pacific Herring statistical catch-age model from 1951 to 2020 in the Prince Rupert District major stock assessment region. See Figure 6 for description.

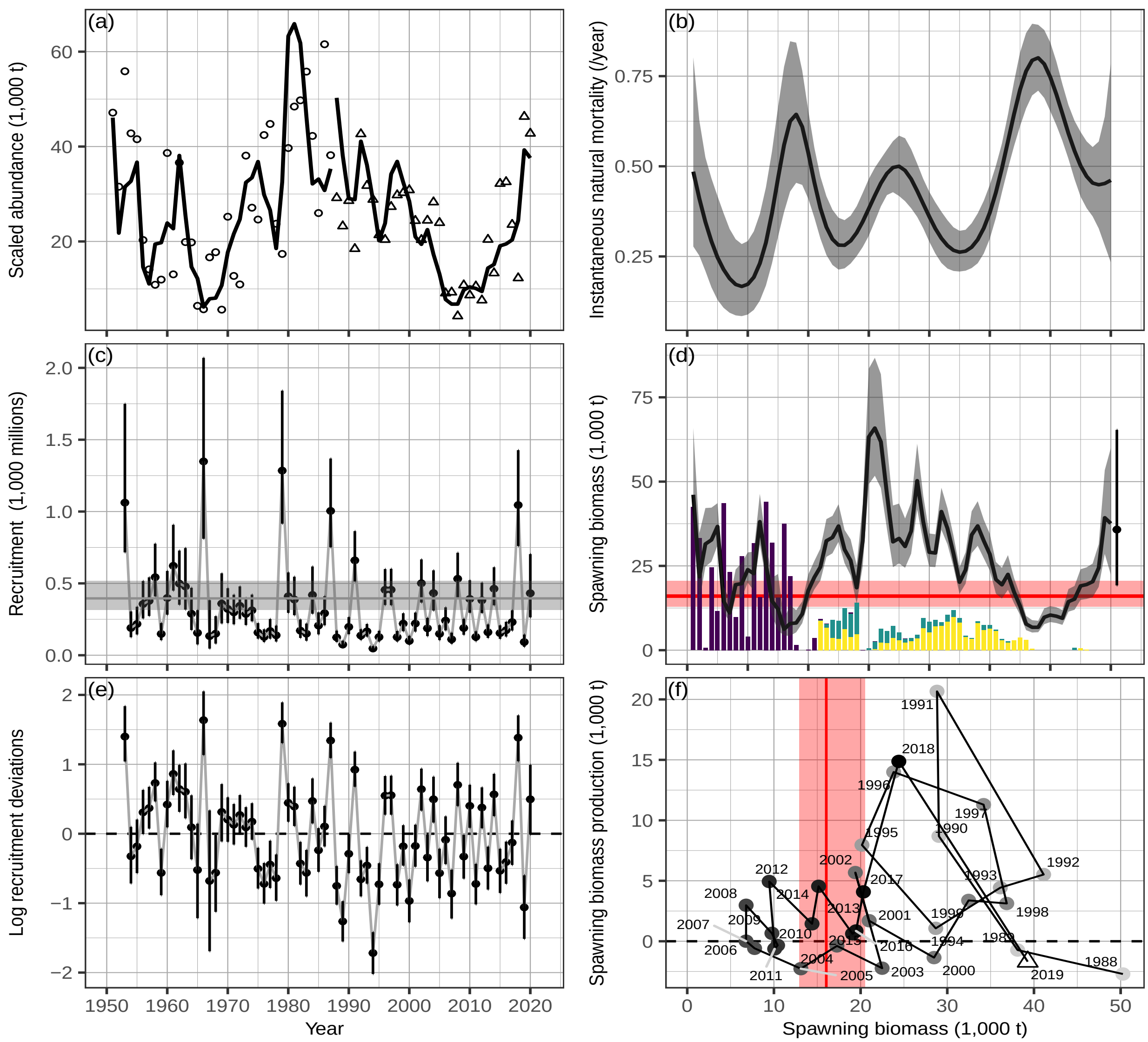

Figure 8. Time series of model output for the Pacific Herring statistical catch-age model from 1951 to 2020 in the Central Coast major stock assessment region. See Figure 6 for description.

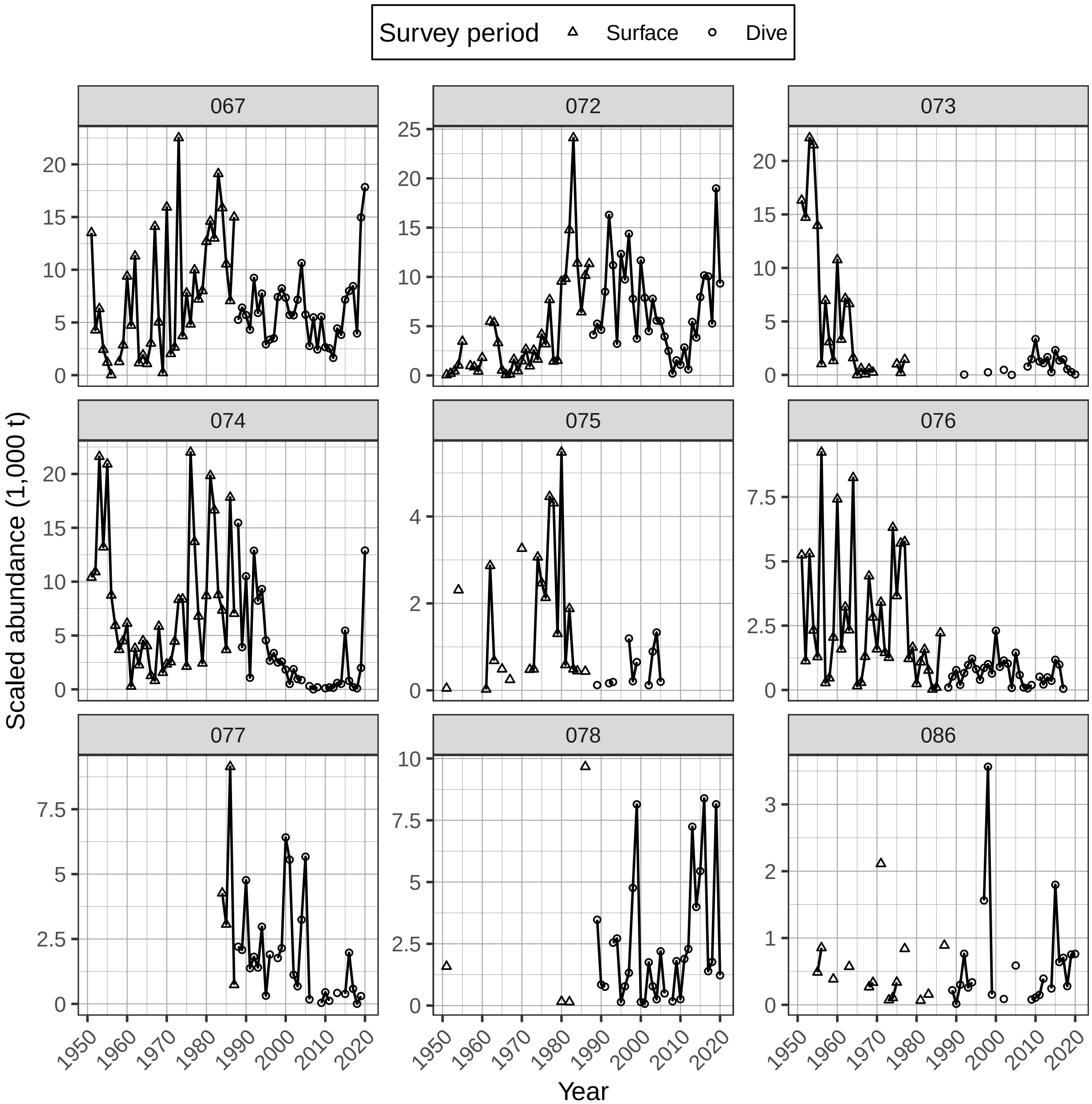

Figure 9. Scaled spawn survey data for Pacific Herring by Section from 1951 to 2020 in the Central Coast major stock assessment region. Spawn survey data (i.e., spawn index) is scaled to abundance by the spawn survey scaling parameter q (median posterior estimate). The spawn index has two distinct periods defined by the dominant survey method: surface surveys (1951 to 1987), and dive surveys (1988 to 2020). Legend: 067 is Kitasu Bay, 074 is Thompson/Stryker, 072 is Lower Spiller, and 078 is Upper Spiller. Note that only a subset of Sections are shown.

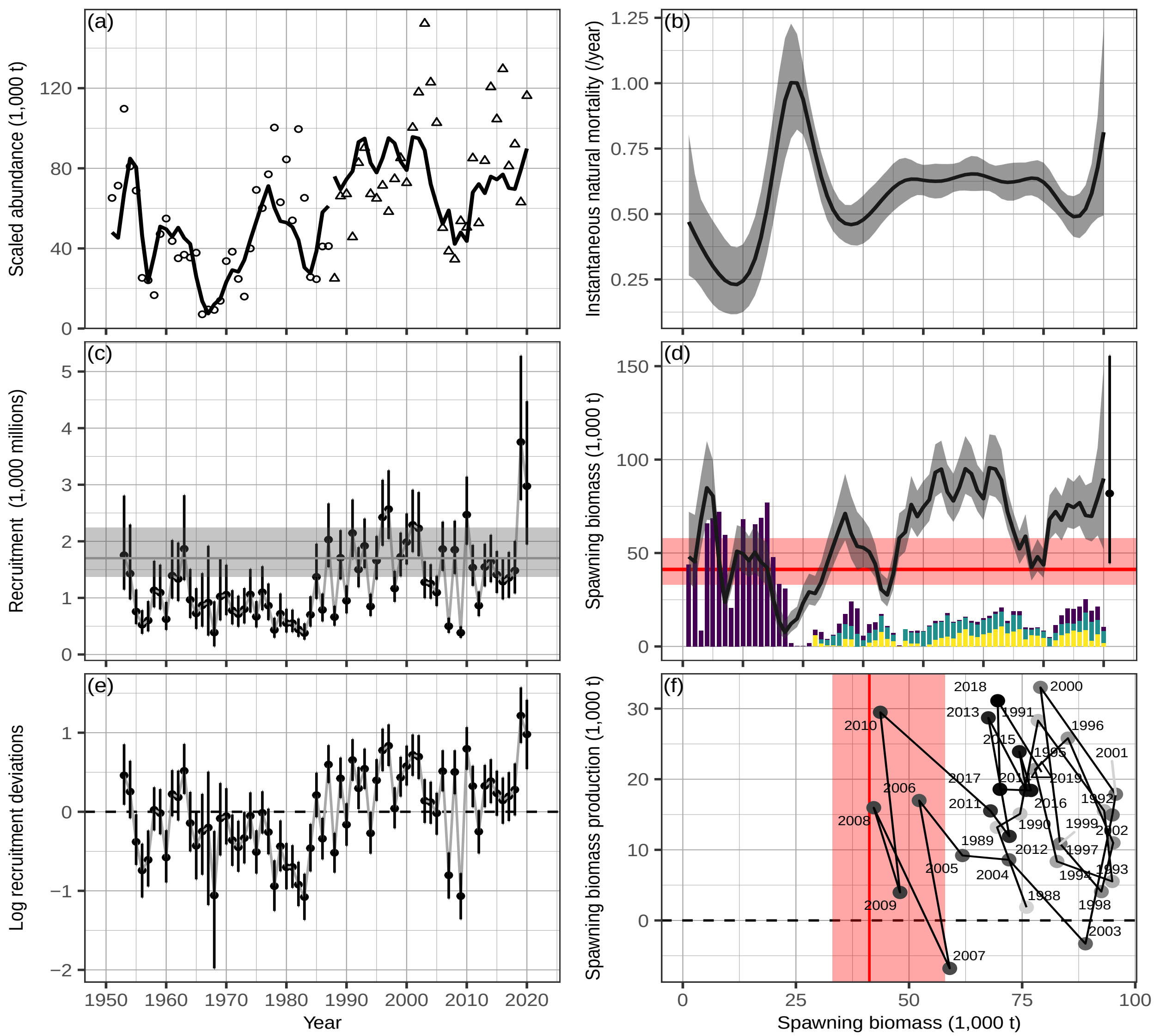

Figure 10. Time series of model output for the Pacific Herring statistical catch-age model from 1951 to 2020 in the Strait of Georgia major stock assessment region. See Figure 6 for description.

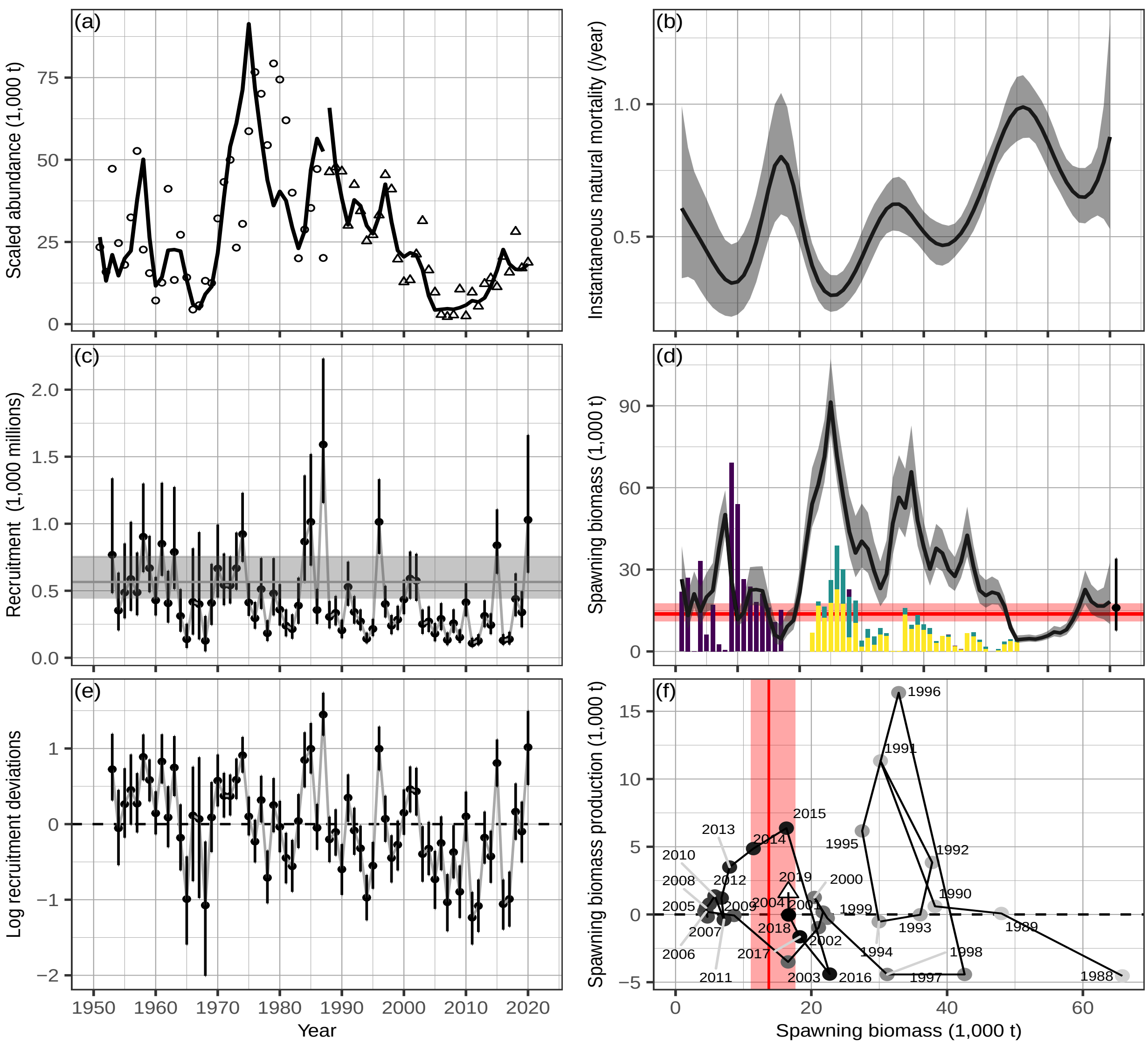

Figure 11. Time series of model output for the Pacific Herring statistical catch-age model from 1951 to 2020 in the West Coast of Vancouver Island major stock assessment region. See Figure 6 for description.

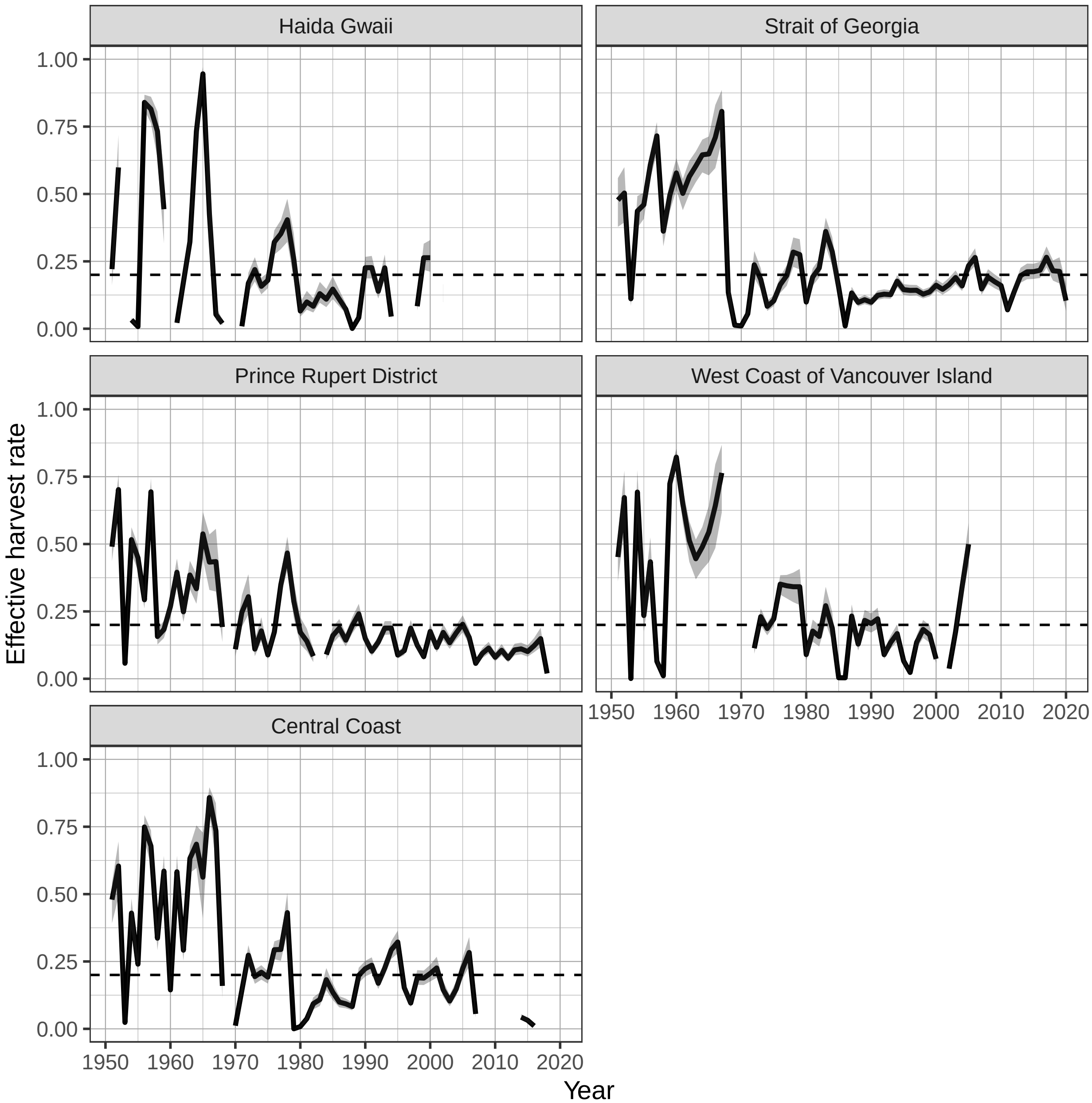

Figure 12. Time series of effective harvest rate U_t for Pacific Herring statistical catch-age models from 1951 to 2020 in the major stock assessment regions. Effective harvest rate in year t is calculated as $U_t = C_t/(C_t + SB_t)$ where C_t is catch in year t, and SB_t is estimated spawning biomass in year t. Black lines and shaded ribbons indicate medians and 90% confidence intervals for U_t, respectively. Horizontal dashed lines indicate $U_t = 0.2$.

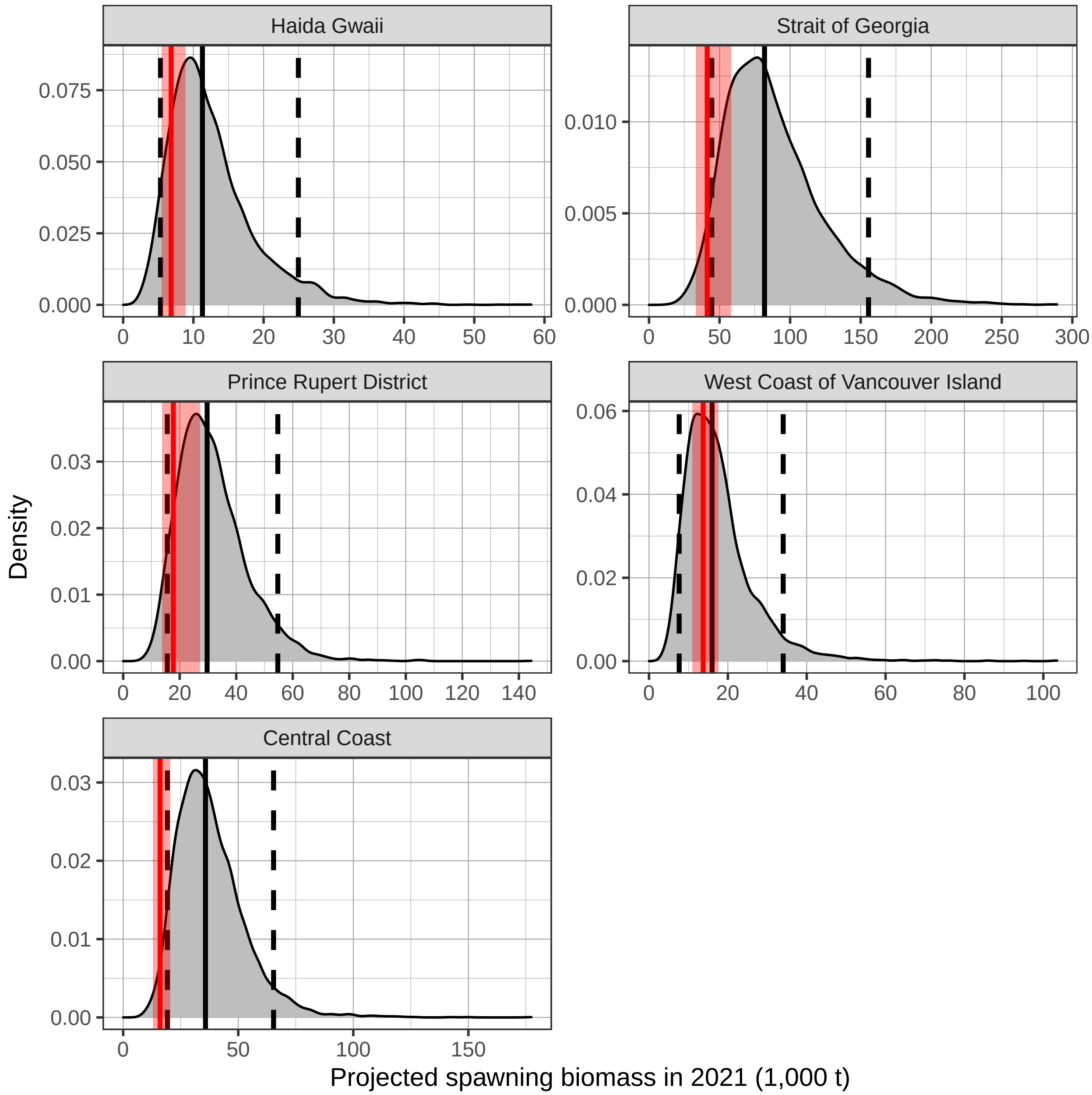

Figure 13. Posterior distributions of projected spawning biomass assuming no fishing in 2021 SB_{2021} in thousands of tonnes (t) for Pacific Herring statistical catch-age models in the major stock assessment regions. Solid and dashed black lines indicate medians and 90% confidence intervals for SB_{2021}, respectively. Vertical red lines and shaded red areas indicate medians and 90% confidence intervals for the limit reference point $0.3SB_0$, respectively, where SB_0 is estimated unfished spawning biomass.

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October 19, 2020

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Appendix

We do not conduct formal analyses of stock trend information for the two Pacific Herring minor SARs: Area 27 (A27) and Area 2 West (A2W). However, we provide the spawn index from 2011 to 2020 (Table 34). We also provide time series of landed commercial catch (Figure 14), biological data including weight-at-age (Figure 15) and proportion-at-age (Figure 16), as well as the spawn index (Figure 17) from 1978 to 2020.

Tables

Table 34. Pacific Herring spawn index in tonnes from 2011 to 2020 in the minor stock assessment regions (SARs). Legend: Area 27 (A27) and Area 2 West (A2W). Notes: the 'spawn index' is not scaled by the spawn survey scaling parameter q, and 'NA' indicates that data are not available.

	SAR	
Year	**A27**	**A2W**
2011	547	2,641
2012	744	2,416
2013	914	2,076
2014	1,307	1,368
2015	2,169	NA
2016	814	3,001
2017	26	NA
2018	1,045	617
2019	192	2,884
2020	NA	6,834

Figures

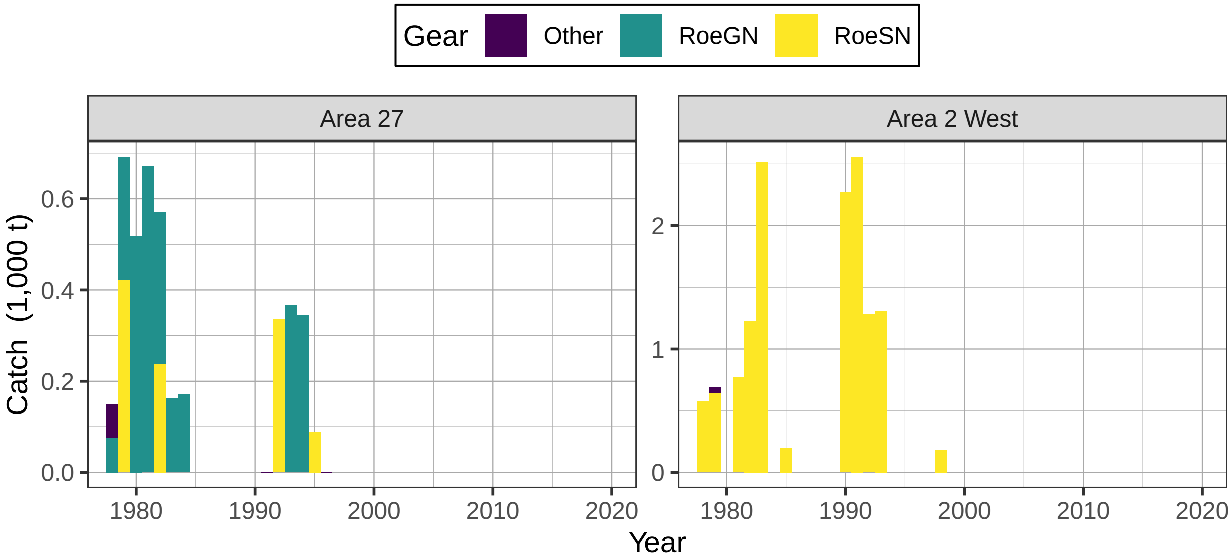

Figure 14. Time series of total landed Pacific Herring catch in thousands of tonnes (t) from 1978 to 2020 in the minor stock assessment regions. Legend: 'Other' represents the reduction, the food and bait, as well as the special use fishery; 'RoeGN' represents the roe gillnet fishery; and 'RoeSN' represents the roe seine fishery.

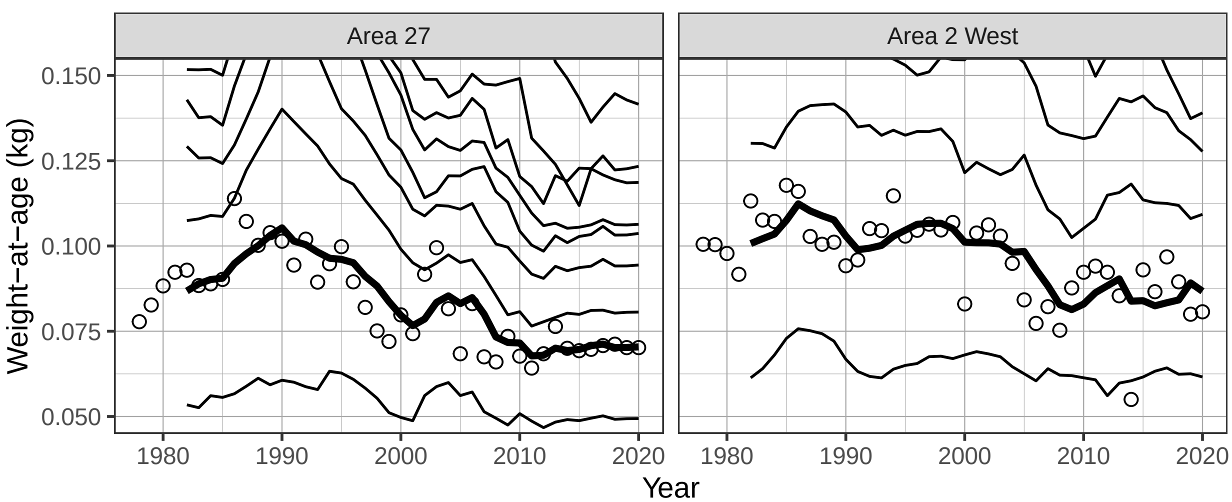

Figure 15. Time series of Pacific Herring weight-at-age in kilograms (kg) for age-3 (circles) and 5-year running mean weight-at-age (lines) from 1978 to 2020 in the minor stock assessment regions. Lines show 5-year running means for age-2 to age-10 herring (incrementing up from bottom line); the thick black line highlights age-3 herring. Missing weight-at-age values (i.e., years where there are no biological samples) are imputed using one of two methods: values at the beginning of the time series are imputed by extending the first non-missing value backwards; other values are imputed as the mean of the previous 5 years. Biological summaries only include samples collected using seine nets (commercial and test) due to size-selectivity of other gear types such as gillnet. The age-10 class is a 'plus group' which includes fish ages 10 and older. Note: vertical axes are cropped at 0.05 and 0.15 kg.

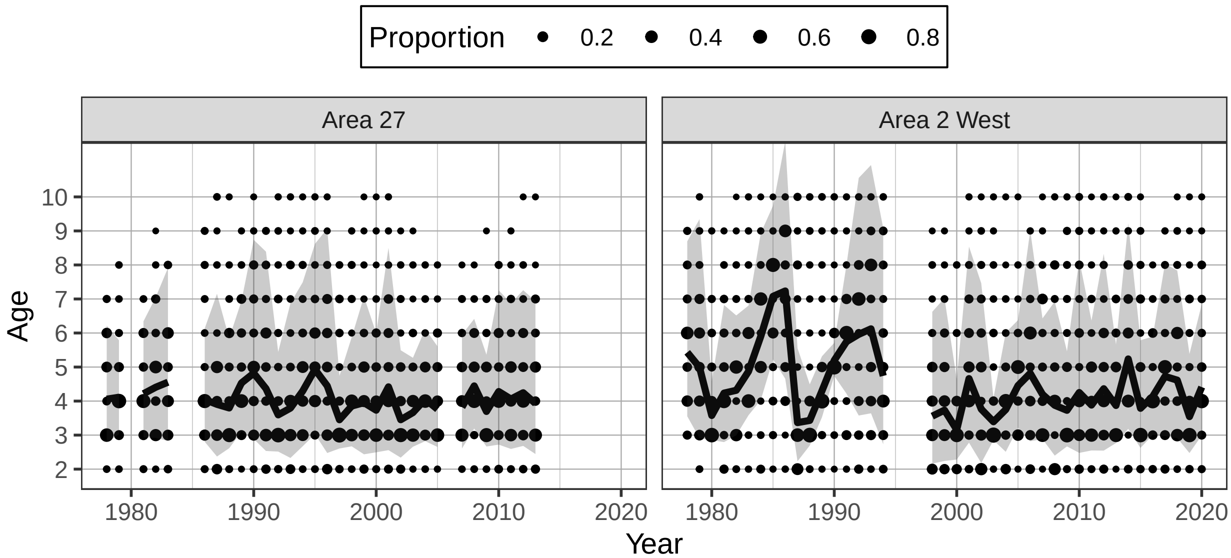

Figure 16. Time series of Pacific Herring proportion-at-age from 1978 to 2020 in the minor stock assessment regions. The black line is the mean age, and the shaded area is the approximate 90% distribution. Biological summaries only include samples collected using seine nets (commercial and test) due to size-selectivity of other gear types such as gillnet. The age-10 class is a 'plus group' which includes fish ages 10 and older.

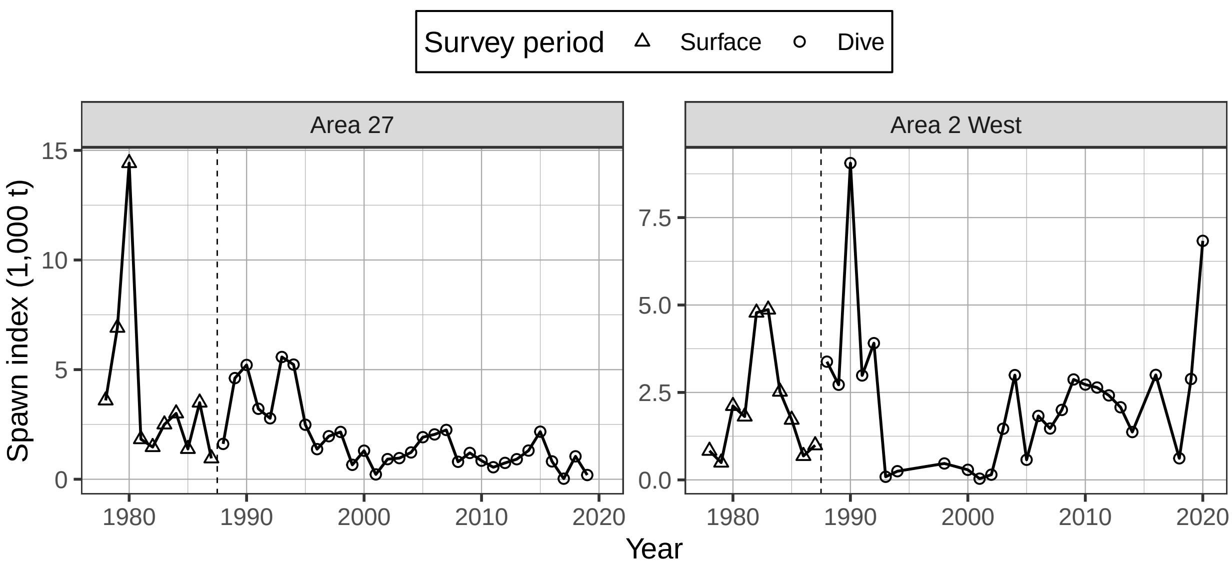

Figure 17. Time series of Pacific Herring spawn index in thousands of tonnes (t) from 1978 to 2020 in the minor stock assessment regions. The spawn index has two distinct periods defined by the dominant survey method: surface surveys (1978 to 1987), and dive surveys (1988 to 2020). The dashed vertical line is the boundary between these two periods. Note: the 'spawn index' is not scaled by the spawn survey scaling parameter q.

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