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STOCK STATUS UPDATE WITH APPLICATION OF MANAGEMENT PROCEDURES FOR PACIFIC HERRING (*CLUPEA PALLASII*) IN BRITISH COLUMBIA: STATUS IN 2019 AND FORECAST FOR 2020

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. 2018). 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). The structure of the 2017 model was not changed for the 2018 and 2019 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, and closed-loop simulations of MP performance for alternative future natural mortality scenarios. The 2018 stock assessment included updated MP recommendations for SoG and WCVI stock assessment regions for 2019 (DFO 2019b). In the spring of 2019, the MSE process was initiated for the northern stock regions. This process included performance evaluation of MPs for Haida Gwaii (HG), Prince Rupert District (PRD), and Central Coast (CC; DFO 2019c).

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

This Science Response results from the Science Response Process of September 30, 2019 on the Stock status update with application of management procedures for BC Pacific Herring: 2019 status and 2020 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 coastwide 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 2019/20 Five Nations Multi-species Fishery Management Plan (FMP) in consultation with the Five Nations. 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 2018/2019, the primary Pacific Herring fisheries were seine roe and gillnet roe fisheries, with a combined coast wide catch of 14,109 tonnes (t). The FB seine fishery had a coast wide catch of 7,310 t. The roe and FB fisheries only operated in SoG in 2018/2019. The SOK fishery was operational in PRD and CC, and special use (SU) minor fishery was operational in SoG only.

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 SOK fishery is licenced based on validated pounds of SOK product (eggs on kelp), however these landings are not easily combined with catches of whole herring and are not currently incorporated in the stock assessment process.

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. 2018). Recommendations for addressing this uncertainty will require quantifying ponding mortality and removals (eggs) associated with SOK fisheries. Consideration of these uncertainties will also occur at a future stage in the MSE process.

Description of the stock assessment process

The SCA model is fitted to commercial catch data, fishery and survey proportions-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. 2018). 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. 2018). 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. 2018). Other adjustments were made to improve computational efficiency and update input data.

A Bayesian framework was used to estimate time series of spawning biomass, instantaneous natural mortality, and age-2 recruitment from 1951 to 2019. Advice to managers for the major SARs includes posterior estimates of current stock status (SB_{2019}), stock status relative to the LRP of $0.3SB_0$, and spawning biomass in 2020 assuming no catch (SB_{2020}). 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. (2018).

Cleary et al. (2018) reported results from two SCA model fits that differed in assumptions about dive survey (from 1988 to 2019) catchability q_2: 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. 2018, Appendix D). Assuming $q_2 = 1$ at least produces a “minimum” biomass estimate so that any other assessment errors and management implementation errors are buffered (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). Simulations to quantify the risks associated with continued application of a management procedure where $q_2 = 1$ were conducted because fisheries management quota decisions since 2015 have been based on AM2. Scaling the assessment with values of $q_2 < 1$ is likely to result in larger absolute assessment errors than those estimated when $q_2 = 1$. 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. (2018, Appendix D).

Analysis and response

Input data

Input data to the stock assessment are summarized in Table 1. Relative to the previous assessment, the only change made to input data was to update the time series to include data from the 2018/2019 herring season (July 1 to June 30). Note that we refer to ‘year’ instead of ‘herring season' in this report; therefore 2019 refers to the 2018/2019 Pacific Herring season.

Catch data

For the purposes of stock assessment, catch data are summarized by gear type and fishing category 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 2010 to 2019 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 nearly 100% in 2019. Total SOK harvest or the major SARs from 2010 to 2019 is presented in Table 3.

Biological data

Biological samples are collected as described in Cleary et al. (2018) 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 2019, although to a lesser degree for PRD.

Abundance data

The surface (1951 to 1987) and dive (1988 to 2019) spawn survey methods involve collecting information on spawn length (parallel to shore), spawn width (perpendicular to shore), number of egg layers by vegetation type, and other data. These data 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 2019 spawn survey followed all standard protocols as described in Cleary et al. (2018). Time series of spawn index by major stock assessment region, from 1951 to 2019 are summarized in Figure 5. In 2019, there was a decrease in survey biomass in SoG and WCVI (Figure 5 and Tables 7 & 8), and an increase in survey biomass in HG, PRD, and CC (Figure 5 and Tables 4, 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. Statistical Areas, Sections, and Groups are not intended to represent sub-stock structure or 'known' stocklets.

First Nations observations

Local observations from 2019 were provided by First Nations participants in the Herring Technical Working Group. This working group, established in 2016, consists of DFO Science and Fisheries Management and technical representatives nominated by numerous coastal First Nations and the herring industry. Observations reported here describe local perspectives on Pacific Herring in four of the management areas.

Prince Rupert District

Observations from the Lax Kw'alaams Band: This year in the Prince Rupert District, Lax Kw'alaams had several fishermen out on the water. Overall, very little spawning was observed this season, and what was observed was non-contiguous and with much fewer layers than observed in previous years. Fishermen reported observing isolated pockets of herring in Tuck Inlet schooling in the area for a few days and then disappearing (north of Prince Rupert, Section 042). There were also humpback whales observed feeding in the Inlet, possibly causing the herring to move to deeper water to avoid predation and to spawn. Lax Kw'alaams fishermen were unable to gather enough herring to satisfy FSC needs for the community. Lax Kw'alaams Fisheries Technicians spent a full seven days during herring season, monitoring harvest and recording herring behaviour and locations. Technicians were unable to locate herring schools in any of the normal geographic areas monitored each year. On-grounds correspondence with harvesters confirmed the 2019 season was very poor and most reported seeing no active herring spawning.

Central Coast

For Klemtu area including Area 6, the spawn was much earlier than in past few years. The timing corresponds to what would be considered normal timing of a generation ago, with spawn occurring from March 19th—25th. The spawn was relatively long in duration based on previous years, and appeared to cover much of Kitasu Bay, however, the spawn was patchy. While some spawn in Kitasu Bay was quite thick, most was only a few layers of eggs deposited. Meyers and Thistle Pass showed relatively strong spawn, better than recent years. The East Higgins spawn continues to be poor, with only a single small bay experiencing any spawn. Spawn in Clifford Bay appeared to be limited to the outer island and northern reach. West Aristazabal was generally low, though storm force winds resulted in a reduced presence/observation on West Aristazabal and Clifford Bay in 2019.

Strait of Georgia

Observations from Q'ul-lhanumutsun Aquatic Resources Society: No herring spawn was observed south of Dodd Narrows in 2019.

The Tla'amin Nation report observing a very minimal spawning activity in Powell River in 2019. A single very light spawn occurred in Okeover Inlet with herring eggs occurring on the rocks and seaweed along the beach.

West Coast of Vancouver Island

As in most years, small spawning events occurred in Hesquiaht Harbour (Area 24) in January and February, and some February spawning in Areas 23 and 25. The main spawning events in all areas were from early to mid-March. Nuu-chah-nulth assessment crews found unspawned herring in the eastern part of Area 23 in late March, and a small spawn was reported in early April in Area 23. 'Sporadic' was the term most people used to describe herring spawn activity in 2019.

Most spawning events did not cover large areas and were less than a day in duration. The exceptions were multi-day spawns around Stuart Bay and Ittatsoo in Area 23 beginning on March 8th, and in Hesquiaht Harbour around Anton Spit beginning on March 5th. There were multiple spawning locations in Area 25 including Nuchatlaht, Esperanza Inlet, Yuquot, and Strange Island. Most were small as well, but there were some larger events in a couple of areas, notably around Strange Island, Rosa Island, and Bajo Reef.

Nuu-chah-nulth harvesters set whole trees and lines of tree branches to harvest herring spawn on bough. Trees and boughs were set in both usual herring spawning locations, and in active spawning locations in Barkley Sound (Area 23), Clayoquot Sound (Area 24), Nootka Sound, Esperanza Inlet, and Nuchatlitz (Area 25). Herring spawn on bough harvests were similar to 2018, mixed. In some areas, some trees had 4–10 layers on the branches, but most had only 1–4 layers. Despite the efforts, the herring spawn on bough harvests were not sufficient to meet the requests from Nuu-chah-nulth communities.

Stock status update

Analyses of stock trend information for AM2 are presented following methods of Cleary et al. (2018) for the Pacific Herring major stocks. Perceptions of stock status based on outputs from the SCA model (AM2) are summarized for each stock in a six-panel figure (e.g., Figure 6). The six panels (a–f) include:

a. Time series of maximum posterior density (MPD) estimates of the spawn survey data in thousands of tonnes. The spawn survey data (i.e., spawn index) is scaled to abundance via 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 2019). Two q parameters are implemented in the estimation procedure: q_1 with an uninformative prior, and q_2 with an informative prior approximating 1.0.
b. Time series of natural mortality (M) estimates.
c. Time series reconstruction of number of age-2 recruits.
d. Time series of total catch and estimated spawning biomass with reference line at model estimates of $0.3SB_0$.
e. Time series of (log) deviations from the estimated Beverton-Holt recruitment function.
f. Phase plot of spawning biomass production for the dive survey period (MPD estimates), with reference line at model estimates of $0.3SB_0$.

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. (2018) 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 2019c). Candidate USRs are:

1. $0.4SB_0$,
2. $0.6SB_0$,
3. Average spawning biomass from 1951 to 2019, SB_{ave}, and
4. Average spawning biomass during a productive period (Cleary et al. 2018), $SB_{ave-prod}$.

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 $0.6SB_0$ (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 over the most recent few years. The 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). In particular, 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). The most recent year, between 2018 and 2019, biomass remains very low and there is evidence of positive productivity. The effective harvest rate U_t since 2000 has been at or near zero (Figure 11), with the last commercial roe fishery in 2002, and the last commercial SOK fishery in 2004.

Estimated spawning biomass in 2019 is 6,944 t (SB_{2019}, median posterior value) or 30% of SB_0 (Tables 19 & 24). Spawning biomass in 2019 is estimated to be at the LRP of $0.3SB_0$ with a 50.1% 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. 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., 2001–2004, 2010-2013) 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 2019, roughly doubling from 0.25 to 0.5 yr^{-1} (Figure 7b). 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, 2017-2019, and an increase in the spawn index in the last year were still not sufficient to lead to an increasing trend in biomass (Figure 7f). Commercial catches from 2007-2018 have remained low (below 2,000 t) and there was no commercial catch in 2019. The estimated natural mortality appears to be unchanged from last year, resulting in what appears to be a small increase in production. An increasing trend in weight-at-age has been observed since about 2010, although the change does not appear to be as large as in the HG, CC, SoG and WCVI SARs.

The model estimates spawning biomass in 2019, SB_{2019}, at 23,223 t (posterior median), equal to 38.9% of SB_0 (Tables 20 & 25). Commercial fisheries have occurred annually in PRD since the mid-1980s, with the exception of 2019, during which the effective harvest rate U_t was estimated to be at or below 20% (Figure 11) in all years except 1989. Spawning biomass in 2019 is estimated to be greater than the LRP of $0.3SB_0$ with a 75.9% 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, and then declining modestly 2016-2018. In 2019 there was an increase in estimated spawning biomass. 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 2015 whereupon natural mortality again increased. Recruitment deviations were slightly negative (lower than predicted by the stock-recruitment function) on average from about 1990 to 2017, and have increased to above average in 2018 and 2019 (Figure 8e). In 2019 there is evidence of strong production, similar to the 1990 to 1999 period (Figure 8f); however, the biomass state is not nearly as high as was seen during that period.

A fixed cutoff HCR was implemented in 1986, and from 1986-2007 the effective harvest rate U_t is estimated to fluctuate above and below the 20% target rate, with median estimates exceeding 20% frequently (Figure 11). 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 has operated yearly since 2014, however these removals are not included in the estimation of U_t.

The model estimates spawning biomass in 2019, SB_{2019}, at 33,366 t (posterior median), equal to 60.7% of SB_0 (Tables 21 & 26). Spawning biomass in 2019 is estimated to be greater than the LRP of $0.3SB_0$ with a 98.2% probability (Table 26).

Strait of Georgia

The estimated spawning biomass for the SoG stock decreased in 2019, although the uncertainty associated with the last few years of spawning biomass along with the forecast biomass SB_{2019}, is quite large (Figure 9d). 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 9b). 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 the recent decreasing trend in estimated spawning biomass. The large uncertainty in both spawning biomass and natural mortality estimates in 2019 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 9a). 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 2019 (Figure 9c) with the recruitment deviations showing especially large recruitment of age-2 fish in 2019 (Figure 9e). The SoG juvenile herring survey reported an increase in abundance of age-0 fish from 2016 to 2017 (Strait of Georgia Juvenile Herring Survey, September 2017, Canadian Manuscript Report of Fisheries and Aquatic Sciences, unpublished report). The sampling program targets prespawning aggregations and the assessment assumes 25% of age-2 herring are mature. 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. The estimated 2019 age-2 recruitment will be adjusted by the model next year with the addition of 2020 sample data (i.e., when the 2017 cohort is sampled as age-3s). Analysis of surplus production shows that for the year between 2018-2019, the SoG SAR is estimated to be in a high production, high biomass state, similar to 1989, 1990, 2012 and 2016 (Figure 9f).

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 most years between 2013 and 2019 (Figure 11). The model estimates spawning biomass in 2019, SB_{2019}, at 64,281 t (posterior median), equal to 46.4% of SB_0 (Tables 22 & 27). Spawning biomass in 2019 is estimated to be greater than the LRP of $0.3SB_0$ with a 87.3% 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 10d). 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 10a). The increase in spawning biomass from 2013 coincides with a decline in estimated natural mortality from a historic high in the late 2000s (Figure 10b). Recruitment deviations have been negative (lower than predicted by the stock-recruit function) on average since about 2003 (Figure 10e), 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. The absence of a commercial fishery since 2005 means the realized harvest rate has been near zero for the last 14 years (Figure 11). In recent years there has been modest evidence for an increase in production and biomass. The production estimates in the 2018-2019 year are at a higher spawning biomass level than those estimated during the low production, low biomass period of the last half of the 2000s and early 2010s (Figure 10f).

The model estimates spawning biomass in 2019, SB_{2019}, at 20,664 t (posterior median), equal to

44.2% of SB_0 (Tables 23 & 28). Spawning biomass in 2019 is estimated to be greater than the LRP of $0.3SB_0$ with a 86.5% 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 11.

Application of MPs and harvest options for 2020

Generally, harvest advice for the major stocks of Pacific Herring has been based on a 1-year forecast of pre-fishery spawning biomass and application of a HCR that is a hybrid of fixed escapement and a target harvest rate (e.g., Hall et al. (1988)). Although the target harvest rate has varied among regions in recent years (e.g., CC and PRD SARs; DFO (2017)), the "historical" practice was to apply a target harvest rate of 20% when the forecast is estimated to be above a fixed commercial fishery cutoff of $0.25SB_0$ defined in the 1996 stock assessment (DFO 2016). This rule is referred to as the "fixed cutoff rule."

Renewal of the Pacific Herring management framework included a commitment to MSE simulation-evaluation of the performance of historical fixed cutoff and alternative MPs in relation to conservation and fisheries management objectives. The first cycle of the MSE process was completed for the WCVI and SoG SARs in 2018 (DFO 2019a); a similar process was used to evaluate harvest strategies for HG, PRD, and CC in 2019 (DFO 2019c).

The ranking of objectives and selection of MPs that meet objectives using MSE is an iterative process. The first cycle of Pacific Herring MSE includes, as a starting point, four core fisheries management objectives (DFO 2019c) which reflect DFO policy, and were applied to each major SAR:

1. Avoid 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 monitoring data and assessment model (e.g., Cleary et al. 2018). The current assessment model assumes natural mortality is time-varying. The first MSE cycle introduced 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 2019c), while the DIM and conM scenarios were identified as Robustness OM scenarios. There is however currently no correct scientifically supported method for predicting the natural mortality and therefore all three scenarios are included.

Results presented here represent all three OM scenarios.

Several lessons were learned from the analysis:

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. 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 management procedures (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).

Harvest options for 2020 reflect application of simulation-tested MPs for each major SAR.

Haida Gwaii

The HG stock has persisted in a low biomass, low productivity state since 2000. 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). In the absence of fishing, spawning biomass in 2020 is forecast at 4,296 t (posterior median). Results of the simulation-evaluations found that non 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%).[1]

The projected spawning biomass in 2020 is forecast to be below $0.3SB_0$ with 79.7% probability in the absence of fishing (Table 24 and Figure 12).

DFO has committed to developing and implementing a rebuilding plan for Haida Gwaii Pacific Herring by the end of fiscal year 2020/21.[2] Work is underway through a technical working group

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

[2] 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

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 2020 is 0 t.

Prince Rupert District

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 due to spawning biomass declined 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%)[1], 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 average ~12% (Figure 11), during which the stock showed no sign of growth, and is estimated to fluctuate at or near $0.3SB_0$ (Figure 7d). Furthermore, 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 2020 is forecast to decrease slightly from 23,223 t in 2019 to an estimated 22,627 t (posterior medians). The forecast spawning biomass in 2020 is estimated to be below the LRP of $0.3SB_0$ with 29.4% probability in the absence of fishing (Table 25).

Harvest options for 2020 are presented in Table 29. These options reflect application of MPs to the 2020 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 2019c), all MPs and scenarios listed in Table 29 include MP performance against the four core objectives.

Central Coast

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

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.

spawning biomass above the LRP with high probability (at least 75%)[1]. 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 2020 is forecast at 29,770 t (posterior median), decreasing from 33,366 t in 2019 (Table 26). The 2020 spawning biomass is forecast to be below the LRP of $0.3SB_0$ with 11.3% probability in the absence of fishing.

Harvest options for 2020 are presented in Table 30. These options reflect application of MPs to the 2020 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 2019c), all MPs and scenarios listed in Table 30 include MP performance against 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 2020. Results presented here may inform this on-going commitment.

Strait of Georgia

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, including the historical fixed cutoff MP which applied a constant escapement of 21,200 t based on the 1996 stock assessment and 20% harvest rate (DFO 2019a). Management procedures that included a 30,000 t catch cap were able to maintain spawning biomass above a biomass level of $0.6SB_0$ with 60% probability or higher across all OM scenarios.

A 30,000 t catch cap was evaluated for the SoG; this cap was not often triggered, and thus did not limit the commercial fishery very often in simulations. The purpose of the catch cap is to provide a model-free means of mitigating the effects of large positive assessment errors on a year-to-year basis. Additional simulation-evaluations were conducted in 2019 to further explore the role of catch caps in mitigating assessment errors (DFO 2019c). 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).

Science advice in 2018 recommended discontinuing the use of the historical fixed cutoff HCR and adopting a HCR with two OCPs for these reasons (DFO 2019a):

1. The fixed cutoff values were calculated outside of the current assessment model, last updated in 1996, and therefore ignore 22 years of stock and fishery monitoring data, as well as substantial changes to the structural form of the assessment model.
2. Use of separate lower and upper OCPs allows for altering the slope of the ramp portion of the HCR to better meet stock and fishery objectives by avoiding fishery closures and encouraging stock growth as more is learned about stock dynamics and the effects of fishing.

In the absence of fishing, spawning biomass in 2020 is forecast at 54,242 t (posterior median) and is forecast to be below the LRP of $0.3SB_0$ with 27.8% probability in the absence of fishing.

Harvest recommendations for SoG stock in 2018/19 were provided by application of a MP that utilizes stock assessment estimates of forecast spawning biomass and operational control points at $0.3SB_0$ and $0.6SB_0$, with a 20% target harvest rate and a maximum catch cap of 30,000 t (DFO 2019a, Figure 4).

Harvest options for 2020 are presented in Table 31. These options reflect application of MPs to the 2020 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. For ease of comparison with MSE results (DFO 2019c), all MPs and scenarios listed in Table 31 include MP performance against the four core objectives.

West Coast of Vancouver Island

For the WCVI, simulation results showed that no tested MP could meet the conservation objective of maintaining spawning biomass above the LRP with high probability (at least 75%)[1] across the three future natural mortality (M) scenarios (DFO 2019a). In addition, for the scenario where M is most similar to the last 10 years (DIM), the historical fixed cutoff HCR only meet the conservation objective 56% of the time.

Of the MPs that were simulation-tested across the three M scenarios, the “best-performing” MP maintained spawning biomass above the LRP with a 74% probability. This MP implements a lower control point at the assessment model estimate of $0.5SB_0$, a 10% target harvest rate, and a maximum catch cap of 2,000 t.

In the absence of fishing, spawning biomass in 2020 is forecast at 21,928 t (posterior median) and is forecast to be below the LRP of $0.3SB_0$ with 14.2% probability in the absence of fishing.

Given the best performing MP for the WCVI did not meet the minimum “high” probability of 75%, further simulation-testing of HCRs that include additional measures to ensure persistent stock growth away from the critical zone and towards identified biomass targets may be required. Updates to the operating model (addition of 2018 and 2019 data) and evaluation of additional MPs and objectives (including new objectives) is scheduled to occur in 2020/2021.

As such, the harvest recommendation for the WCVI stock in 2020 is 0 t.

Conclusions

The 2019 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. 2018) with data time series update to 2019.

In the first MSE cycle for HG, none of the MPs tested could meet the conservation objective with at least 75% probability (DFO 2019c), thus harvest options are not provided for 2020. 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 and SoG management areas for the Reference OM scenario (DFO 2019c). As such, harvest options for 2020 for PRD, CC, and SoG are reported using MPs that meet the minimum conservation criteria (Table 29 - Table 31).

A commercial fishery closure was maintained for the WCVI management area in 2018/19 in order to support continued rebuilding. Given the best performing MP for the WCVI did not meet the minimum “high” probability of 75%, further simulation-testing of HCRs that include additional measures to ensure persistent stock growth away from the critical zone and towards identified biomass targets is recommended. Updates to the operating model (addition of 2018 and 2019 data) and evaluation of additional MPs and objectives (including new objectives) is scheduled to occur in 2020/2021. Harvest recommendation for the WCVI stock in 2020 is 0 t.

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 2019 Pacific Herring stock assessment. The spawn index has two distinct periods defined by the dominant survey method: surface surveys (1951 to 1987), and dive surveys (1988 to 2019). Note: the ‘spawn index’ is not scaled by the spawn survey scaling parameter q.

Source	Data	Years
Roe gillnet fishery	Catch	1972 to 2019
Roe seine fishery	Catch	1972 to 2019
Other fisheries	Catch	1951 to 2019
Test fishery (Seine)	Biological: number-at-age	1975 to 2019
Test fishery (Seine)	Biological: weight-at-age	1975 to 2019
Roe seine fishery	Biological: number-at-age	1972 to 2019
Roe seine fishery	Biological: weight-at-age	1972 to 2019
Roe gillnet fishery	Biological: number-at-age	1972 to 2019
Other fisheries	Biological: number-at-age	1951 to 2019
Other fisheries	Biological: weight-at-age	1951 to 2019
Surface survey	Abundance: spawn index	1951 to 1987
Dive survey	Abundance: spawn index	1988 to 2019

Table 2. Total landed catch in tonnes of Pacific Herring 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: if present, 'WP' indicates that data are withheld due to privacy concerns.

	SAR				
Year	**HG**	**PRD**	**CC**	**SoG**	**WCVI**
2010	0	1,485	0	8,323	0
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

Table 3. Total spawn-on-kelp harvest, reported as pounds of Pacific Herring eggs on kelp, 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: if present, 'WP' indicates that data are withheld due to privacy concerns.

	SAR				
Year	**HG**	**PRD**	**CC**	**SoG**	**WCVI**
2010	0	108,834	0	0	0
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	15,418	356,042	0	0

Table 4. Spawn index in tonnes, and proportion of the spawn index by Group for Pacific Herring 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**	**Cumshewa**	**Juan Perez/Skincuttle**	**Louscoone**	**Selwyn**
2010	6,845	0.000	0.655	0.022	0.323
2011	7,554	0.000	0.749	0.026	0.226
2012	9,720	0.000	0.821	0.020	0.158
2013	16,025	0.007	0.864	0.079	0.050
2014	10,566	0.000	0.932	0.000	0.068
2015	13,102	0.000	0.940	0.000	0.060
2016	6,888	0.000	0.947	0.000	0.053
2017	3,016	0.000	0.982	0.000	0.018
2018	4,588	0.000	0.766	0.000	0.234
2019	11,624	0.025	0.919	0.016	0.040

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

		Proportion		
Year	**Spawn index**	**03**	**04**	**05**
2010	28,607	0.036	0.744	0.219
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

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

		Proportion		
Year	**Spawn index**	**06**	**07**	**08**
2010	8,671	0.306	0.605	0.089
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

Table 7. Spawn index in tonnes, and proportion of the spawn index by Group for Pacific Herring 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**
2010	50,454	0.886	0.000	0.002	0.112
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	62,994	0.985	0.000	0.014	0.000

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

		Proportion		
Year	**Spawn index**	**23**	**24**	**25**
2010	2,464	0.446	0.079	0.475
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

Table 9. Posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates of key parameters for 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 2019; $\overline{R}_{init}$ 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 2019; 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	214.213	282.255	388.892	286.689
h	0.653	0.785	0.897	0.805
M	0.232	0.407	0.691	0.378
$\overline{R}$	147.730	175.516	210.283	184.859
$\overline{R}_{init}$	9.336	30.229	152.760	33.545
ρ	0.213	0.276	0.348	0.263
ϑ	0.777	0.941	1.133	1.010
q_1	0.332	0.404	0.483	0.394
q_2	0.983	0.999	1.016	0.999
τ	0.785	0.874	0.983	0.854
σ	0.473	0.541	0.619	0.510

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

Parameter	5%	50%	95%	MPD
R_0	253.289	331.091	481.729	314.792
h	0.537	0.696	0.849	0.723
M	0.256	0.456	0.791	0.428
$\overline{R}$	177.752	203.265	237.047	207.228
$\overline{R}_{init}$	67.536	222.050	1,260.290	250.842
ρ	0.219	0.288	0.367	0.289
ϑ	0.972	1.190	1.438	1.278
q_1	0.468	0.547	0.624	0.543
q_2	0.985	1.001	1.018	1.001
τ	0.686	0.772	0.875	0.746
σ	0.425	0.491	0.567	0.475

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

Parameter	5%	50%	95%	MPD
R_0	314.979	398.996	528.344	385.221
h	0.674	0.802	0.909	0.825
M	0.273	0.484	0.837	0.445
$\overline{R}$	230.464	263.188	302.217	264.100
$\overline{R}_{init}$	54.504	197.990	1,396.839	255.930
ρ	0.182	0.244	0.321	0.228
ϑ	0.990	1.199	1.437	1.290
q_1	0.280	0.328	0.380	0.331
q_2	0.982	0.999	1.016	0.999
τ	0.708	0.792	0.888	0.774
σ	0.389	0.452	0.526	0.420

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

Parameter	5%	50%	95%	MPD
R_0	1,338.107	1,656.120	2,248.984	1,600.890
h	0.578	0.733	0.869	0.766
M	0.269	0.466	0.783	0.454
$\overline{R}$	948.097	1,092.070	1,269.746	1,123.560
$\overline{R}_{init}$	38.268	154.348	930.065	276.953
ρ	0.211	0.282	0.365	0.270
ϑ	1.227	1.500	1.823	1.609
q_1	0.857	1.019	1.192	1.004
q_2	0.983	1.000	1.016	0.999
τ	0.609	0.691	0.783	0.673
σ	0.372	0.433	0.503	0.410

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

Parameter	5%	50%	95%	MPD
R_0	426.121	549.868	735.522	541.299
h	0.601	0.729	0.855	0.741
M	0.342	0.609	0.995	0.580
$\overline{R}$	312.919	360.646	420.896	366.631
$\overline{R}_{init}$	33.765	165.769	1,149.039	256.484
ρ	0.244	0.314	0.398	0.304
ϑ	1.071	1.301	1.568	1.395
q_1	0.708	0.851	1.007	0.854
q_2	0.983	0.999	1.016	0.999
τ	0.642	0.725	0.821	0.706
σ	0.430	0.491	0.562	0.467

Table 14. Posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates of age-2 recruitment (millions) for the Haida Gwaii major stock assessment region.

Year	5%	50%	95%	MPD
2010	159.877	229.203	323.635	235.962
2011	104.409	153.330	220.953	158.247
2012	433.086	612.216	855.475	632.460
2013	56.839	83.278	124.136	86.120
2014	89.535	131.960	194.217	136.618
2015	62.916	91.946	137.827	95.481
2016	129.700	195.657	293.755	200.962
2017	171.114	260.946	406.006	272.393
2018	32.633	60.115	112.755	59.602
2019	443.032	851.959	1,511.970	905.908

Table 15. Posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates of age-2 recruitment (millions) for the Prince Rupert District major stock assessment region.

Year	5%	50%	95%	MPD
2010	219.200	296.659	400.947	303.286
2011	118.065	161.916	220.645	166.717
2012	175.448	238.469	326.310	246.435
2013	60.814	87.884	124.700	89.952
2014	323.159	457.885	635.803	470.728
2015	143.415	209.169	298.875	216.055
2016	70.037	110.218	170.547	112.560
2017	206.273	321.840	493.564	324.638
2018	191.466	386.385	668.298	432.165
2019	82.718	370.240	1,702.767	286.319

Table 16. Posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates of age-2 recruitment (millions) for the Central Coast major stock assessment region.

Year	5%	50%	95%	MPD
2010	299.725	392.849	521.617	396.601
2011	95.862	127.527	168.922	127.975
2012	284.457	376.303	499.604	377.544
2013	115.855	156.750	210.452	157.858
2014	359.592	488.530	653.905	491.897
2015	102.364	141.190	195.382	142.707
2016	123.325	169.719	231.199	171.491
2017	153.978	214.900	298.168	218.072
2018	419.942	749.811	1,160.454	821.712
2019	117.249	653.796	3,258.063	512.493

Table 17. Posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates of age-2 recruitment (millions) for the Strait of Georgia major stock assessment region.

Year	5%	50%	95%	MPD
2010	1,854.157	2,384.730	3,060.825	2,408.400
2011	1,110.591	1,443.700	1,847.371	1,449.190
2012	617.013	807.567	1,037.362	812.841
2013	1,116.015	1,445.095	1,868.193	1,468.570
2014	1,222.176	1,601.585	2,058.393	1,627.350
2015	1,086.816	1,443.465	1,887.468	1,479.830
2016	1,008.980	1,376.000	1,835.743	1,426.570
2017	1,113.826	1,551.700	2,120.466	1,609.600
2018	1,058.712	1,478.835	2,091.952	1,528.920
2019	2,803.077	4,188.705	6,191.937	4,210.040

Table 18. Posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates of age-2 recruitment (millions) for the West Coast of Vancouver Island major stock assessment region.

Year	5%	50%	95%	MPD
2010	304.796	413.067	558.377	416.556
2011	75.578	105.579	147.057	106.085
2012	87.815	120.862	169.683	122.166
2013	210.432	294.567	411.598	299.915
2014	164.714	228.627	318.033	234.233
2015	565.807	779.876	1,066.291	802.950
2016	93.061	130.252	184.238	133.440
2017	103.574	148.726	216.291	150.897
2018	306.436	453.153	674.291	456.145
2019	238.389	392.723	639.705	389.914

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) for the Haida Gwaii major stock assessment region.

	Spawning biomass				Depletion			
Year	**5%**	**50%**	**95%**	**MPD**	**5%**	**50%**	**95%**	**MPD**
2010	5.559	7.172	9.300	7.197	0.212	0.312	0.442	0.324
2011	5.684	7.471	9.833	7.515	0.217	0.326	0.467	0.339
2012	8.004	10.517	13.888	10.641	0.305	0.456	0.655	0.480
2013	11.052	14.695	19.708	14.906	0.421	0.636	0.919	0.672
2014	7.929	10.523	14.073	10.659	0.304	0.456	0.662	0.480
2015	5.100	6.958	9.478	7.000	0.199	0.300	0.448	0.315
2016	3.591	4.997	6.947	4.962	0.141	0.216	0.328	0.224
2017	3.946	5.566	7.870	5.459	0.157	0.241	0.365	0.246
2018	3.042	4.723	7.108	4.513	0.125	0.204	0.322	0.203
2019	3.547	6.944	12.692	6.774	0.151	0.300	0.551	0.305

Table 20. Posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates of spawning biomass in thousands of tonnes and depletion for 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**
2010	14.353	17.441	21.479	17.684	0.187	0.296	0.421	0.320
2011	15.087	18.687	23.405	18.984	0.196	0.318	0.458	0.344
2012	13.953	17.343	21.749	17.623	0.183	0.294	0.428	0.319
2013	14.016	17.399	21.850	17.719	0.184	0.295	0.429	0.321
2014	13.325	16.581	20.803	16.796	0.178	0.281	0.404	0.304
2015	15.676	19.827	25.137	20.034	0.212	0.335	0.485	0.363
2016	13.647	17.575	22.600	17.580	0.189	0.296	0.428	0.318
2017	11.622	15.797	21.335	15.614	0.169	0.265	0.392	0.283
2018	11.664	17.298	25.615	17.174	0.175	0.290	0.449	0.311
2019	13.141	23.223	39.807	21.916	0.209	0.389	0.679	0.397

Table 21. Posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates of spawning biomass in thousands of tonnes and depletion for the Central Coast major stock assessment region. See Table 19 for description.

	Spawning biomass				Depletion			
Year	**5%**	**50%**	**95%**	**MPD**	**5%**	**50%**	**95%**	**MPD**
2010	8.279	10.386	13.133	10.384	0.134	0.190	0.265	0.200
2011	7.905	9.969	12.863	10.012	0.128	0.183	0.258	0.193
2012	7.411	9.414	12.042	9.432	0.120	0.173	0.241	0.182
2013	11.325	14.482	18.395	14.522	0.184	0.265	0.371	0.280
2014	12.202	15.608	19.805	15.711	0.199	0.284	0.395	0.303
2015	15.497	19.900	25.271	20.149	0.254	0.364	0.510	0.389
2016	15.242	19.759	25.425	20.000	0.254	0.361	0.504	0.386
2017	14.818	19.606	25.611	19.807	0.247	0.358	0.502	0.382
2018	13.439	20.394	29.228	20.899	0.234	0.370	0.558	0.403
2019	19.331	33.366	55.574	31.157	0.347	0.607	1.006	0.601

Table 22. Posterior (5^{th}, 50^{th}, and 95^{th} percentile) and maximum posterior density (MPD) estimates of spawning biomass in thousands of tonnes and depletion for 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**
2010	34.566	41.564	49.746	41.430	0.203	0.303	0.411	0.322
2011	53.228	64.079	76.473	63.855	0.314	0.468	0.632	0.497
2012	57.218	68.435	81.877	68.410	0.335	0.503	0.675	0.532
2013	54.725	65.572	78.343	65.872	0.321	0.480	0.644	0.513
2014	64.062	76.507	92.030	77.442	0.373	0.561	0.754	0.603
2015	64.480	77.987	94.172	79.370	0.378	0.570	0.779	0.618
2016	67.840	82.674	101.337	84.360	0.399	0.602	0.829	0.657
2017	60.347	75.073	94.655	76.263	0.362	0.547	0.763	0.594
2018	52.840	68.423	89.674	67.909	0.328	0.499	0.703	0.529
2019	36.204	64.281	111.761	61.135	0.246	0.464	0.837	0.476

Table 23. Posterior (5^{th}, 50^{th}, and 95^{th} percentile) and maximum posterior density (MPD) estimates of spawning biomass in thousands of tonnes and depletion for 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**
2010	4.336	5.614	7.338	5.622	0.082	0.121	0.175	0.125
2011	5.120	6.781	9.039	6.843	0.099	0.147	0.214	0.152
2012	4.847	6.366	8.492	6.427	0.093	0.137	0.199	0.143
2013	5.781	7.461	9.769	7.557	0.110	0.162	0.231	0.168
2014	8.370	10.891	14.265	11.092	0.158	0.237	0.335	0.247
2015	11.925	15.771	20.871	16.070	0.231	0.341	0.488	0.357
2016	16.836	22.646	30.510	22.974	0.330	0.491	0.701	0.511
2017	14.366	19.553	26.019	19.348	0.288	0.420	0.598	0.430
2018	13.353	19.033	26.478	18.381	0.274	0.408	0.600	0.409
2019	11.411	20.664	35.721	19.508	0.240	0.442	0.785	0.434

Table 24. Posterior (5th, 50th, and 95th percentile) estimates of proposed reference points for 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_{2020} is projected spawning biomass in 2020 assuming no fishing.

Reference point	5%	50%	95%
SB_0	18.248	23.056	30.319
$0.3SB_0$	5.475	6.917	9.096
SB_{2019}	3.547	6.944	12.692
SB_{2019}/SB_0	0.151	0.300	0.551
$SB_{2019}/0.3SB_0$	0.504	1.001	1.838
$P(SB_{2019} < 0.3SB_0)$	–	0.499	–
SB_{2020}	1.655	4.296	12.149
SB_{2020}/SB_0	0.073	0.184	0.500
$SB_{2020}/0.3SB_0$	0.243	0.614	1.665
$P(SB_{2020} < 0.3SB_0)$	–	0.797	–
$P(SB_{2020} < 0.6SB_0)$	–	0.970	–
Proportion aged 3	0.12	0.43	0.79
Proportion aged 4-10	0.10	0.28	0.56

Table 25. Posterior (5th, 50th, and 95th percentile) estimates of proposed reference points for the Prince Rupert District major stock assessment region. See Table 24 for description.

Reference point	5%	50%	95%
SB_0	45.213	58.546	87.672
$0.3SB_0$	13.564	17.564	26.302
SB_{2019}	13.141	23.223	39.807
SB_{2019}/SB_0	0.209	0.389	0.679
$SB_{2019}/0.3SB_0$	0.696	1.297	2.262
$P(SB_{2019} < 0.3SB_0)$	–	0.241	–
SB_{2020}	11.103	22.627	45.698
SB_{2020}/SB_0	0.175	0.378	0.772
$SB_{2020}/0.3SB_0$	0.584	1.259	2.575
$P(SB_{2020} < 0.3SB_0)$	–	0.294	–
$P(SB_{2020} < 0.6SB_0)$	–	0.857	–
Proportion aged 3	0.06	0.20	0.50
Proportion aged 4-10	0.42	0.71	0.89

Table 26. Posterior (5th, 50th, and 95th percentile) estimates of proposed reference points for the Central Coast major stock assessment region. See Table 24 for description.

Reference point	5%	50%	95%
SB_0	43.844	54.534	71.396
$0.3SB_0$	13.153	16.360	21.419
SB_{2019}	19.331	33.366	55.574
SB_{2019}/SB_0	0.347	0.607	1.006
$SB_{2019}/0.3SB_0$	1.156	2.022	3.352
$P(SB_{2019} < 0.3SB_0)$	–	0.018	–
SB_{2020}	13.224	29.770	59.835
SB_{2020}/SB_0	0.241	0.542	1.096
$SB_{2020}/0.3SB_0$	0.804	1.807	3.653
$P(SB_{2020} < 0.3SB_0)$	–	0.114	–
$P(SB_{2020} < 0.6SB_0)$	–	0.590	–
Proportion aged 3	0.06	0.21	0.52
Proportion aged 4-10	0.39	0.69	0.88

Table 27. Posterior (5th, 50th, and 95th percentile) estimates of proposed reference points for the Strait of Georgia major stock assessment region. See Table 24 for description.

Reference point	5%	50%	95%
SB_0	108.543	136.306	196.563
$0.3SB_0$	32.563	40.892	58.969
SB_{2019}	36.204	64.281	111.761
SB_{2019}/SB_0	0.246	0.464	0.837
$SB_{2019}/0.3SB_0$	0.820	1.547	2.791
$P(SB_{2019} < 0.3SB_0)$	–	0.126	–
SB_{2020}	27.184	54.242	110.086
SB_{2020}/SB_0	0.190	0.389	0.806
$SB_{2020}/0.3SB_0$	0.634	1.298	2.687
$P(SB_{2020} < 0.3SB_0)$	–	0.278	–
$P(SB_{2020} < 0.6SB_0)$	–	0.847	–
Proportion aged 3	0.13	0.33	0.63
Proportion aged 4-10	0.25	0.48	0.71

Table 28. Posterior (5th, 50th, and 95th percentile) estimates of proposed reference points for the West Coast of Vancouver Island major stock assessment region. See Table 24 for description.

Reference point	**5%**	**50%**	**95%**
SB_0	37.267	46.201	60.046
$0.3SB_0$	11.180	13.860	18.014
SB_{2019}	11.411	20.664	35.721
SB_{2019}/SB_0	0.240	0.442	0.785
$SB_{2019}/0.3SB_0$	0.801	1.473	2.616
$P(SB_{2019} < 0.3SB_0)$	–	0.135	–
SB_{2020}	10.997	21.928	44.530
SB_{2020}/SB_0	0.238	0.471	0.963
$SB_{2020}/0.3SB_0$	0.793	1.569	3.211
$P(SB_{2020} < 0.3SB_0)$	–	0.142	–
$P(SB_{2020} < 0.6SB_0)$	–	0.716	–
Proportion aged 3	0.12	0.32	0.64
Proportion aged 4-10	0.26	0.49	0.74

Table 29. Management procedure (MP) performance for the Prince Rupert District major stock assessment region under three operating model (OM) scenarios: density-dependent mortality (DDM), density-independent 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. 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); SB_t is spawning biomass in year t; SB_0 is estimated unfished spawning biomass; average annual variability (AAV); C_t is catch in year t; and $\overline{C}$ is average catch. MPs are defined in DFO (2019a) and DFO (2019c). Note: dashes indicate that TAC and HR do not apply, either because the MP specifies no fishing, or because the MP fails to meet Objective 1.

Scenario		Conservation	Biomass	Yield				
		Objective 1 (LRP)	**Objective 2**	**Objective 3**	**Objective 4**	**Catch < 650 t**	**2020 TAC by MP (1000 t)**	**HR**
		$\geq 75\%$	$\geq 50\%$	$< 25\%$	max	min		
OM	**MP**	$P(SB_t > 0.3SB_0)$	$P(SB_t \geq 0.6SB_0)$	AAV	$\overline{C}$	$P(C_t < 650\ \mathrm{t})$		
DDM	NoFish_FSC	79%	44%	3.82	0.27	100%	–	–
DDM	HS30-60_HR0.05	78%	40%	36.50	1.28	44%	0.28	0.01
DDM	HS50-60_HR0.2_cap2.5	78%	40%	39.43	1.43	57%	0.00	0.00
DDM	minE0.5B0_HR0.1	78%	37%	51.86	1.85	57%	0.00	0.00
DDM	HS30-60_HR0.1_cap2.5	77%	38%	33.35	1.64	39%	0.57	0.03
DDM	minE0.5B0_HR0.2	76%	28%	67.14	2.71	58%	0.00	0.00
DDM	minE12.1_HR0.2	61%	18%	41.80	4.74	18%	–	–
DIM	NoFish_FSC	68%	32%	3.98	0.27	100%	–	–
DIM	HS30-60_HR.05	66%	27%	41.91	0.97	53%	–	–
DIM	HS50-60_HR.2_cap2.5	66%	27%	41.89	0.94	67%	–	–
DIM	minE.5B0_HR.1	66%	24%	57.00	1.20	67%	–	–
DIM	HS30-60_HR.1_cap2.5	65%	26%	41.46	1.43	48%	–	–
DIM	minE.5B0_HR.2	63%	18%	75.94	1.56	70%	–	–
conM	NoFish_FSC	100%	73%	3.61	0.27	100%	–	–
conM	HS50-60_HR.2_cap2.5	100%	66%	40.10	1.76	38%	0.00	0.00
conM	HS30-60_HR.05	100%	65%	37.00	2.02	22%	0.28	0.01
conM	HS30-60_HR.1_cap2.5	99%	63%	24.63	2.12	19%	0.57	0.03
conM	minE.5B0_HR.1	98%	58%	52.45	3.11	37%	0.00	0.00
conM	minE.5B0_HR.2	96%	43%	62.26	5.17	37%	0.00	0.00

Table 30. Management procedure (MP) performance for the Central Coast major stock assessment region. See Table 29 for description.

Scenario		Conservation Objective 1 (LRP)	Biomass Objective 2	Yield Objective 3	Yield Objective 4	Yield Catch < 650 t	2020 TAC by MP (1000 t)	HR
		$\geq 75\%$	$\geq 50\%$	$< 25\%$	max	min		
OM	MP	$P(SB_t > 0.3SB_0)$	$P(SB_t \geq 0.6SB_0)$	AAV	$\overline{C}$	$P(C_t < 650\,\text{t})$		
DDM	NoFish_FSC	78%	42%	6.74	0.27	100%	–	–
DDM	HS30-60_HR0.05	77%	37%	39.92	1.09	45%	1.20	0.04
DDM	minE0.5B0_HR0.1	76%	33%	52.30	1.54	57%	2.29	0.08
DDM	HS30-60_HR0.1_cap5.0	75%	32%	46.10	1.81	33%	2.41	0.08
DDM	minE17.6_HR0.2	70%	20%	62.84	3.26	38%	–	–
DIM	NoFish_FSC	58%	21%	9.33	0.27	100%	–	–
DIM	HS30-60_HR.05	55%	17%	40.94	0.66	64%	–	–
DIM	minE.5B0_HR.1	55%	15%	44.30	0.78	74%	–	–
DIM	HS30-60_HR.1_cap5.0	52%	14%	53.32	1.00	52%	–	–
conM	NoFish_FSC	100%	84%	6.67	0.27	100%	–	–
conM	HS30-60_HR.05	99%	75%	39.69	2.68	15%	1.20	0.04
conM	HS30-60_HR.1_cap5.0	99%	69%	26.62	3.93	11%	2.41	0.08
conM	minE.5B0_HR.1	98%	67%	45.77	4.62	24%	2.29	0.08

Table 31. Management procedure (MP) performance for the Strait of Georgia major stock assessment region. See Table 29 for description.

Scenario		Conservation	Biomass	Yield				
		Objective 1 (LRP)	Objective 2	Objective 3	Objective 4	Catch < 650 t	2020 TAC	HR
		$\geq 75\%$	$\geq 50\%$	$< 25\%$	max	min	by MP	
OM	**MP**	$P(SB_t > 0.3SB_0)$	$P(SB_t \geq 0.6SB_0)$	AAV	$\overline{C}$	$P(C_t < 650$ t$)$	**(1000 t)**	
DDM	NoFish_FSC	100%	97%	0.00	0.14	100%	–	–
DDM	minE0.5B0_HR0.1_cap30.0	99%	92%	23.50	21.48	2%	0.00	0.00
DDM	HS30-60_HR0.1_cap30.0	99%	92%	22.98	21.48	0%	1.61	0.03
DDM	minE21.2_HR0.1	99%	91%	29.64	23.44	0%	5.42	0.10
DDM	minE0.5B0_HR0.2	98%	79%	28.35	39.87	3%	0.00	0.00
DDM	HS30-60_HR0.2_cap30.0	98%	78%	27.83	39.87	0%	3.22	0.06
DDM	minE21.2_HR0.2	97%	78%	26.97	39.87	0%	10.85	0.20
DIM	NoFish_FSC	99%	98%	0.00	0.14	100%	–	–
DIM	minE21.2_HR0.1	99%	93%	29.63	24.88	0%	5.42	0.10
DIM	minE0.5B0_HR0.1_cap30.0	99%	93%	22.94	22.63	2%	0.00	0.00
DIM	HS30-60_HR0.1_cap30.0	99%	93%	22.94	22.63	0%	1.61	0.03
DIM	minE0.5B0_HR0.2	98%	85%	28.73	43.92	3%	0.00	0.00
DIM	HS30-60_HR0.2_cap30.0	97%	85%	27.97	43.92	1%	3.22	0.06
DIM	minE21.2_HR0.2	97%	84%	27.14	43.92	0%	10.85	0.20
conM	NoFish_FSC	100%	84%	0.00	0.14	100%	–	–
conM	minE21.2_HR0.1	99%	60%	33.54	13.80	0%	5.42	0.10
conM	minE0.5B0_HR0.1_cap30.0	99%	60%	36.19	13.43	6%	0.00	0.00
conM	HS30-60_HR0.1_cap30.0	99%	60%	35.22	13.56	1%	1.61	0.03
conM	minE0.5B0_HR0.2	93%	35%	38.63	23.31	9%	0.00	0.00
conM	HS30-60_HR0.2_cap30.0	92%	33%	34.28	23.76	1%	3.22	0.06
conM	minE21.2_HR0.2	91%	31%	28.27	24.08	0%	10.85	0.20

Figures

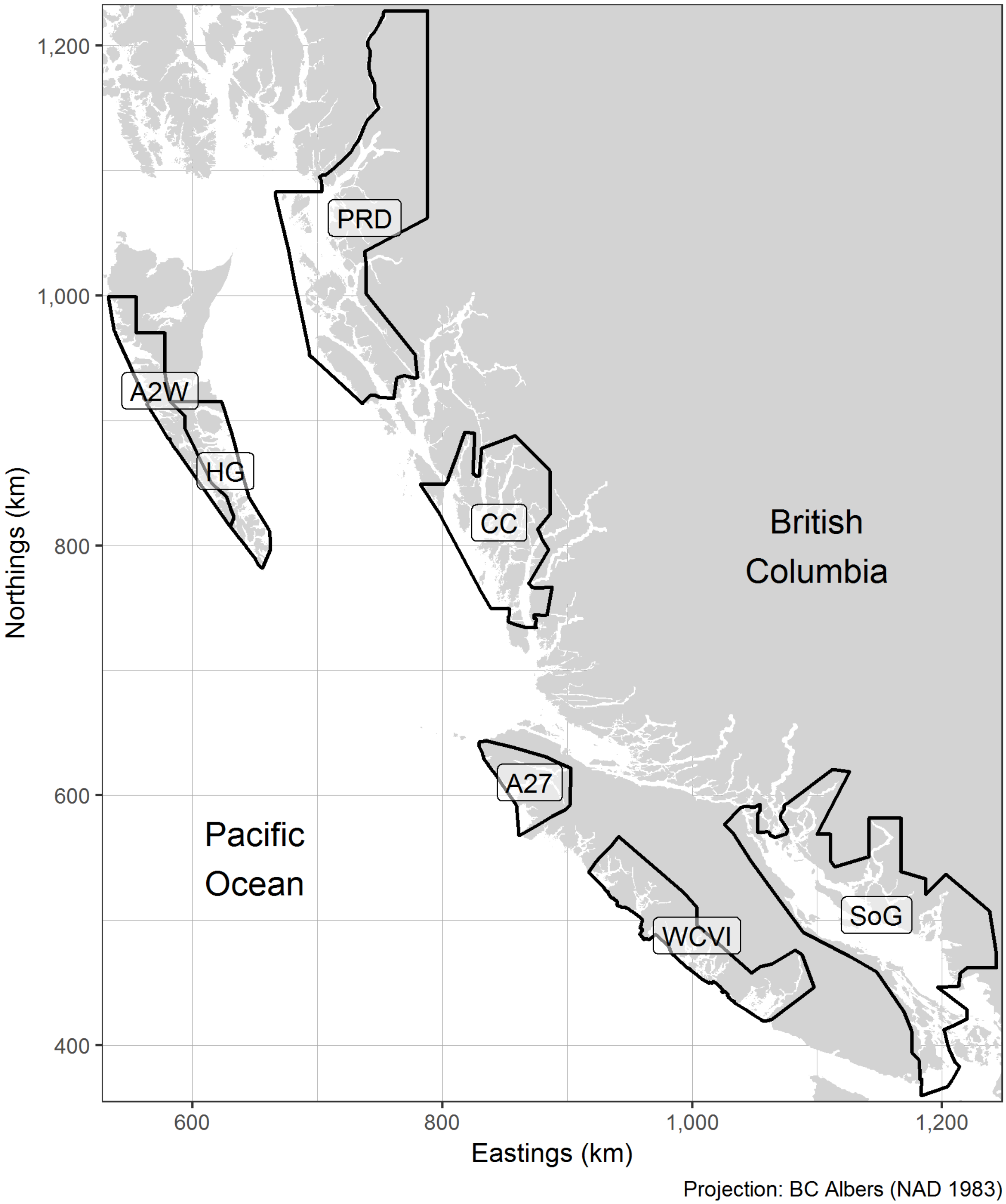

Figure 1. Boundaries for the Pacific Herring stock assessment regions (SARs) in British Columbia. The major SARs are Haida Gwaii (HG), Prince Rupert District (PRD), Central Coast (CC), Strait of Georgia (SoG), and West Coast of Vancouver Island (WCVI). The minor SARs are Area 27 (A27) and Area 2 West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

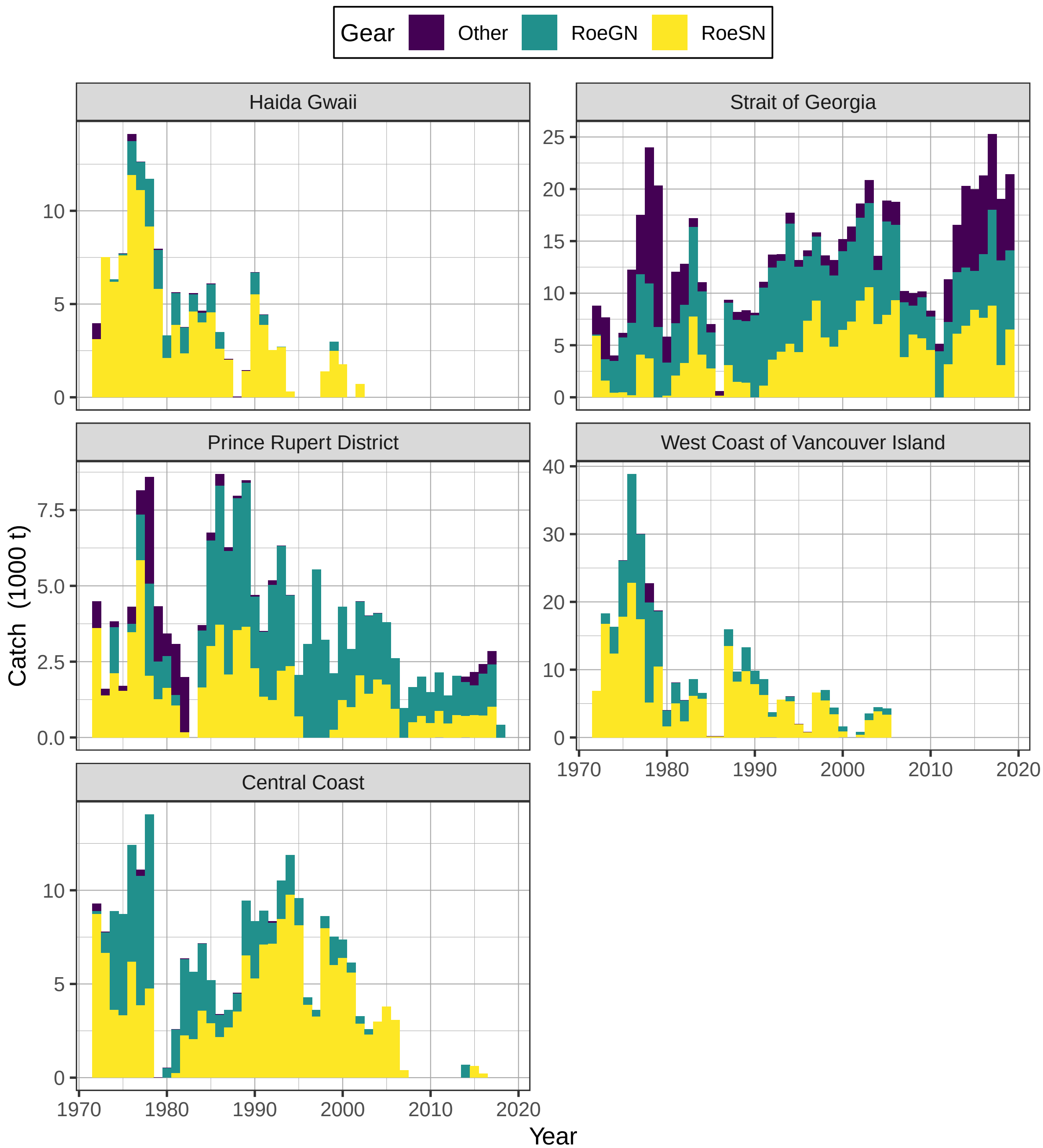

Figure 2. Time series of total landed catch in thousands of tonnes (t) of Pacific Herring from 1972 to 2019 in the major stock assessment regions. See Figures 6 to 10 for catches during the reduction period (1951 to 1971). Legend: 'Other' represents the reduction, the food and bait, as well as the special use fishery; 'RoeGN' represents the roe gillnet fishery; and 'RoeSN' represents the roe seine fishery.

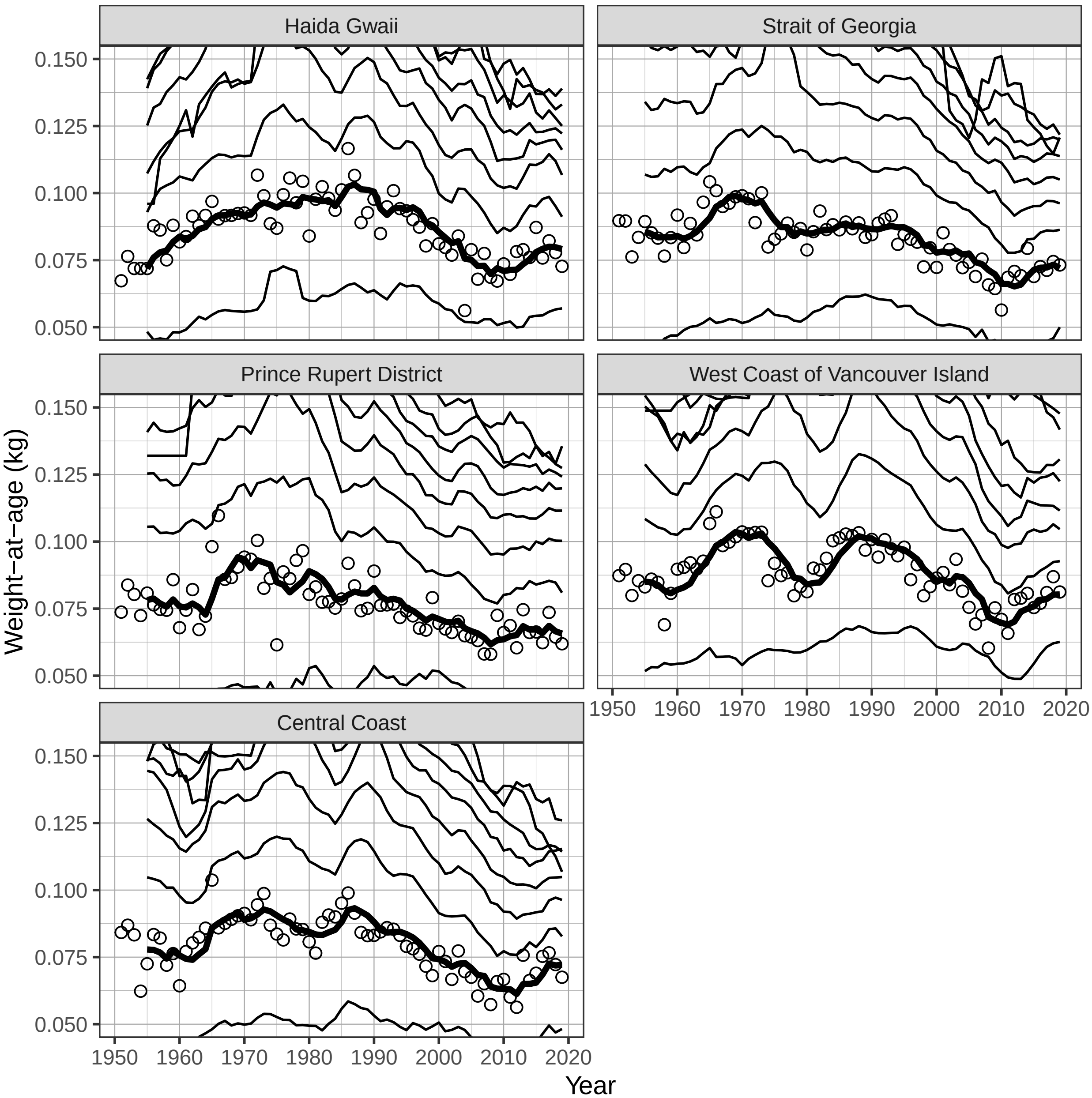

Figure 3. Time series of weight-at-age in kilograms (kg) for age-3 (circles) and 5-year running mean weight-at-age (lines) for Pacific Herring from 1951 to 2019 in the major stock assessment regions. Lines show 5-year running means for age-2 to age-10 herring (incrementing higher from the lowest line); 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: missing values at the beginning of the time series are imputed by extending the frst non-missing value backwards; other missing 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.

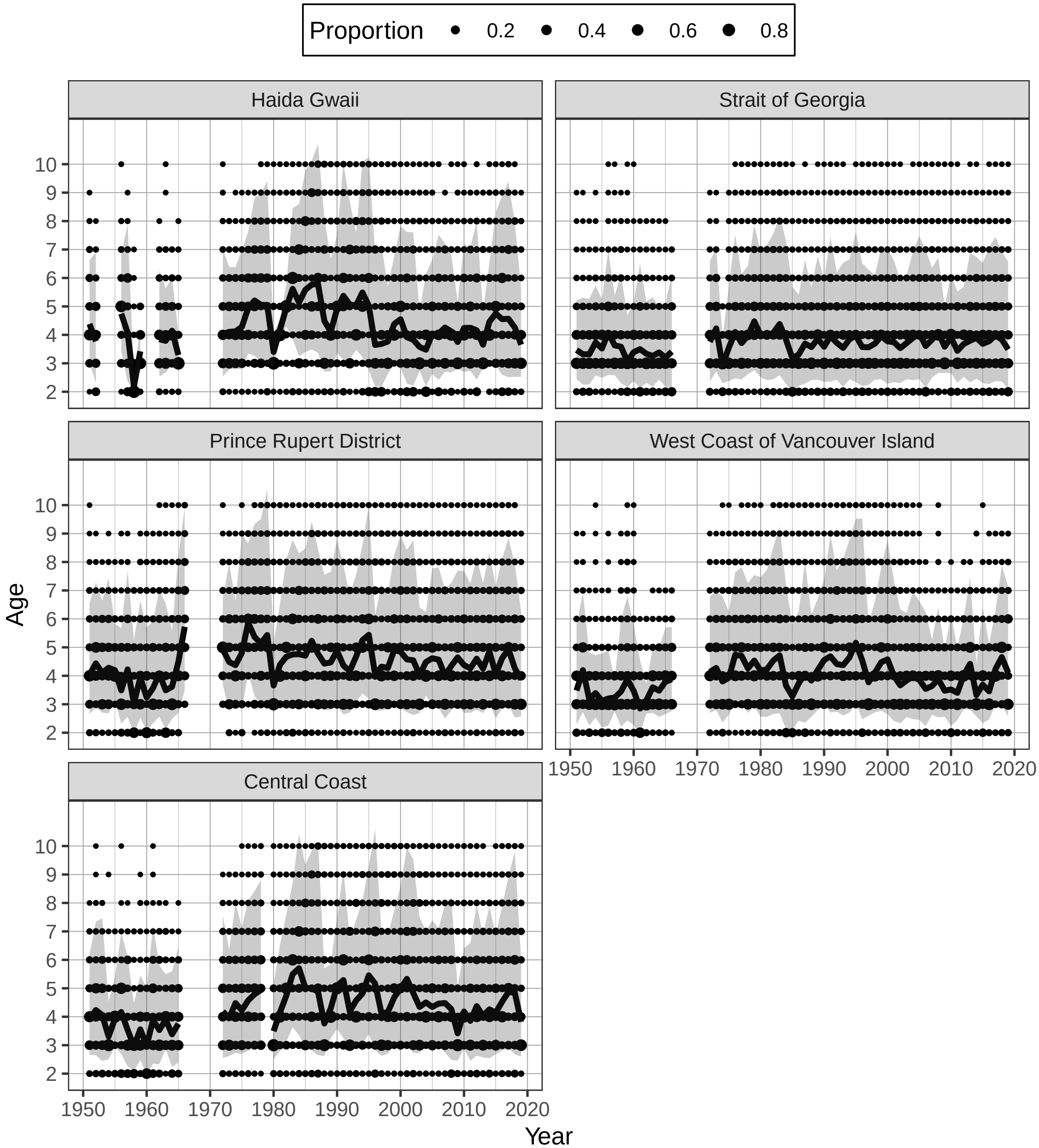

Figure 4. Time series of proportion-at-age for Pacific Herring from 1951 to 2019 in the major stock assessment regions. The black line is the mean age, and the shaded area is the approximate 90% distribution. Biological summaries only include samples collected using seine nets (commercial and test) due 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.

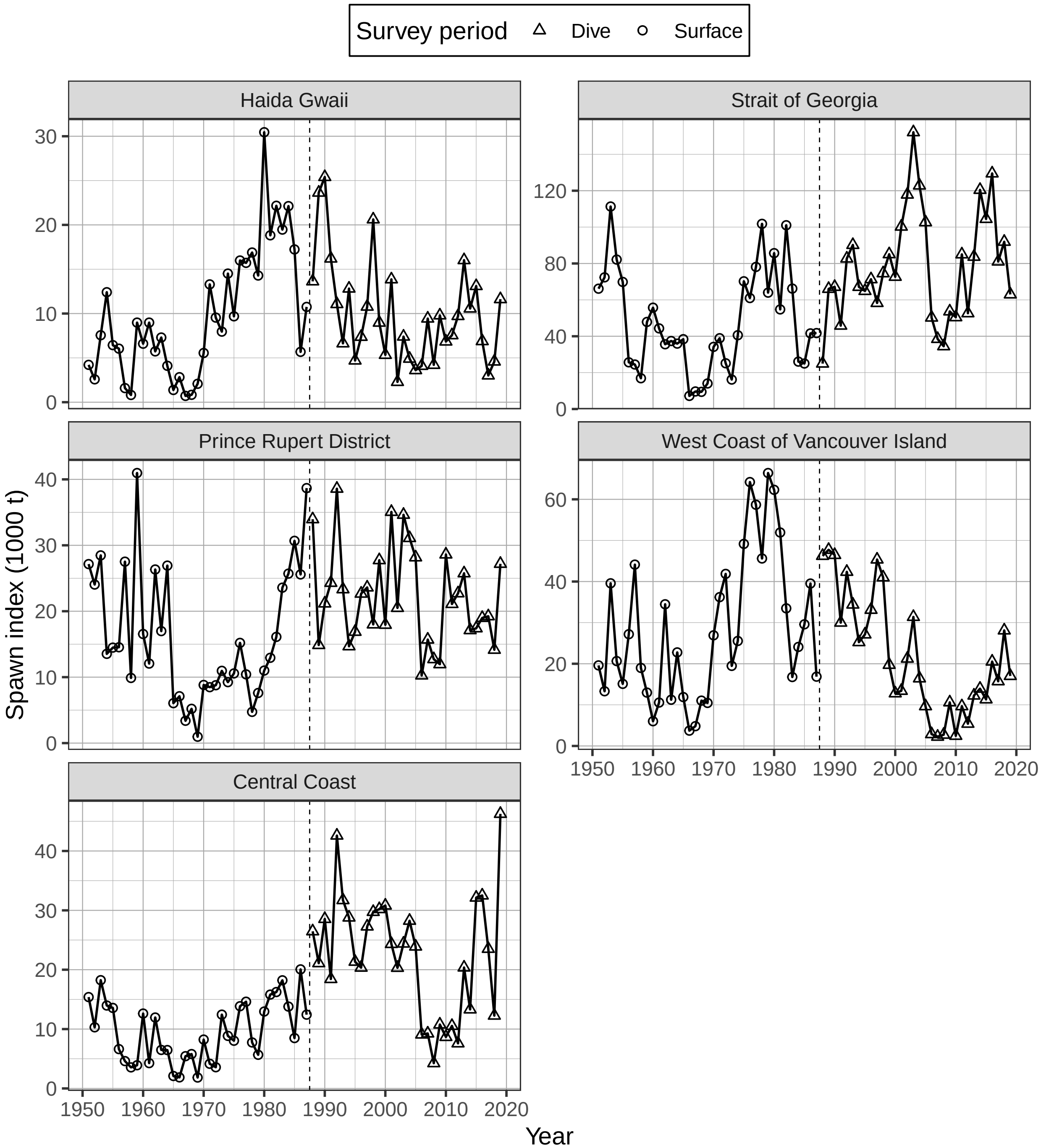

Figure 5. Time series of spawn index in thousands of tonnes (t) for Pacific Herring from 1951 to 2019 in the major stock assessment regions. The spawn index has two distinct periods defned by the dominant survey method: surface surveys (1951 to 1987), and dive surveys (1988 to 2019). The dashed vertical line is the boundary between these two periods. Note: the 'spawn index' is not scaled by the spawn survey scaling parameter q.

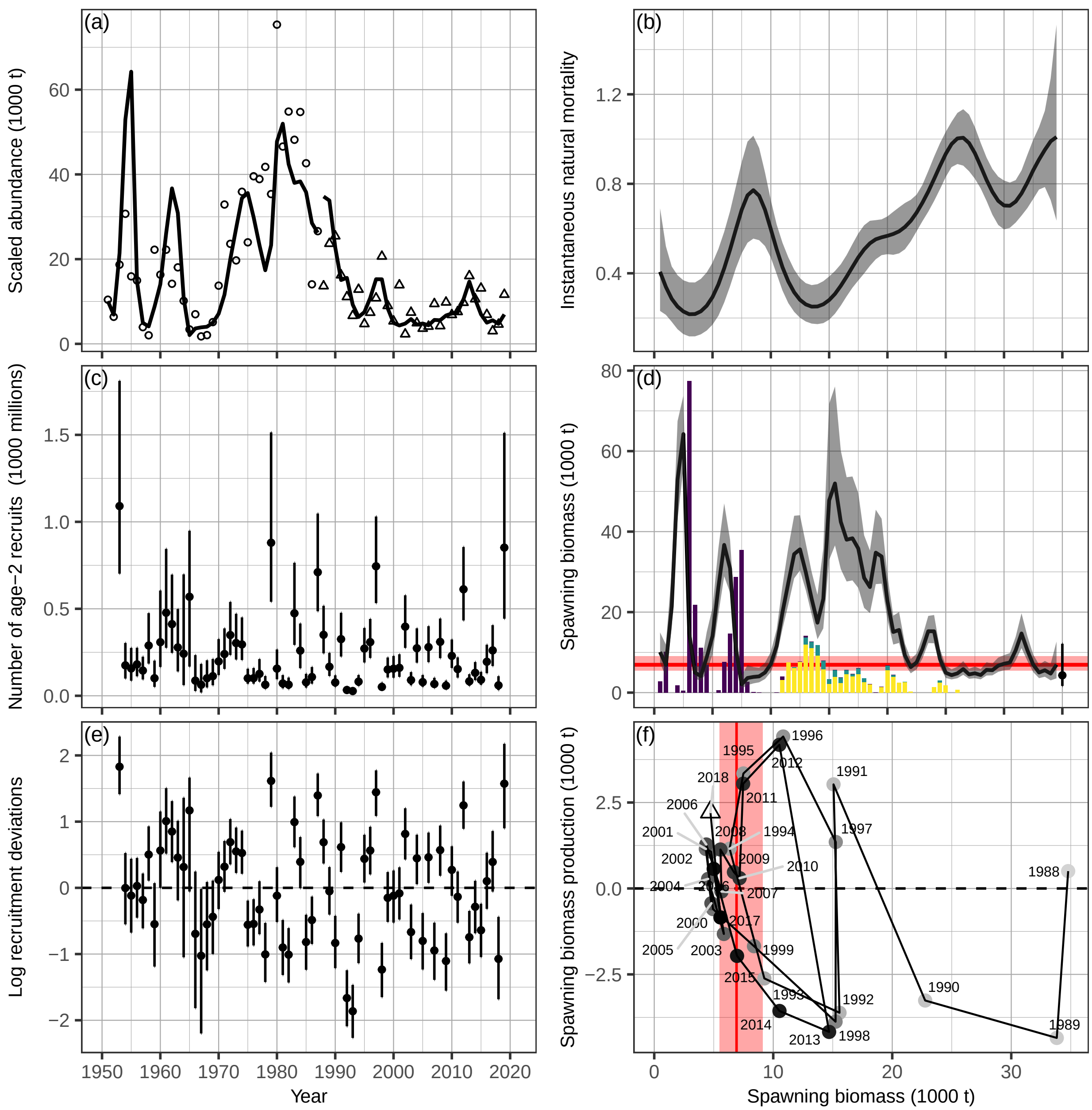

Figure 6. Model output for Pacific Herring in the Haida Gwaii major stock assessment region. Panel (a): model fit to scaled spawn survey data in thousands of tonnes (t). Spawn survey data (i.e., spawn index) is scaled to abundance by the spawn survey scaling parameter q. Panel (b): posterior estimates of instantaneous natural mortality rate. Panel (c): reconstructed number of age-2 recruits in thousands of millions. Panel (d): posterior estimate of spawning biomass SB_t in year t in thousands of tonnes. Circle and vertical line indicate the median and 90% credible interval, respectively, of forecast spawning biomass in 2020 in the absense of fishing. Vertical bars indicate commercial catch C_t, 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): circles and vertical lines indicate medians and 90% credible intervals, respectively. Panel (f): phase plot of spawning biomass production ($\frac{SB_{t+1}-SB_t+C_{t+1}}{SB_t}$) for the dive survey period (1988 to 2018; maximum posterior density estimates). Grey shading becomes darker in chronological order; the triangle indicates 2018. 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.

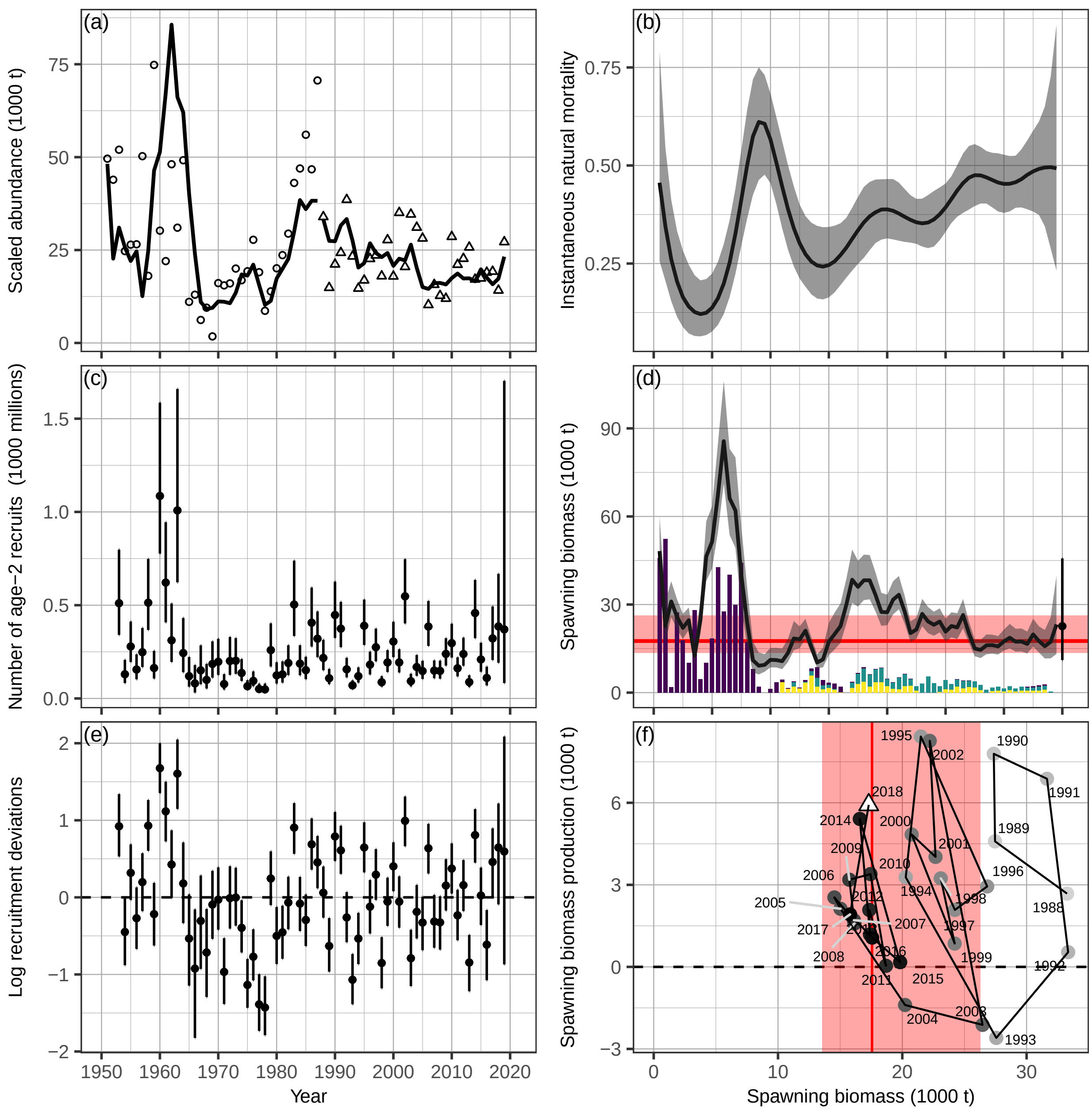

Figure 7. Model output for Pacific Herring in the Prince Rupert District major stock assessment region. See Figure 6 for description.

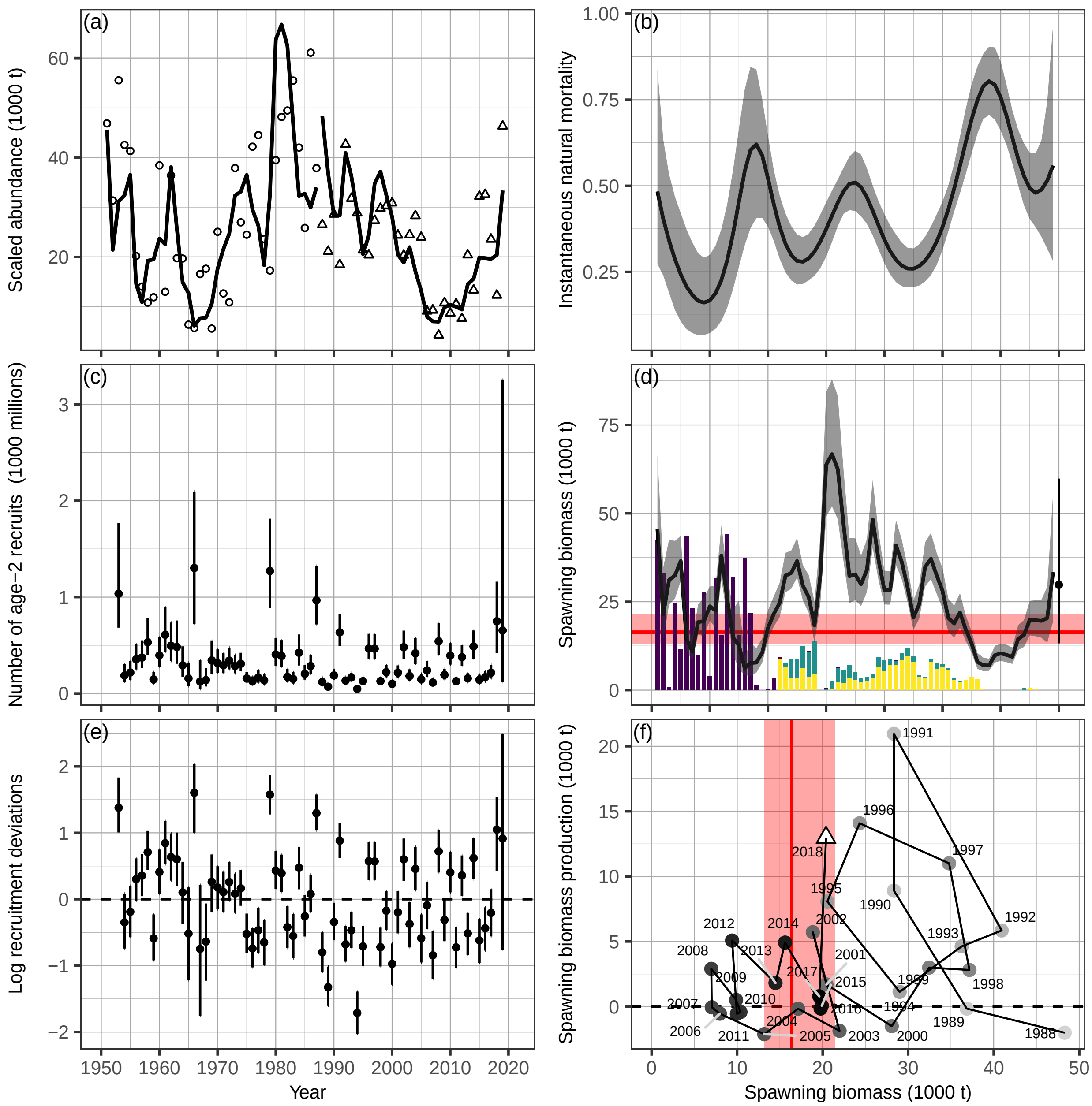

Figure 8. Model output for Pacific Herring in the Central Coast major stock assessment region. See Figure 6 for description.

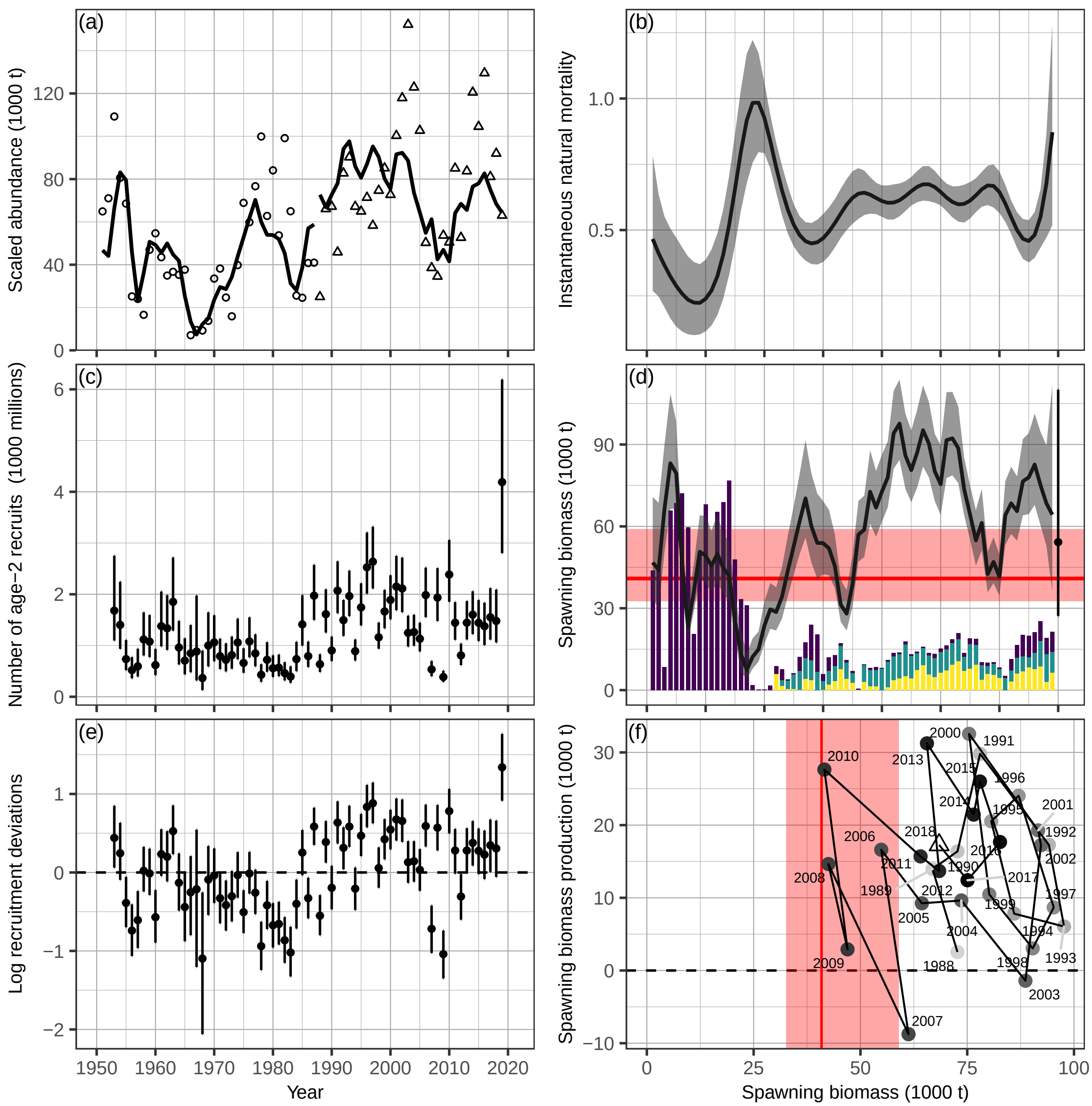

Figure 9. Model output for Pacific Herring in the Strait of Georgia major stock assessment region. See Figure 6 for description.

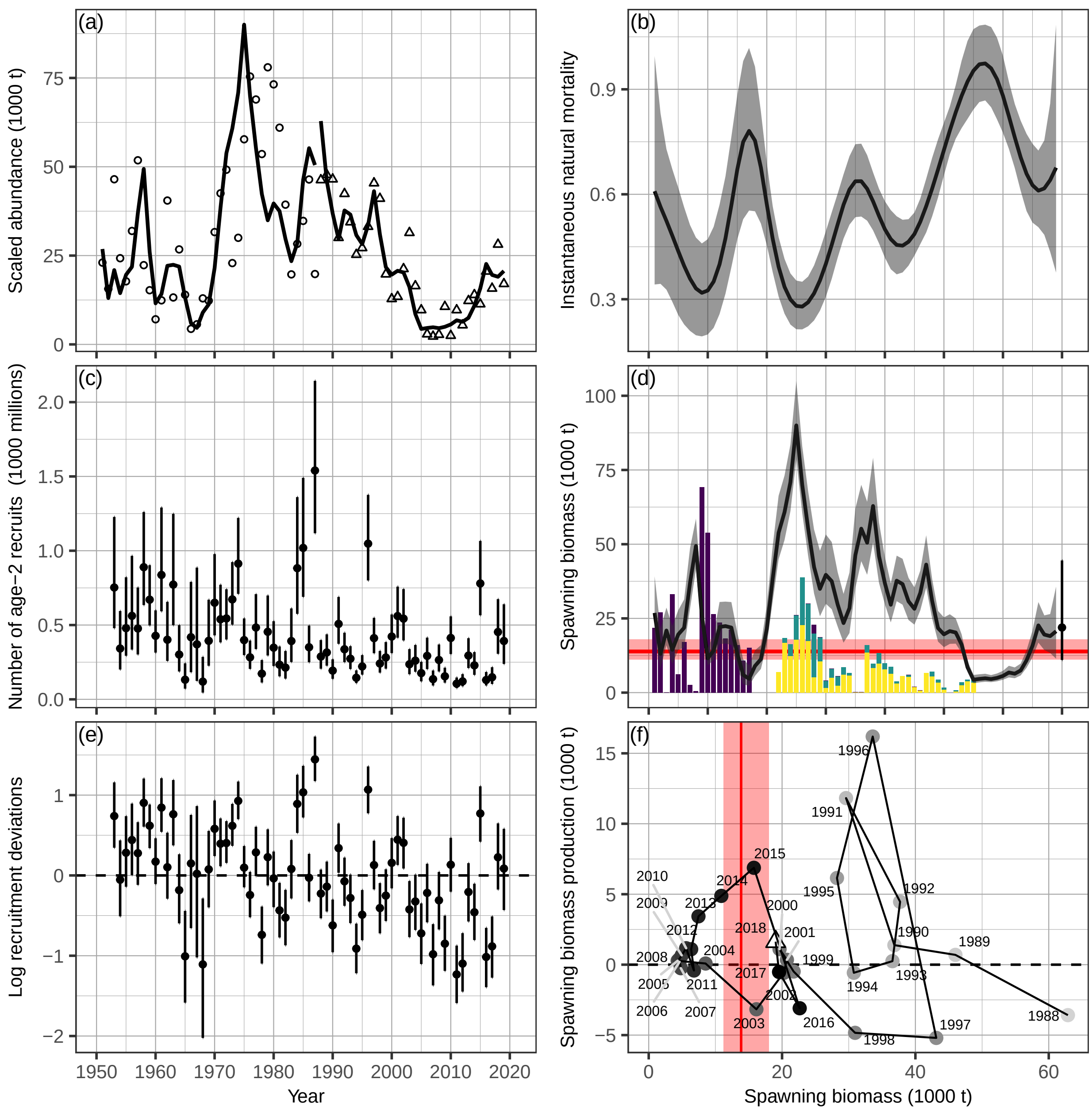

Figure 10. Model output for Pacific Herring in the West Coast of Vancouver Island major stock assessment region. See Figure 6 for description.

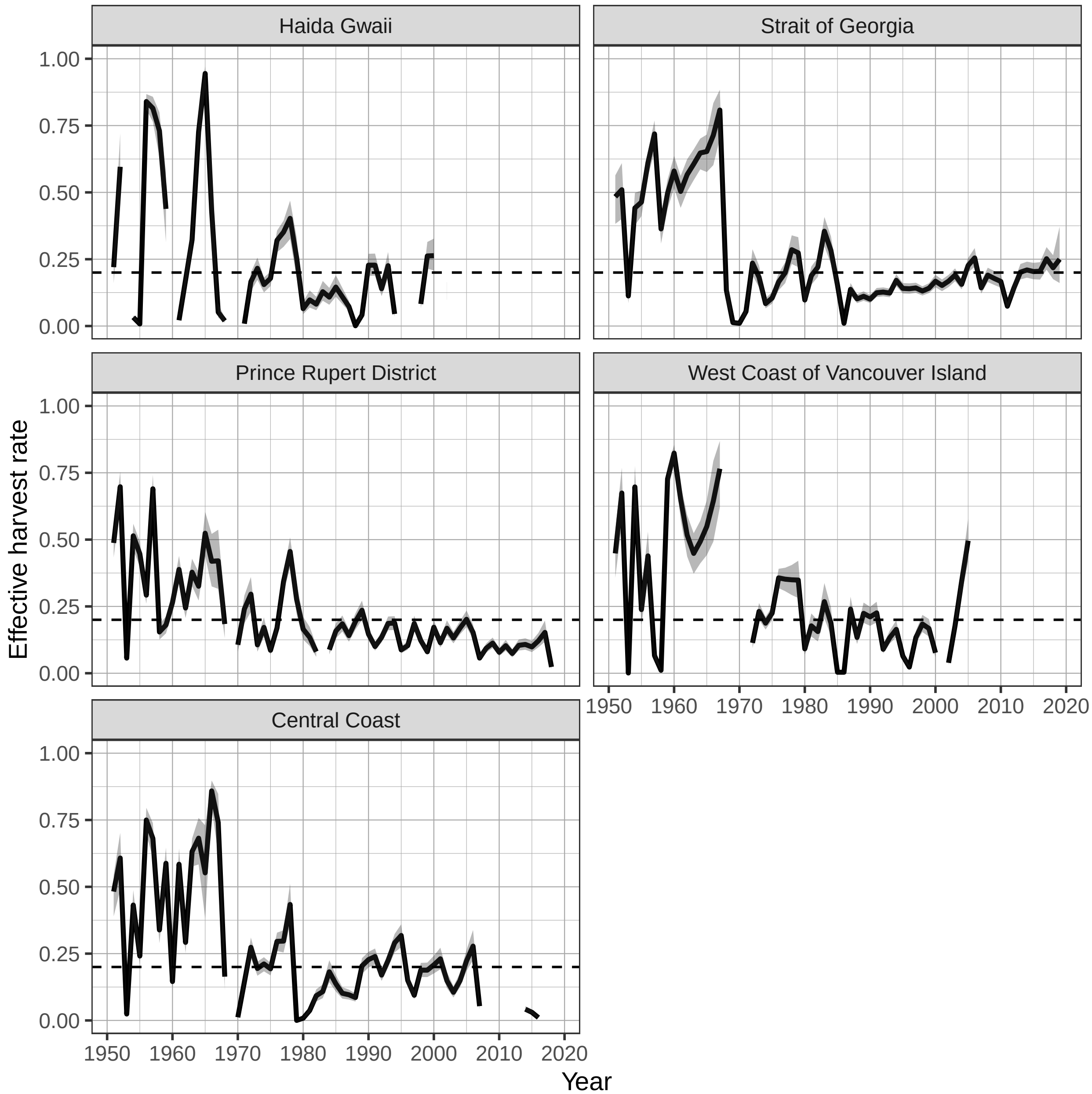

Figure 11. Time series of effective harvest rate U for Pacific Herring from 1951 to 2019 in the major stock assessment regions. Effective harvest rate in year t is calculated as $U_t = C_t/(C_t + SB_t)$ where C_t is catch in year t, and SB_t is estimated spawning biomass in year t. Black lines and shaded ribbons indicate medians and 90% confidence intervals for U_t, respectively. Horizontal dashed lines indicate $U_t = 0.2$.

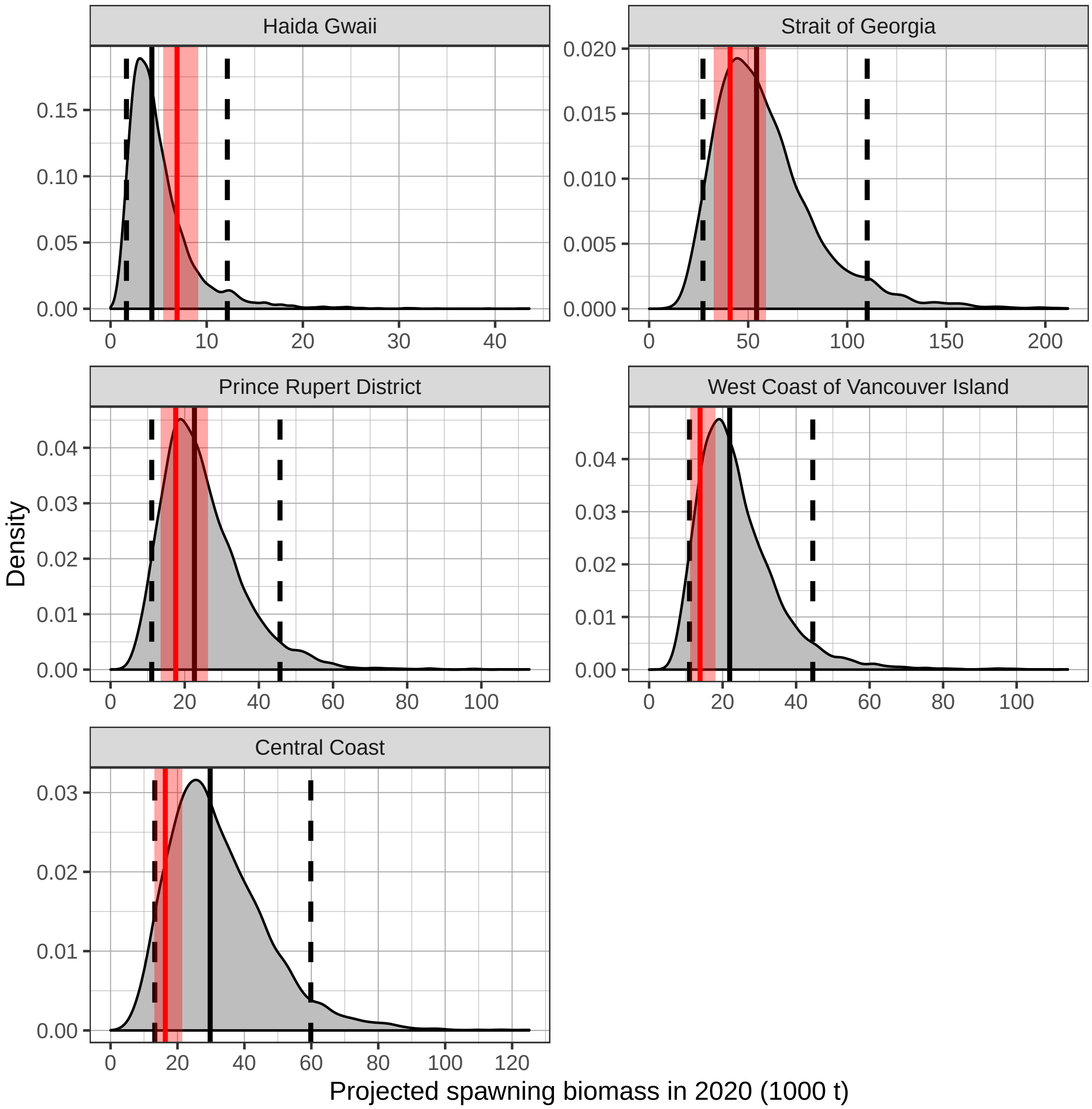

Figure 12. Projected spawning biomass assuming no fishing in 2020 SB_{2020} in thousands of tonnes (t) for Pacific Herring in the major stock assessment regions. Solid and dashed vertical lines indicate medians and 90% confidence intervals for SB_{2020}, respectively. Vertical red lines and shaded red 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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Sources of information

Cleary, J.S., Hawkshaw, S., Grinnell, M.H., and Grandin, C. 2018. Status of B.C. Pacific Herring (*Clupea pallasii*) in 2017 and forecasts for 2018. DFO Can. Sci. Advis. Sec. Res. Doc. 2018/028.

DFO. 2009. A fishery decision-making framework incorporating the precautionary approach. Fisheries and Oceans Canada online: (last reportedly modified 23 May 2009, however, figures have since changed).

DFO. 2012. A review of the Pacific Herring assessment framework and stock assessment and management advice for Pacific Herring 2011 status and 2012 forecasts. DFO Can. Sci. Advis. Sec. Proceed. Ser. 2011/062.

DFO. 2013. Guidance for the development of rebuilding plans under the precautionary approach framework: Growing stocks out of the critical zone. Sustainable fisheries framework (SFF): A fishery decision-making framework incorporating the precautionary approach.

DFO. 2016. Stock assessment and management advice for B.C. Pacific Herring: 2016 status and 2017 forecast. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/052.

DFO. 2017. Pacific Region integrated fisheries management plan, Pacific Herring. November 7, 2017 to November 6, 2018.: 178 p.

DFO. 2019a. 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. Advis. Rep.

DFO. 2019b. Stock assessment and management advice for B.C. Pacific Herring: 2018 status and 2019 forecast. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/001.

DFO. 2019c. Evaluation of management procedures for Pacific Herring (*Clupea pallasii*) in Haida Gwaii, Prince Rupert District and the Central Coast management areas of British Columbia. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep.

Hall, D.L., Hilborn, R., Stocker, M., and Walters, C.J. 1988. Alternative harvest strategies for pacific herring (*Clupea harengus pallasi*). Can. J. Fish. Aquat. Sci 45(12): 888–897.

Kronlund, A.R., Forrest, R.E., Cleary, J.S., and Grinnell, M.H. 2017. The selection and role of limit reference points for Pacific Herring (*Clupea pallasii*) in British Columbia, Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2018/009: ix + 125p.

Martell, S.J., Schweigert, J., Haist, V., and Cleary, J.S. 2012. Moving towards the sustainable fisheries framework for Pacific Herring: Data, models, and alternative assumptions; stock assessment and management advice for the British Columbia Pacific Herring stocks: 2011 assessment and 2012 forecasts. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/136: v + 151p.

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 2010 to 2019 (Table 33). We also provide time series of landed commercial catch (Figure 13), biological data including weight-at-age (Figure 14) and proportion-at-age (Figure 15), as well as the spawn index (Figure 16) from 1978 to 2019.

Table 33. Spawn index in tonnes of Pacific Herring in the minor stock assessment regions (SARs) from 2010 to 2019. Legend: Area 27 (A27) and Area 2 West (A2W). Notes: the 'spawn index' is not scaled by the spawn survey scaling parameter q, and, if present, 'NA' indicates that data are not available.

	SAR	
Year	**A27**	**A2W**
2010	846	2,725
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

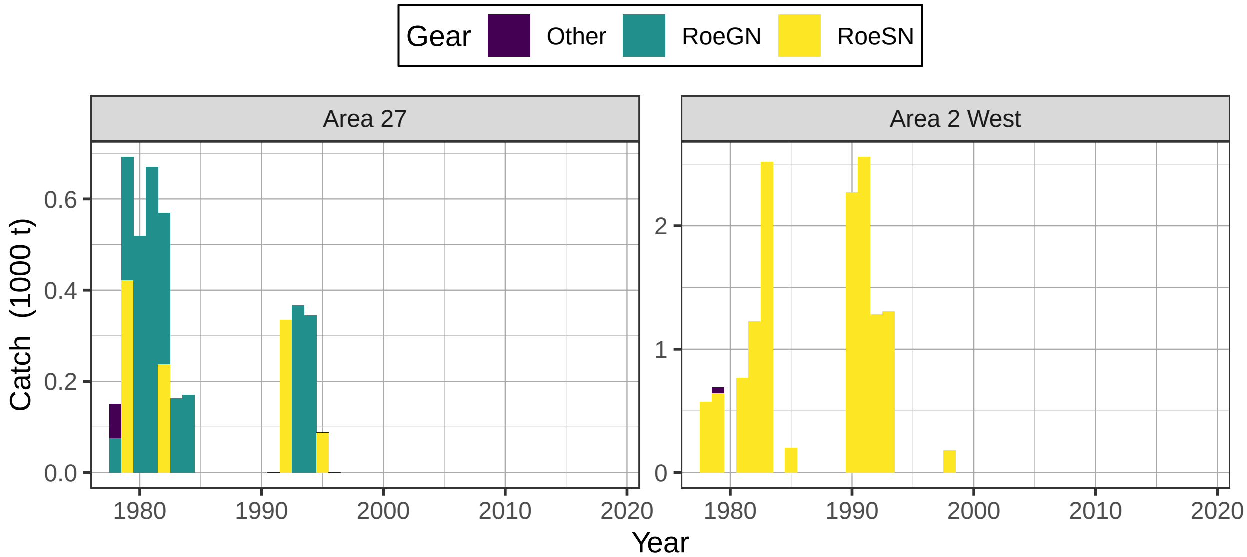

Figure 13. Time series of total landed catch in thousands of tonnes (t) of Pacific Herring from 1978 to 2019 in the minor stock assessment regions. Legend: 'Other' represents the reduction, the food and bait, as well as the special use fishery; 'RoeGN' represents the roe gillnet fishery; and 'RoeSN' represents the roe seine fishery.

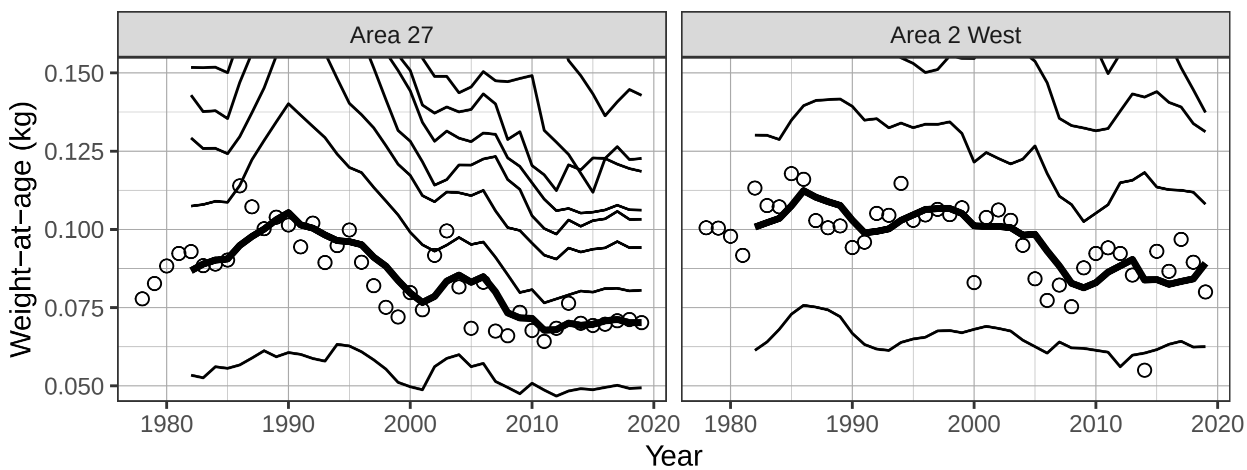

Figure 14. Time series of weight-at-age in kilograms (kg) for age-3 (circles) and 5-year running mean weight-at-age (lines) for Pacific Herring from 1978 to 2019 in the minor stock assessment regions. Lines show 5-year running means for age-2 to age-10 herring (incrementing higher from the lowest line); 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: missing values at the beginning of the time series are imputed by extending the frst non-missing value backwards; other missing 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.

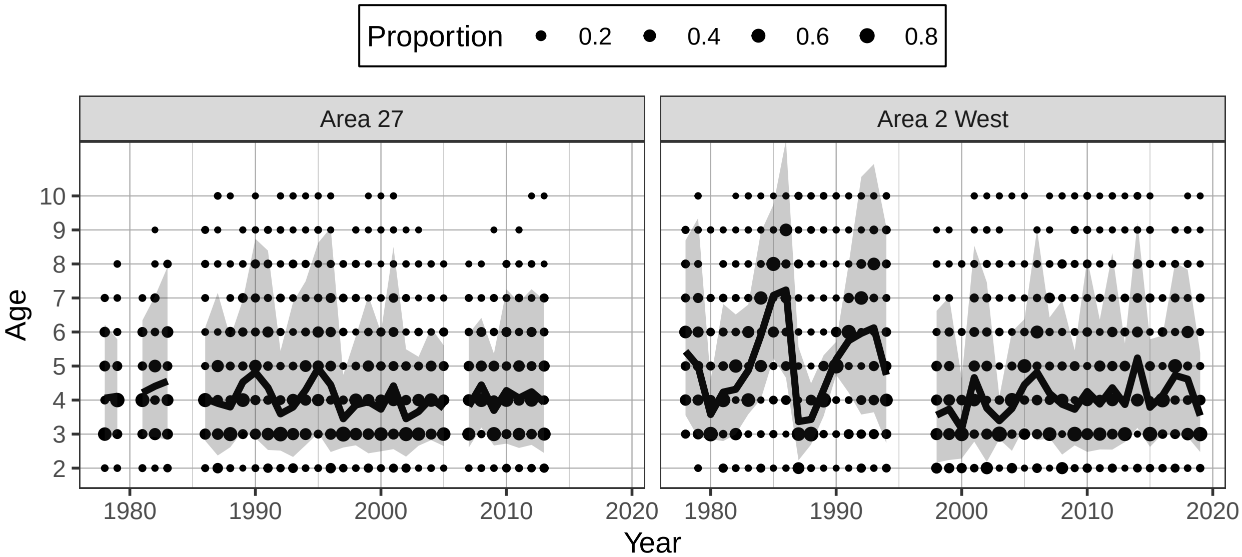

Figure 15. Time series of proportion-at-age for Pacific Herring from 1978 to 2019 in the minor stock assessment regions. The black line is the mean age, and the shaded area is the approximate 90% distribution. Biological summaries only include samples collected using seine nets (commercial and test) 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.

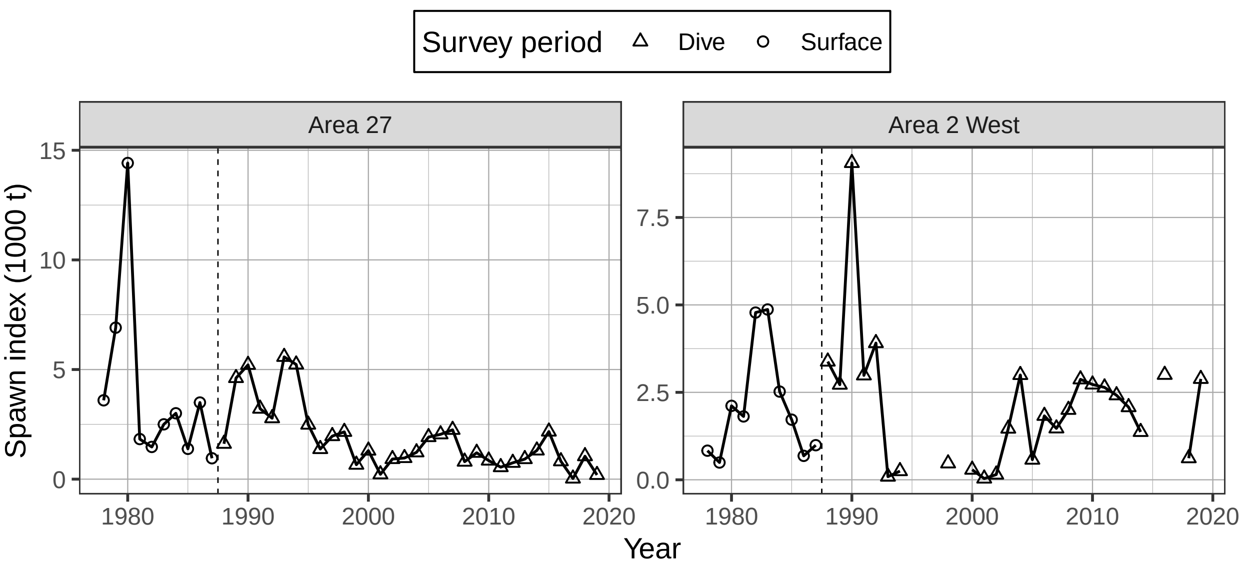

Figure 16. Time series of spawn index in thousands of tonnes (t) for Pacific Herring from 1978 to 2019 in the minor stock assessment regions. The spawn index has two distinct periods defned by the dominant survey method: surface surveys (1951 to 1987), and dive surveys (1988 to 2019). The dashed vertical 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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