STOCK STATUS UPDATE WITH APPLICATION OF MANAGEMENT PROCEDURES FOR PACIFIC HERRING (*CLUPEA PALLASII*) IN BRITISH COLUMBIA: STATUS IN 2021 AND FORECAST FOR 2022

Context

Pacific Herring (*Clupea pallasii*) abundance in British Columbia (BC) is assessed using a statistical catch-age (SCA) model (Martell et al. 2012). In 2017, the Pacific Herring stock assessment included updates to the SCA model, 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 SCA model has not changed since 2017.

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 in the summer of 2018, where performance of Pacific Herring management procedures (MPs) were assessed against conservation objectives for the Strait of Georgia (SoG) and West Coast of Vancouver Island (WCVI) stock assessment regions (SARs) (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 Haida Gwaii (HG), Prince Rupert District (PRD), and Central Coast (CC) SARs (DFO 2020a). In the summer of 2020, updates were made to the MSE simulations for the WCVI and SoG management areas, and in the summer of 2021, similar updates were made to the MSE simulations for the PRD and CC management areas. For all four stocks, updates include 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 the SoG and WCVI SARs for 2019 (DFO 2019b).
2. The 2019 stock assessment included MP recommendations for the SoG and WCVI SARs as per 2018, and updated MP recommendations for the HG, PRD, and CC SARs (DFO 2020b).
3. The 2020 stock assessment includes updated MP recommendations for the SoG and WCVI SARs, and MP recommendations for HG, PRD, and CC SARs as per 2019 (DFO 2020b).

4. The 2021 stock assessment includes MP recommendations for the SoG and WCVI SARs as per 2020 (DFO 2021a), and updated MP recommendations for the PRD and CC SARs. Management measures to support long-term recovery of HG herring are being developed through the rebuilding plan process.

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 2021 and recommend harvest advice for 2022 as simulation-tested MPs to inform the development of the 2021/2022 Integrated Fisheries Management Plan, where appropriate. Estimated stock trajectories, current status of stocks for 2021, management procedure options, and harvest advice recommendations from those MPs for 2022 reflect methods of Cleary et al. (2019) and, where applicable, recommendations from the aforementioned 2018, 2019 and 2020 MSE analyses (Section "Application of MPs and harvest options for 2022").

This Science Response results from the Science Response Process of September 15, 2021 on the Stock status update with application of management procedures for Pacific Herring (*Clupea pallasii*) in British Columbia: Status in 2021 and forecast for 2022.

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 major SARs. For the minor SARs, we present available catch data, biological data, and spawn survey data (Section "Minor stock assessment regions"). Beginning in 2021 we include similar data for the special area, Area 10 (Section "Special areas"). Formal analyses of stock trends are not included for minor SARs and special areas due to data availability. Note that special areas are not SARs; therefore they are excluded from regular monitoring and analyses. In addition, note that Area 10 is a subset of the Central Coast Sections that are outside the SAR boundary.

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), and roe herring. There is also a small recreational fishery.

First Nations fish for whole herring, herring roe, and herring eggs for FSC purposes. Whole herring are fished by seine, gillnet, rake, dip net, and jig. Herring eggs are collected as spawn on seaweed such as kelp (i.e., SOK), or spawn on 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. Five Nuu-chah-nulth First Nations located on the West Coast of Vancouver Island – Ahousaht, Ehattesaht, Hesquiaht, Mowachaht/Muchalaht, and Tla-o-qui-aht (the 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. DFO developed a 2021/22 Five Nations Multi-species Fishery Management Plan (FMP). Feedback provided by the Five Nations during consultations was considered by DFO in the development of the 2021/22 FMP. 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. The implementation of the Five Nations' right-based sale fishery is an ongoing process. The 2021/22 FMP was developed to implement the right-based multi-species fishery to accommodate the Five Nations' Aboriginal rights consistent with the 2018 decision of the British Columbia Supreme Court. On April 19, 2021, the British Columbia Court of Appeal released its decision in relation to the appeal brought forward by the Five Nations. As a result, the department is reviewing the 2021/22 FMP. Following this review, the 2021/22 FMP may be amended and in-season management changes to this IFMP may occur. Changes to the FMP will be announced by fishery notice.

On the Central Coast, Heiltsuk First Nation have an Aboriginal right to commercially harvest Pacific Herring SOK. The Heiltsuk currently hold nine SOK licenses in this area, 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 2020/2021, the primary Pacific Herring fisheries were seine roe and gillnet roe fisheries, with a combined coast wide catch of 10,245 tonnes (t). The FB seine fishery had a coast wide catch of 4,151 t. The roe, FB and SU fisheries operated in SoG only in 2020/2021. Three SOK operators participated in the CC SOK fisheries in 2020/2021. There were no commercial SOK fisheries in PRD in 2020/2021.

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 to inform 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 2021. Advice to managers for the major SARs includes posterior estimates of current stock status (SB_{2021}), stock status relative to the LRP of $0.3SB_0$, and spawning biomass in 2022 assuming no catch (SB_{2022}). 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 2021): 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 (DFO 2012; Martell et al. 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

Compared to 2020, the COVID-19 pandemic had fewer impacts to Pacific Herring data collection and analysis in 2021. Spawn surveys proceeded as usual in most areas in 2021, with dive surveys in all major areas except Haida Gwaii. Haida Gwaii would normally have a dive survey, but had a surface survey in 2021 due to COVID-19. The collection and analysis of biological data was not affected by the COVID-19 pandemic in 2021.

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 similar update was conducted in the summer of 2021 for the PRD and CC management areas. Results from MP evaluations reflect most recent updates for all 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 to predict natural mortality; 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, is 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 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 more heavily 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 (e.g., 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 2020/2021 herring season (July 1 to June 30). Note that we refer to 'year' instead of 'herring season' in this report; therefore 2021 refers to the 2020/2021 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 2012 to 2021 from the roe, food and bait, and special use fisheries appear in Table 2. The proportion of coast-wide catch that comes from SoG was 22% in 1990, and 100% in 2021. Total SOK harvest (pounds of validated product) for the major SARs from 2012 to 2021 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 4) and annual number-at-age, shown as proportion-at-age (Figure 5).

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 2021, although to a lesser degree for PRD.

Abundance data

The spawn index survey collects information on spawn length (i.e., distance parallel to shore), spawn width (i.e., distance 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 survey period from 1951 to 1987, and dive survey period from 1988 to 2021. 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'. The 2021 spawn survey followed standard dive survey protocols for the PRD, CC, SoG, and WCVI SARs as described in Cleary et al. (2019), and a surface survey protocol for the HG SAR due to COVID-19. Time series of spawn index by major stock assessment region (SAR) from 1951 to 2021 are summarized in Figure 6. In 2021, there was an increase in survey biomass (i.e., index values) for the PRD and WCVI SARs, and a decrease in survey biomass for HG, CC, and SoG SARs (Figure 6 and Tables 4 to 8).

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.

Incidental mortality

In order to advance progress towards a holistic ecosystem-based management (EBM) approach for Pacific Herring we present the information currently available to describe indirect effects on herring populations, such as incidental mortality. Some fisheries and aquaculture activities in BC cause incidental mortality to Pacific Herring. Similar to SOK harvest as well as FSC and recreational catch, incidental mortality is currently only indirectly accounted for in Pacific Herring stock assessment by estimating annual rates of natural mortality, and is considered minor relative to commercial harvest.

This year we include newly available data for incidental mortality in finfish aquaculture activities by SAR from 2014 to 2020 (Figure 3). Note that incidental mortality data are reported by Pacific Fishery Management Area (PFMA) which are analogous to Statistical Areas, but PFMAs are larger and can extend beyond SAR boundaries. Data indicate the number of Pacific Herring dead and released, with the following caveats:

1. Data for 2020 are considered incomplete,

2. Unknown mortality rate for “released” fish,
3. Unknown length, weight, age, and sex of fish, and
4. “Herring-like” fish are assumed to be herring when decomposition hinders identification.

First Nations observations

The COVID-19 pandemic continues to impact First Nations participation in herring survey activities as well as participation in traditional harvest activities (FSC). Assembling local observations was not possible for the 2020 season, however in 2021, local observations were provided by coastal First Nations participants for most areas. The following descriptions were provided by First Nations contributors.

Haida Gwaii

The Selwyn and Cumshewa Inlets stock has seen steady declines over the past decade to the point where this past season there almost was no spawn to be found. The spawn occurred very late in the season (late April) and was in outer Selwyn near Rockfish Harbour (rather than inside Selwyn near Traynor Bay). The spawn this year was considered to be fairly minimal for Selwyn Inlet standards and insufficient to extend into Cumshewa Inlet.

This year in the Skincuttle and Upper Burnaby area, the bulk of the spawning occurred on the Skincuttle side, but in other years it has occurred more north of the narrows in upper Burnaby Strait. This stock is just barely maintaining itself. Abundance is low enough that natural recruitment just barely makes up for natural mortality – so we see some years of slight recovery followed by other years of decline, but no real growth even in the absence of a fishery now in almost 20 years.

The Juan Perez Sound inlets normally will support spawns when there are a lot of recruits in the population and first time spawners can out number old repeat spawners. That has not been the case now for some time. Lately spawns have been small and infrequent in the inlets of Juan Perez Sound, as was the case in 2021.

There has not been a significant presence of herring abundance in outer Louscoone for a number of years now. In years of abundance, the local stock was always found to be well up inside the inlet and often presented a very light spawn near the head in the early portion of the season (early to mid March). This stock seldom exceeded 500 tons – however in recent years it has been much less. The other stock appears to be more migratory- found in the outer portions of Louscoone Inlet and rarely spawns in Louscoone. One theory is outer Louscoone is used as a staging area and that these herring would then migrate elsewhere (possibly to the Central Coast) to spawn. Now, abundance is not high enough to allow herring to build up in outer Louscoone early in the season – so we only see evidence of the minor local stock.

There was some effort for the traditional harvest of k’aaw in both Skincuttle Inlet and Selwyn Inlet in early to mid April, 2021. The open kelp lines set up in Jedway Bay, Skincuttle Inlet, were successful with approximately 2,000 lbs of good quality k’aaw being harvested. The open kelp lines set up in the cove just south of Traynor Bay, Selwyn Inlet, were unsuccessful due to the absence of spawn. There were no other (known) attempts for the harvest of k’aaw on Haida Gwaii during the 2021 herring season.

Prince Rupert District

Overall, very little spawn was observed this season by members and staff of the Lax Kw'alaams Band. Lax Kw'alaams Fisheries Technicians, in coordination with Metlakatla Guardians, spent ten full days during the herring season monitoring harvest and recording herring behaviour and locations. During the surveys, technicians were unable to locate herring schools in any of the normal geographic areas monitored each year. This year in the Prince Rupert District, Lax Kw'alaams had several fishermen out on the water. On-grounds correspondence with harvesters confirmed that herring spawn in the 2021 season was quite poor and ephemeral, and most reported seeing no active herring spawning in important harvest areas. However, the FSC harvest incidentally reported spawn in a couple of areas and was more promising than previous years. A few more community members were able to obtain some spawn-on-branches for the first time in many years, with sufficient layers to justify a small harvest. However, Lax Kw'alaams fishermen were unable to gather enough herring to satisfy FSC needs for the majority of the community.

Central Coast

Observations in Area 06: The overall herring spawn continued to improve in 2021 as the stock has continued to build over the past few years. Kitasu Bay appeared to have similar or higher abundance that 2020. Herring sizes were typical for the area but seemed to be more uniform in overall size. The spawn was longer than average with 7 to 8 days of continuous spawn that appeared to cover much of Kitasu Bay. The sea lion activity was significant as in previous years but due to the high abundance of herring, sea lions appeared to avoid the herring ponds which in previous years were directly targeted by feeding sea lions. The community food gathering was successful for both spawn on branch and there was some surplus from SOK operations to support the community as well. Kelp size and quality was very good in the Bay as compared to previous years.

Observations in Area 07: The 2021 herring season saw drastic changes to the herring spawning patterns, yield and roe thickness compared to previous years. The normal pattern for the herring spawning is when herring spawn in one location for 5 to 7 days in specific areas. This season the herring were spawning very sporadically and for short periods of time. In most areas the spawn would last only for a day and then herring would move to another location.

Predation by whales, seals, and sea lions has increased dramatically in the last 20 years and more so in the last few years causing shifts in spawning behaviour and patterns. Fishers observed multiple whales right up in the shallows feeding on the herring and disrupting or stopping the spawn.

Most of the spawning in the Spiller area was limited to inside and outside of the Tate Lagoon area with minimal spawning in the rest of Spiller area. Inside Tate Lagoon, the average layers were generally around 3 to 4 layers. Fishers set kelp in every identified spawn location including Spiller, Thompson, Norman Morrison, Dundavin, Idol, Foote, mid Spiller, Bachelor, Berry, and Mustang Bay all of which saw an average of 2 to 3 layers.

Our fishers reported that despite having kelp set at multiple spawn areas, the herring observed were smaller on average and the layers of roe on the kelp was minimal indicating smaller spawning herring. The build up of roe took long and averaged only 2 to 3 layers.

The consensus among fishers and management was that this year was worse than the previous two years and were unable to attain sufficient FSC or fulfill our herring roe spawn on kelp quota despite a lot of effort.

Strait of Georgia

In the Northern SoG, A-Tlegay Fisheries assisted the herring assessment program by providing additional dive survey coverage and attempting to collect cast net samples on active spawns. A-Tlegay divers surveyed spawn from Willow Point south down to Bates Beach (and beyond), Herring Sections 135 and 141. Through an outreach program, spawns were also reported to A-Tlegay from local mainland inlet areas. As a result, A-Tlegay was able to dive on two spawns in Bute Inlet and 1 spawn in Teakerne Arm (Section 151).

West Coast of Vancouver Island

In general, herring spawn was sporadic and short in duration in Barkley and Nootka Sounds with a spawn lasting several days in Hesquiaht Harbour.

In Nootka, herring were in the deep off of Yuquot for a couple of weeks and then they moved outside to Bajo Reef/Beano Creek area in mid-March. Bird and marine mammal activity shifted from the vicinity of Yuquot out to Bajo/Beano area. Ray Williams of Yuquot reported a small spawn in the lower end of Tahsis Inlet, but it could not be located by the spawn reconnaissance crew. There was a small harvest of spawn on kelp (60 lb total) just off the rocks of Escalante.

There was a small spawn in the shallows in the Port Langford area of Nuchatlitz on March 9th and later in Rosa Harbour. Only 20% of the trees set for spawn-on-bough collections were successful in the area.

In Area 23, the spawns were small and short in duration around mid-March. The main spawn was around Muscle Beach to Macoha on March 12th. Most trees set for spawn-on-boughs collections reported having mostly 2 to 4 layers of eggs and were set back in the water to hatch.

There were several trees for home use set by First Nations at this active spawn during sample collections. Activity was noted in front of the beach North and South of Maggie River but they did not appear to be actively spawning. Other spawn investigated around this time was at Mussel beach. At the end of March a small spawn was reported at Lyall point.

In Area 24, most spawning activity was in and around Hesquiaht Harbour from about the first week in March until near the end of the month. Hesquiaht Harbour is not a great area for SOB due to the prevalence of sandy bottom substrates and windy conditions.

Stock status update

Analyses of stock trend information for AM2 are presented following methods of Cleary et al. (2019) for the Pacific Herring major SARs. 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 7). The panels show:

a. Model fit to scaled spawn survey data,

b. Instantaneous natural mortality rate M estimates,

c. Number of age-2 recruits,

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

e. Recruitment deviations (log scale) from the Beverton-Holt recruitment function, and

f. 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 2021). Thus, two q parameters are implemented in the estimation procedure: q_1 (1951 to 1987) with an uninformative prior, and q_2 (1988 to 2021) with an informative prior approximating 1.0.

The surface survey methodology has been used on occasion from 1988 to 2021. Generally this occurs when herring spawn is observed in locations where a dive survey team is not available, or when spawning occurs very early (e.g., January or February) or late (e.g., May) in the season. In these instances, spawning 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 and 2021, a full surface survey was conducted for the HG SAR and in this assessment the resulting survey biomass estimates are 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 2021, 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 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 7d). 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 7a) that were supported by above average recruitment of age-2 fish in 2012 (Figure 7c, d). An increasing trend in the estimated natural mortality rate since 1980 (Figure 7b) largely absorbed surplus production attributable to above average recruitment events (e.g., 1997 and 2012; Figure 7c, d). Estimated natural mortality has increased sharply since the early 2010s following a decline from a peak rate around 2002. 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 7f). There is an increase in survey biomass in 2019 and 2020, and above-average recruitment of age-2s in 2018, and below-average recruitment in 2019 and 2020. In the most recent two years, between 2019 and 2020 and 2020 and 2021, production is estimated to be neither positive nor negative (i.e., production is 0), preceded by two consecutive years of positive productivity. Overall, biomass remains low relative to historical patterns and natural mortality rates remain at historic high levels (up to 2016). The most recent 3 years show a decline in estimated natural mortality, responding to an increase in spawn biomass (2019-2021) and below average recruitment (2019-2021). The effective harvest rate U_t since 2000 has been at or near zero (Figure 13), with the last commercial roe fishery in 2002, and the last commercial SOK fishery in 2004.

Estimated unfished spawning biomass SB_0 is 23,453 t, and the LRP of $0.3SB_0$ is 7,036 t (posterior medians). Compared to last year, estimated spawning biomass in 2021 SB_{2021} decreased to 13,701 t (posterior median), which is equal to 58.0% of SB_0 (Tables 19 & 24). Spawning biomass in 2021 is estimated to be above the LRP with a 97.2% probability (Table 24). Management measures to support long-term recovery of herring stocks in Haida Gwaii are being developed through the rebuilding plan process (Section “Application of MPs and harvest options for 2022”).

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 8d). However, after the mid-1980s, estimated spawning biomass steadily declined before stabilizing at a relatively low level (but above historic lows) by around 2005. 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; biomass increased again in 2021. 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 8a. 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} and then stabilized from 2005 to 2021 at a median rate of 0.45 (Figure 8b). The trend in natural mortality from 1980 to 2005 coincides with the decline in spawning biomass (Figure 8d), during which recruitment deviations fluctuated around 0 without any strong positive or negative trends (Figure 8e). Above average age-2+ recruitments in 2014, 2017 and 2018, and an increase in the spawn index in the last three years appears to be sufficient to lead to an increase in estimated spawning biomass in 2019 through 2021, relative to 2018 (Figure 8f). Commercial catches from 2007 to 2018 have remained low (below 2,000 t) and there was no commercial catch in 2019, 2020, or 2021. 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 2021.

Estimated unfished spawning biomass SB_0 is 60,448 t, and the LRP of $0.3SB_0$ is 18,135 t (posterior medians). Compared to last year, estimated spawning biomass in 2021 SB_{2021} increased to 30,046 t (posterior median), which is equal to 48.7% of SB_0 (Tables 20 & 25). Spawning biomass in 2021 is estimated to be above the LRP with a 89.9% probability (Table 25). Commercial fisheries have occurred annually in PRD since the mid-1980s, with the exception of 2019 to 2021, during which the effective harvest rate U_t was estimated to be at or below 20% (Figure 13) in all years except 1989.

Central Coast

Estimated spawning biomass declined from a historic high around 1980 to historic low levels in the period of 2005 to 2015 (Figure 9d). 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, 2018 and 2021. 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 9a), where fluctuations correspond opposite to the fluctuations in estimated natural mortality (Figure 9b). For example, the decline in spawn index (and estimated spawning biomass) to the historic lows around 2008 followed an increasing trend in estimated natural mortality through the same period. Estimated natural mortality moderated around 2008, which was followed by an increase in spawn index (and estimated spawning biomass) until 2017 whereupon natural mortality ceased declining. Recruitment deviations were slightly negative (i.e., lower than predicted by the stock-recruit function) on average from about 1990 to 2017, and were above average in 2019 and 2020 (Figure 9e). The model estimates very similar spawning biomass from 2019 through 2021 (Table 21), 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 9f). However, surplus production is estimated to be negative in the years between 2019/2020 and 2020/2021.

An examination of spawn biomass by Herring Section shows the recent decline in herring spawn to have largely occurred in Spiller Channel (Sections 072 and 078) and Kitasu Bay/East Higgins (Section 067; Figure 10). The majority of Area 07 spawn in 2021 appears concentrated in Thompson/Stryker (Section 074). Occurrence of spawn in Thompson/Stryker in 2020 and 2021 represents the first significant spawns for this section in many years. The decline in spawn observations in 2020 and 2021 in Spiller Channel (Sections 072 and 078) brings the spawn biomass in those Sections down to the low levels observed around 2010 (Figure 9d). The mechanisms driving fluctuations of spawn throughout the Central Coast are not well understood.

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 13). 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. A commercial SOK fishery did not occur in Area 07 in 2020 due to COVID-19, however it successfully resumed in 2021 (Table 3).

Estimated unfished spawning biomass SB_0 is 52,844 t, and the LRP of $0.3SB_0$ is 15,853 t (posterior medians). Compared to last year, estimated spawning biomass in 2021 SB_{2021} decreased to

30,027 t (posterior median), which is equal to 56.1% of SB_0 (Tables 21 & 26). Spawning biomass in 2021 is estimated to be above the LRP with a 96.9% probability (Table 26).

Strait of Georgia

The estimated spawning biomass for the SoG stock declined in 2019, increased in 2020, and declined in 2021. Accordingly, the uncertainty associated with the last few years of spawning biomass along with the forecast biomass SB_{2021}, is quite large (Figure 11d). 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 11b). The model estimates natural mortality has been increasing since 2016, and has now reached a level last estimated in the late 1960s. This coincides with large shifts in survey biomass in the last five years, with the index declining from 2016 to 2017, 2018 to 2019, and 2020 to 2021. The large uncertainty in both spawning biomass and natural mortality estimates in 2021 may be in part a function of the declining trend in the spawn index starting in 2016 following the increasing trend that began in 2010 (Figure 11a). The model fits an averaged trajectory through the spawn index values of the 2010s and is currently underfitting the survey data from 2014 though 2016 and 2020. The model estimates above average recruitment in most years from 2010 to 2021 (Figure 11c), with especially large positive deviations in 2019 and 2020 (Figure 11e). The large uncertainty around estimated age-2 recruitment in 2019 and 2020 was observed in the previous years' assessment and remains apparent now that these age-2s are fully recruited to the fishing/sampling 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, followed by negative production for the year between 2020 and 2021 (Figure 11f).

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 distributed evenly above and below 20% (Figure 13). The model estimates the median effective harvest rate exceeded 25% in 2006 and 2017.

Estimated unfished spawning biomass SB_0 is 137,132 t, and the LRP of $0.3SB_0$ is 41,140 t (posterior medians). Compared to last year, estimated spawning biomass in 2021 SB_{2021} decreased to 79,947 t (posterior median), which is equal to 57.5% of SB_0 (Tables 22 & 27). Spawning biomass in 2021 is estimated to be above the LRP with a 96.1% 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 12d). 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 12a). Historically high natural mortality rates occur in the late 2000s and have since declined, though show an increasing trend from 2015 to 2021 (Figure 12b). Recruitment deviations have been negative (i.e., lower than predicted by the stock-recruit function) on average since about 2003 (Figure 12e), with the exception of 2015, 2020 and 2021. The reduction in estimated natural mortality below historical high levels and absence of removals from a commercial fishery appear 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 zero for the last 15 years (Figure 13). There is modest evidence for an increase in biomass above the LRP since 2016 and production estimates for the year between 2019 and 2020, and 2020 and 2021 are positive (Figure 12f).

Investigation of WCVI MCMC diagnostics revealed autocorrelation in the estimation of fishery selectivity-at-50% ($\hat{a}_1$) and its standard deviation ($\hat{\gamma}_1$) for the "other" fisheries category (i.e., reduction, food and bait, as well as special use). Autocorrelation in parameter estimation may indicate bias in the posterior distribution or local minima. In this instance, autocorrelation likely resulting from there being no new commercial fishery data since 2005. Running longer chains resulted in only minor improvements. If and when fisheries resume in the future, the addition of new fishery data may reduce this apparent autocorrelation and any resulting bias.

Estimated unfished spawning biomass SB_0 is 45,606 t, and the LRP of $0.3SB_0$ is 13,682 t (posterior medians). Compared to last year, estimated spawning biomass in 2021 SB_{2021} increased to 23,083 t (posterior median), which is equal to 50.5% of SB_0 (Tables 23 & 28). Spawning biomass in 2021 is estimated to be above the LRP with a 91.7% probability (Table 28).

Management performance

Management procedure performance can be investigated using the time series of effective harvest rate U. Estimated effective harvest rate U in each year t is $U_t = C_t/(C_t + SB_t)$, where C_t is catch in year t, and SB_t is estimated spawning biomass in year t. Time series of U_t relative to the target harvest rate of 20% are presented in Figure 13.

Application of MPs and harvest options for 2022

Harvest options for 2022 reflect application of simulation-tested MPs for each major SAR. MPs included for SoG and WCVI combines information from the first MSE cycle (DFO 2019a) with updated MP evaluations conducted in September 2020 (DFO 2021b). MPs included for PRD and CC combines information from the first MSE cycle for northern SARs (DFO 2020a) with updated MP evaluations conducted in the summer of 2021 (this document). 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. Finally, MPs are not provided for HG due to requirements for a rebuilding plan (detailed below).

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 (and since 2004 for the SOK fishery). Survey biomass increased in 2019 and 2020, however biomass estimates are highly uncertain given persistent high natural mortality. 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 (i.e., at least 75%, DFO 2009).[1]

In the absence of fishing, spawning biomass in 2022 SB_{2022} is forecast to be 16,844 t (posterior median; Table 24). Spawning biomass in 2022 is forecast to be below the LRP of $0.3SB_0$ (7,036 t) with a 1.9% probability, in the absence of fishing (Table 24 and Figure 14).

DFO has committed to developing and implementing a rebuilding plan for Haida Gwaii Pacific Herring. Work finalizing the draft for consultation continues via a technical working group comprised of members of the Council of Haida Nation, DFO, and Parks Canada. The consultation period is anticipated to commence in fall 2021. Guidance for developing rebuilding plans (DFO 2013) states that the primary objective of any rebuilding plan is to promote stock growth out of

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

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.

Based on MP evaluations and the ongoing rebuilding plan process, the harvest recommendation for the HG stock in 2022 is 0 t. Because Haida Gwaii has an on-going rebuilding plan process, we did not update the HG OM with recent data (as we did for PRD and CC; see below).

Prince Rupert District

The PRD estimated stock biomass has shown little trend from 2005 to 2018, with a modest increase from 2019 to 2021.

In the summer 2021, we updated the conditioning of the MSE operating model for PRD with 2019 and 2020 spawn, catch, and biological data. We re-ran MSE simulations to generate updated probability values for the MPs presented in September 2019 (DFO 2020b) and 2020 (DFO 2021a). No new MPs or objectives were included.

The updated closed-loop feedback simulations for PRD show that MPs with harvest rates at 5, 10, and 20% maintain spawning biomass above the LRP with 78 to 100% probability, over all three OM scenarios (Table 29).

While MPs with harvest rates ranging from 5% to 20% were able to meet the core conservation objective of maintaining spawning biomass above the LRP with high probability (i.e., 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 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 13), during which the stock showed no sign of growth before 2018 and is estimated to fluctuate at or near the LRP of $0.3SB_0$ (Figure 8d). Spawning biomass depletion increased above $0.3SB_0$ in 2019 and remained above in 2020 and 2021. Although there is not evidence of a low biomass and low productivity state for PRD in the past 30-years, 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 2022 SB_{2022} is forecast to be 32,864 t (posterior median; Table 25). Spawning biomass in 2022 is forecast to be below the LRP of $0.3SB_0$ (18,135 t) with a 9.0% probability, in the absence of fishing (Table 25 and Figure 14).

Harvest options for 2022, resulting from simulation-tested MPs, are presented in Table 29, and include probability values that reflect updated OM conditioning.

Relative to 2018 OM conditioning, the updated simulations show an improvement in MP performance relative of the conservation objective, driven by an increase in spawn index and lower estimated natural mortality rates in the most recent years of the historical time series (up to 2020). This outcome corroborates previous observations that MP evaluations appear to be more heavily influenced by the last three to five years of stock status and natural mortality trends used to condition the OM.

Harvest options listed in Table 29 reflect application of MPs to the 2022 forecast biomass for PRD, whereby each MP meets the conservation objective with a minimum 75% probability under the Reference OM (i.e., DDM) scenario. Harvest options under the two Robustness OM scenarios are also included. For ease of comparison with MSE cycle 1 (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 larger increases/decreases in spawn abundance (Figure 9a) than was observed prior to 2005.

Similar to PRD, in the summer 2021 we updated the conditioning of the MSE operating model with 2019 and 2020 spawn, catch, and biological data. We re-ran MSE simulations to generate updated probability values for the MPs presented in September 2019 (DFO 2020b) and 2020 (DFO 2021a). No new MPs or objectives were included.

Management procedures, harvest options, and updated probabilities of obtaining objectives for 2022 under the three OM scenarios are presented in Table 30. Harvest options listed in Table 30 reflect application of MPs to the 2022 forecast biomass for CC, whereby each MP meets the conservation objective with a minimum 75% probability under the Reference OM (i.e., DDM) scenario.

Relative to 2018 OM conditioning, the updated simulations show an improvement in MP performance of the conservation objective, driven by an increase in estimated spawn index and lower estimated natural mortality rates in the most recent years of the time series (up to 2020). This corroborates previous observations that MP evaluations seem more heavily influenced by the last three to five years of stock status and natural mortality trends. Note this latest update does not include data from 2021, which show a decline in spawn index over the 2019 and 2020 observations (Figure 9a).

The updated simulations show that MPs with harvest rates at 5% and 10% maintain spawning biomass above the LRP with 84 to 100% probability over all three OM scenarios (Table 30). Since multiple MPs meet the conservation objective of maintaining spawning biomass above the LRP with at least 75%, further ranking of the objectives provides 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. Additionally, the current CC operating model is unable to directly address Heilstuk Nation conservation objectives related to age and size of herring, nor objectives on a finer spatial scale or those specific to SOK fisheries. These limitations exist for all five major stocks.

In the absence of fishing, spawning biomass in 2022 SB_{2022} is forecast to be 29,940 t (posterior median; Table 26). Spawning biomass in 2022 is forecast to be below the LRP of $0.3SB_0$ (15,853 t) with a 6.6% probability, in the absence of fishing (Table 26 and Figure 14).

Finally, DFO acknowledges commitment to the Heiltsuk Nation for the development of a Joint Fisheries Management Plan for Pacific Herring in the Central Coast in 2022. 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 2021b). 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 three 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 2022 SB_{2022} is forecast to be 78,665 t (posterior median; Table 27). Spawning biomass in 2022 is forecast to be below the LRP of $0.3SB_0$ (41,140 t) with a 5.4% probability, in the absence of fishing (Table 27 and Figure 14).

Harvest options for 2022, resulting from simulation-tested MPs, are presented in Table 31. These options reflect application of MPs to the 2022 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 three scenarios (DFO 2021b).

In 2021, we investigated the sensitivity of SoG MP performance to changes in allocation of TAC between the roe seine and roe gillnet fleets. The recent 20 year average catches show the food and bait, roe seine, and roe gillnet fleets take 21%, 40%, and 39% of the catch and represents the status quo allocation used for this analysis.

We consider two changes in allocation of TAC between roe seine and roe gillnet fleets: high gillnet allocation (i.e., 90% gillnet) and high seine allocation (i.e., 90% seine). MPs consider only movement between roe fleets, thus no changes are made to the overall food and bait allocation. Comparisons among TAC allocation are implemented using the HS30-60_HR20 MP with an index based procedure. This analysis was designed to investigate relative differences between allocation MPs. Thus we used an index-based approach in lieu of fitting the assessment model to calculate the TAC for each simulated year, to save computational time.

Results show there is no difference in conservation performance between simulated TAC allocation procedures (Table 32). That is, the simulations show that movement of TAC between the roe fishery fleets does not appear to impact the probability of avoiding the LRP over the 15-year simulation period. Note that these results consider recent stock status of SoG herring, and that due to structure of the current herring simulation model, the simulation approach does not provide insight into year-to-year changes in age composition, spawn distribution, or spawning behaviour. However, these results do indicate that given the overlap in catch at age between the two fleets, the harvest rates applied to the population and the age structure of the population, the differences in age and size selectivity between the two gears is not large enough to impact the status of the population. Finally, probability values in Table 32 should not be directly compared to those in Table 31 due to differences in assessment method implemented in the simulations (index-based vs. current stock assessment model) and the conditioning data used (spawn survey data up to 2020 and biological data up to 2019 vs. both spawn survey and biological data up to 2020).

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% probability, 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 2021b). The updated closed-loop feedback simulations for the WCVI show that MPs with harvest rates of 5, 10, and 15% maintained spawning biomass above the LRP with between 81 and 93% probability, over all three OM scenarios (Table 33). Improved MP performance in the 2020 update for WCVI, relative to the first WCVI MSE cycle, is due to an increased spawn index in 2018 and 2019 and increased status relative to SB_0. Performance improvement is observed under all three scenarios.

In the absence of fishing, spawning biomass in 2022 SB_{2022} is forecast to be 19,228 t (posterior median; Table 28). Spawning biomass in 2022 is forecast to be below the LRP of $0.3SB_0$ (13,682 t) with a 21.9% probability, in the absence of fishing (Table 28 and Figure 14).

Harvest options for 2022, resulting from simulation-tested MPs, are presented in Table 33. These options reflect application of MPs to the 2022 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 33 include updated performance metrics for the four core objectives under all three scenarios (DFO 2021b).

Conclusions

The 2021 Science Response includes 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 updated to include 2021.

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 2022. DFO has committed to developing and implementing a rebuilding plan for Haida Gwaii Pacific Herring. Based on MP evaluations, the harvest recommendation for the HG SAR is 0 t.

The MSE process identifies a range of MPs that meet the conservation objective with at least 75% probability for the PRD, CC, SoG, and WCVI SARs for the Reference OM scenario (DFO 2020a, 2021b). As such, harvest options or MP calculations for 2022 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 33).

Science advice for the minor SARs is limited to presentation of catch data, biological data, and spawn survey data (Section “Minor stock assessment regions”). Similarly, science advice for the special area, Area 10 is limited to presentation of catch data, biological data, and spawn survey data (Section “Special areas”).

Tables

Table 1. Input data for the 2021 Pacific Herring statistical catch-age model for the major SARs. The spawn index has two distinct periods defined by the dominant survey method: surface surveys (1951 to 1987), and dive surveys (1988 to 2021). Note: the 'spawn index' is not scaled by the spawn survey scaling parameter q.

Source	Data	Years
Roe gillnet fishery	Catch	1972 to 2021
Roe seine fishery	Catch	1972 to 2021
Other fisheries	Catch	1951 to 2021
Test fishery (Seine)	Biological: number-at-age	1975 to 2021
Test fishery (Seine)	Biological: weight-at-age	1975 to 2021
Roe seine fishery	Biological: number-at-age	1972 to 2021
Roe seine fishery	Biological: weight-at-age	1972 to 2021
Roe gillnet fishery	Biological: number-at-age	1972 to 2021
Other fisheries	Biological: number-at-age	1951 to 2021
Other fisheries	Biological: weight-at-age	1951 to 2021
Surface survey	Abundance: spawn index	1951 to 1987
Dive survey	Abundance: spawn index	1988 to 2021

Table 2. Total landed Pacific Herring catch in tonnes from 2012 to 2021 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
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
2021	0	0	0	14,396	0

Table 3. Total Pacific Herring spawn-on-kelp harvest, reported as pounds of eggs on kelp, from 2012 to 2021 in the major stock assessment regions (SARs). See Table 2 for description.

	SAR				
Year	**HG**	**PRD**	**CC**	**SoG**	**WCVI**
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
2021	0	0	294,269	0	0

Table 4. Haida Gwaii SAR: spawn index in tonnes for Pacific Herring, and proportion of spawn index by Group from 2012 to 2021. Legend: 'Cumshewa/Selwyn' is Section 023 and 024; 'Juan Perez/Skincuttle' is Sections 021 and 025; and 'Louscoone' is Section 006. Note: the 'spawn index' is not scaled by the spawn survey scaling parameter q, and 'NA' indicates that data are not available.

		Proportion		
Year	**Spawn index**	**Cumshewa/Selwyn**	**Juan Perez/Skincuttle**	**Louscoone**
2012	9,720	0.158	0.821	0.020
2013	16,025	0.057	0.864	0.079
2014	10,566	0.068	0.932	0.000
2015	13,102	0.060	0.940	0.000
2016	6,888	0.053	0.947	0.000
2017	3,016	0.018	0.982	0.000
2018	4,588	0.234	0.766	0.000
2019	11,624	0.065	0.919	0.016
2020	20,423	0.077	0.923	0.000
2021	18,234	0.025	0.975	0.000

Table 5. Prince Rupert District SAR: spawn index in tonnes for Pacific Herring, and proportion of spawn index by Statistical Area from 2012 to 2021. See Table 4 for description.

		Proportion		
Year	**Spawn index**	**03**	**04**	**05**
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
2021	33,062	0.068	0.717	0.214

Table 6. Central Coast SAR: spawn index in tonnes for Pacific Herring, and proportion of spawn index by Statistical Area from 2012 to 2021. See Table 4 for description.

		Proportion		
Year	**Spawn index**	**06**	**07**	**08**
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
2021	28,674	0.257	0.697	0.045

Table 7. Strait of Georgia SAR: spawn index in tonnes for Pacific Herring, and proportion of spawn index by Group from 2012 to 2021. 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**
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
2021	70,938	0.773	0.032	0.196	0.000

Table 8. West Coast of Vancouver Island SAR: spawn index in tonnes for Pacific Herring, and proportion of spawn index by Statistical Area from 2012 to 2021. See Table 4 for description.

		Proportion		
Year	**Spawn index**	**23**	**24**	**25**
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
2021	29,339	0.150	0.728	0.122

Table 9. Haida Gwaii SAR: key parameters in the Pacific Herring statistical catch-age model. Parameters are summarised by posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates. 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 2021; $\overline{R}_{init}$ 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 2021; 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	194.041	256.899	351.795	257.557
h	0.662	0.790	0.903	0.809
M	0.209	0.393	0.664	0.372
$\overline{R}$	134.344	159.824	190.928	166.722
$\overline{R}_{init}$	8.430	27.893	136.744	32.159
ρ	0.222	0.286	0.358	0.274
ϑ	0.779	0.941	1.136	1.009
q_1	0.346	0.421	0.505	0.412
q_2	0.983	0.999	1.015	0.998
τ	0.777	0.871	0.977	0.848
σ	0.482	0.548	0.627	0.521

Table 10. Prince Rupert District SAR: key parameters in the Pacific Herring statistical catch-age model. See Table 9 for description.

Parameter	5%	50%	95%	MPD
R_0	247.018	327.525	513.360	311.973
h	0.517	0.686	0.840	0.713
M	0.253	0.438	0.737	0.427
$\overline{R}$	169.222	193.328	224.047	200.240
$\overline{R}_{init}$	65.258	202.341	959.006	249.560
ρ	0.210	0.275	0.350	0.272
ϑ	0.954	1.168	1.405	1.247
q_1	0.484	0.560	0.645	0.550
q_2	0.984	1.001	1.018	1.001
τ	0.703	0.786	0.885	0.764
σ	0.420	0.485	0.563	0.467

Table 11. Central Coast SAR: key parameters in the Pacific Herring statistical catch-age model. See Table 9 for description.

Parameter	5%	50%	95%	MPD
R_0	316.537	400.866	527.625	389.659
h	0.669	0.801	0.905	0.821
M	0.252	0.470	0.805	0.447
$\overline{R}$	235.125	265.054	301.986	266.428
$\overline{R}_{init}$	47.045	187.505	1,108.424	261.097
ρ	0.176	0.234	0.307	0.217
ϑ	0.999	1.207	1.447	1.286
q_1	0.280	0.325	0.372	0.329
q_2	0.983	0.999	1.015	0.999
τ	0.711	0.795	0.889	0.780
σ	0.382	0.441	0.510	0.410

Table 12. Strait of Georgia SAR: key parameters in the Pacific Herring statistical catch-age model. See Table 9 for description.

Parameter	5%	50%	95%	MPD
R_0	1,343.186	1,656.150	2,231.197	1,586.370
h	0.579	0.726	0.867	0.761
M	0.246	0.453	0.765	0.447
$\overline{R}$	944.556	1,078.620	1,241.251	1,103.480
$\overline{R}_{init}$	38.628	147.008	832.016	263.455
ρ	0.211	0.280	0.361	0.269
ϑ	1.234	1.507	1.823	1.607
q_1	0.881	1.044	1.213	1.035
q_2	0.983	0.999	1.015	0.999
τ	0.609	0.690	0.782	0.674
σ	0.373	0.430	0.497	0.409

Table 13. West Coast of Vancouver Island SAR: key parameters in the Pacific Herring statistical catch-age model. See Table 9 for description.

Parameter	5%	50%	95%	MPD
R_0	453.566	580.007	773.461	576.166
h	0.610	0.736	0.855	0.743
M	0.354	0.604	0.985	0.586
$\overline{R}$	334.213	383.038	443.124	389.889
$\overline{R}_{init}$	35.529	163.541	1,131.217	266.912
ρ	0.233	0.303	0.386	0.290
ϑ	1.053	1.283	1.545	1.380
q_1	0.698	0.838	0.989	0.838
q_2	0.983	0.999	1.016	0.999
τ	0.652	0.735	0.834	0.717
σ	0.422	0.485	0.559	0.458

Table 14. Haida Gwaii SAR: age-2 recruitment from 2012 to 2021 for the Pacific Herring statistical catch-age model. Recruitment in millions is summarised by posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates.

Year	5%	50%	95%	MPD
2012	381.964	536.166	758.808	558.189
2013	47.429	72.330	108.041	74.445
2014	71.995	109.667	164.865	113.991
2015	51.206	76.847	116.537	80.024
2016	101.488	150.752	220.513	156.176
2017	164.966	240.426	353.737	247.750
2018	261.563	386.624	577.279	398.650
2019	25.047	48.941	96.299	48.135
2020	29.325	55.299	103.904	55.135
2021	69.172	131.197	250.120	130.404

Table 15. Prince Rupert District SAR: age-2 recruitment from 2012 to 2021 for the Pacific Herring statistical catch-age model. See Table 14 for description.

Year	5%	50%	95%	MPD
2012	173.348	237.650	319.108	241.157
2013	59.597	83.791	118.849	86.131
2014	311.515	429.236	594.653	445.088
2015	137.787	195.892	280.676	204.066
2016	64.536	98.987	152.262	103.398
2017	222.081	323.510	477.635	338.026
2018	525.410	759.549	1,094.013	788.839
2019	26.540	46.800	81.185	46.295
2020	110.809	232.484	421.619	249.882
2021	70.220	264.962	911.305	241.308

Table 16. Central Coast SAR: age-2 recruitment from 2012 to 2021 for the Pacific Herring statistical catch-age model. See Table 14 for description.

Year	5%	50%	95%	MPD
2012	300.749	390.207	506.353	392.488
2013	126.071	167.703	219.266	168.076
2014	367.177	484.524	640.077	491.285
2015	120.803	161.245	217.079	163.931
2016	135.639	179.491	237.149	182.737
2017	191.268	255.231	338.890	259.373
2018	814.021	1,103.055	1,470.033	1,124.140
2019	46.646	67.997	98.601	67.821
2020	300.380	479.632	719.304	488.787
2021	104.724	414.596	1,411.294	405.522

Table 17. Strait of Georgia SAR: age-2 recruitment from 2012 to 2021 for the Pacific Herring statistical catch-age model. See Table 14 for description.

Year	5%	50%	95%	MPD
2012	674.633	864.760	1,105.548	876.226
2013	1,221.030	1,552.130	1,969.382	1,576.590
2014	1,295.686	1,654.700	2,126.434	1,675.160
2015	1,091.719	1,405.230	1,827.327	1,430.830
2016	977.917	1,269.460	1,655.588	1,303.340
2017	1,007.082	1,317.850	1,722.370	1,351.800
2018	1,133.127	1,505.085	1,997.781	1,551.200
2019	2,504.462	3,444.660	4,638.374	3,511.660
2020	1,938.090	2,664.585	3,691.645	2,691.110
2021	835.537	1,234.825	1,865.266	1,241.890

Table 18. West Coast of Vancouver Island SAR: age-2 recruitment from 2012 to 2021 for the Pacific Herring statistical catch-age model. See Table 14 for description.

Year	5%	50%	95%	MPD
2012	95.788	130.470	179.756	130.365
2013	238.955	327.624	448.220	329.667
2014	188.644	259.082	355.761	259.727
2015	655.663	881.078	1,194.979	894.329
2016	97.228	132.695	181.371	135.097
2017	99.252	138.484	189.562	140.250
2018	303.183	426.289	597.453	436.575
2019	218.093	311.300	447.625	317.160
2020	657.473	980.976	1,482.300	998.873
2021	818.887	1,363.730	2,246.001	1,374.820

Table 19. Haida Gwaii SAR: spawning biomass and depletion from 2012 to 2021 for the Pacific Herring statistical catch-age model. Spawning biomass and depletion are summarised by the posterior (5th, 50th, and 95th percentile) and maximum posterior density (MPD) estimates in thousands of tonnes. Note: depletion is relative spawning biomass SB_t/SB_0, where SB_t is spawning biomass in year t, and SB_0 is estimated unfished spawning biomass.

	Spawning biomass				Depletion			
Year	5%	50%	95%	MPD	5%	50%	95%	MPD
2012	6.821	9.045	11.948	9.230	0.262	0.384	0.557	0.410
2013	9.259	12.542	16.933	12.838	0.356	0.532	0.784	0.570
2014	6.819	9.241	12.358	9.365	0.263	0.391	0.574	0.416
2015	4.812	6.484	8.597	6.507	0.185	0.275	0.402	0.289
2016	3.790	5.103	6.752	5.076	0.146	0.216	0.316	0.225
2017	4.929	6.728	9.084	6.645	0.192	0.285	0.418	0.295
2018	7.551	10.404	14.247	10.233	0.294	0.442	0.645	0.454
2019	9.957	13.951	19.265	13.613	0.392	0.593	0.867	0.604
2020	9.432	13.792	20.320	13.366	0.379	0.588	0.897	0.593
2021	8.251	13.701	22.358	13.188	0.338	0.580	0.972	0.585

Table 20. Prince Rupert District SAR: spawning biomass and depletion from 2012 to 2021 for the Pacific Herring statistical catch-age model. See Table 19 for description.

	Spawning biomass				Depletion			
Year	**5%**	**50%**	**95%**	**MPD**	**5%**	**50%**	**95%**	**MPD**
2012	13.892	17.117	21.033	17.216	0.168	0.282	0.402	0.309
2013	13.958	17.122	21.301	17.326	0.170	0.283	0.406	0.311
2014	13.107	16.101	20.051	16.349	0.159	0.266	0.381	0.293
2015	15.258	19.063	23.884	19.371	0.188	0.313	0.455	0.347
2016	13.299	16.818	21.256	17.011	0.165	0.276	0.399	0.305
2017	11.727	15.417	20.107	15.436	0.151	0.252	0.371	0.277
2018	15.134	20.000	26.292	19.826	0.198	0.326	0.485	0.355
2019	23.112	31.212	42.243	30.521	0.310	0.508	0.757	0.547
2020	20.040	29.065	41.623	27.836	0.277	0.469	0.732	0.499
2021	17.674	30.046	48.015	27.925	0.255	0.487	0.817	0.501

Table 21. Central Coast SAR: spawning biomass and depletion from 2012 to 2021 for the Pacific Herring statistical catch-age model. See Table 19 for description.

	Spawning biomass				Depletion			
Year	**5%**	**50%**	**95%**	**MPD**	**5%**	**50%**	**95%**	**MPD**
2012	7.865	9.783	12.237	9.856	0.133	0.185	0.251	0.195
2013	11.968	15.091	18.916	15.207	0.204	0.284	0.390	0.300
2014	12.573	15.897	19.935	16.056	0.213	0.300	0.412	0.317
2015	15.500	19.649	24.801	19.927	0.263	0.371	0.516	0.394
2016	15.375	19.509	24.462	19.774	0.262	0.367	0.507	0.391
2017	15.429	19.654	25.083	19.947	0.263	0.370	0.513	0.394
2018	18.180	23.329	29.894	23.535	0.313	0.440	0.609	0.465
2019	27.669	36.393	47.534	36.200	0.480	0.684	0.959	0.715
2020	23.347	32.673	45.807	32.230	0.411	0.617	0.908	0.637
2021	17.590	30.027	49.964	28.473	0.324	0.561	0.965	0.562

Table 22. Strait of Georgia SAR: spawning biomass and depletion from 2012 to 2021 for the Pacific Herring statistical catch-age model. See Table 19 for description.

	Spawning biomass				Depletion			
Year	**5%**	**50%**	**95%**	**MPD**	**5%**	**50%**	**95%**	**MPD**
2012	61.830	72.990	86.001	72.955	0.354	0.530	0.710	0.564
2013	57.762	68.358	81.594	68.579	0.332	0.498	0.669	0.530
2014	64.622	76.381	91.608	76.895	0.372	0.556	0.747	0.594
2015	62.944	73.924	88.316	74.558	0.361	0.539	0.715	0.576
2016	64.782	75.769	89.359	76.589	0.370	0.552	0.731	0.592
2017	57.816	69.286	82.567	70.095	0.335	0.502	0.677	0.542
2018	57.638	70.854	86.878	71.633	0.341	0.512	0.704	0.554
2019	66.588	83.699	106.611	83.836	0.399	0.604	0.846	0.648
2020	77.111	99.685	130.895	97.670	0.473	0.719	1.022	0.755
2021	47.999	79.947	131.938	75.806	0.314	0.575	0.972	0.586

Table 23. West Coast of Vancouver Island SAR: spawning biomass and depletion from from 2012 to 2021 for the Pacific Herring statistical catch-age model. See Table 19 for description.

	Spawning biomass				Depletion			
Year	**5%**	**50%**	**95%**	**MPD**	**5%**	**50%**	**95%**	**MPD**
2012	5.544	7.127	9.225	7.075	0.107	0.156	0.221	0.159
2013	6.492	8.395	10.904	8.357	0.126	0.184	0.262	0.188
2014	9.202	11.996	15.569	12.022	0.180	0.263	0.374	0.270
2015	13.002	16.760	21.578	16.892	0.252	0.367	0.518	0.380
2016	17.263	22.621	29.225	22.921	0.339	0.495	0.695	0.516
2017	13.262	17.653	23.127	17.869	0.263	0.385	0.547	0.402
2018	11.620	15.647	20.909	15.763	0.232	0.342	0.488	0.355
2019	11.473	15.639	21.167	15.584	0.232	0.342	0.490	0.351
2020	12.460	17.908	25.538	17.562	0.259	0.390	0.574	0.395
2021	12.638	23.083	41.667	22.469	0.274	0.505	0.918	0.505

Table 24. Haida Gwaii SAR: proposed reference points for the Pacific Herring statistical catch-age model. Reference points are summarised by posterior (5^{th}, 50^{th}, and 95^{th} percentile) estimates. 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_{2022} is projected spawning biomass in 2022 assuming no fishing. Note that the age-10 class is a 'plus group' which includes fish ages 10 and older.

Reference point	**5%**	**50%**	**95%**
SB_0	18.625	23.453	30.326
$0.3SB_0$	5.587	7.036	9.098
SB_{2021}	8.251	13.701	22.358
SB_{2021}/SB_0	0.338	0.580	0.972
$SB_{2021}/0.3SB_0$	1.125	1.934	3.240
$P\ (SB_{2021} < 0.3SB_0)$	-	0.028	-
SB_{2022}	8.734	16.844	36.029
SB_{2022}/SB_0	0.367	0.717	1.540
$SB_{2022}/0.3SB_0$	1.222	2.391	5.134
$P\ (SB_{2022} < 0.3SB_0)$	-	0.019	-
$P\ (SB_{2022} < 0.6SB_0)$	-	0.335	-
Proportion aged 3	0.09	0.31	0.67
Proportion aged 4 - 10	0.26	0.56	0.81

Table 25. Prince Rupert District SAR: proposed reference points for the Pacific Herring statistical catch-age model. See Table 24 for description.

Reference point	5%	50%	95%
SB_0	46.151	60.448	96.447
$0.3SB_0$	13.845	18.135	28.934
SB_{2021}	17.674	30.046	48.015
SB_{2021}/SB_0	0.255	0.487	0.817
$SB_{2021}/0.3SB_0$	0.850	1.623	2.723
$P\ (SB_{2021} < 0.3SB_0)$	-	0.101	-
SB_{2022}	16.890	32.864	59.358
SB_{2022}/SB_0	0.262	0.524	0.969
$SB_{2022}/0.3SB_0$	0.874	1.745	3.230
$P\ (SB_{2022} < 0.3SB_0)$	-	0.090	-
$P\ (SB_{2022} < 0.6SB_0)$	-	0.630	-
Proportion aged 3	0.06	0.20	0.49
Proportion aged 4 - 10	0.45	0.73	0.90

Table 26. Central Coast SAR: proposed reference points for the Pacific Herring statistical catch-age model. See Table 24 for description.

Reference point	5%	50%	95%
SB_0	42.742	52.844	68.118
$0.3SB_0$	12.822	15.853	20.435
SB_{2021}	17.590	30.027	49.964
SB_{2021}/SB_0	0.324	0.561	0.965
$SB_{2021}/0.3SB_0$	1.079	1.869	3.215
$P\ (SB_{2021} < 0.3SB_0)$	-	0.032	-
SB_{2022}	15.073	29.940	57.960
SB_{2022}/SB_0	0.284	0.560	1.105
$SB_{2022}/0.3SB_0$	0.946	1.868	3.684
$P\ (SB_{2022} < 0.3SB_0)$	-	0.066	-
$P\ (SB_{2022} < 0.6SB_0)$	-	0.564	-
Proportion aged 3	0.06	0.22	0.53
Proportion aged 4 - 10	0.40	0.68	0.87

Table 27. Strait of Georgia SAR: proposed reference points for the Pacific Herring statistical catch-age model. See Table 24 for description.

Reference point	5%	50%	95%
SB_0	110.075	137.132	199.254
$0.3SB_0$	33.022	41.140	59.776
SB_{2021}	47.999	79.947	131.938
SB_{2021}/SB_0	0.314	0.575	0.972
$SB_{2021}/0.3SB_0$	1.047	1.915	3.240
$P\ (SB_{2021} < 0.3SB_0)$	-	0.039	-
SB_{2022}	43.760	78.665	143.850
SB_{2022}/SB_0	0.297	0.564	1.035
$SB_{2022}/0.3SB_0$	0.989	1.880	3.449
$P\ (SB_{2022} < 0.3SB_0)$	-	0.054	-
$P\ (SB_{2022} < 0.6SB_0)$	-	0.564	-
Proportion aged 3	0.08	0.23	0.51
Proportion aged 4 - 10	0.38	0.62	0.81

Table 28. West Coast of Vancouver Island SAR: proposed reference points for the Pacific Herring statistical catch-age model. See Table 24 for description.

Reference point	5%	50%	95%
SB_0	36.700	45.606	58.880
$0.3SB_0$	11.010	13.682	17.664
SB_{2021}	12.638	23.083	41.667
SB_{2021}/SB_0	0.274	0.505	0.918
$SB_{2021}/0.3SB_0$	0.913	1.683	3.059
$P\ (SB_{2021} < 0.3SB_0)$	-	0.083	-
SB_{2022}	9.504	19.228	39.673
SB_{2022}/SB_0	0.212	0.421	0.866
$SB_{2022}/0.3SB_0$	0.706	1.404	2.886
$P\ (SB_{2022} < 0.3SB_0)$	-	0.219	-
$P\ (SB_{2022} < 0.6SB_0)$	-	0.799	-
Proportion aged 3	0.09	0.27	0.57
Proportion aged 4 - 10	0.30	0.55	0.78

Table 29. Prince Rupert District SAR: management procedure (MP) performance for the Pacific Herring statistical catch-age model. Performance metrics are given for 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	2022	
OM	**MP**	$SB_t > 0.3SB_0$	$\geq 0.4SB_0$	$\geq 0.6SB_0$	AAV	$\overline{C}$	**TAC**	**HR**
DDM	NoFish_FSC	94%	85%	63%	0.00	0.14	–	–
DDM	HS30-60_HR05	92%	81%	57%	45.95	1.80	1.21	0.04
DDM	HS50-60_HR20_cap2.5	92%	82%	56%	28.61	1.77	1.56	0.05
DDM	minE0.5B0_HR10	92%	80%	50%	43.08	3.17	1.48	0.05
DDM	HS30-60_HR10_cap2.5	91%	80%	55%	28.12	2.00	2.42	0.08
DDM	minE0.5B0_HR20	89%	72%	36%	60.35	4.77	1.48	0.05
DDM	minE0.3B0_HR10	88%	74%	45%	34.62	3.69	3.26	0.10
DIM	NoFish_FSC	87%	75%	47%	0.00	0.14	–	–
DIM	HS30-60_HR05	85%	70%	43%	50.95	1.34	1.21	0.04
DIM	HS50-60_HR20_cap2.5	85%	70%	43%	42.55	1.46	1.56	0.05
DIM	HS30-60_HR10_cap2.5	84%	68%	42%	35.97	1.74	2.42	0.08
DIM	minE.5B0_HR10	83%	66%	34%	49.21	2.47	1.48	0.05
DIM	minE0.3B0_HR10	78%	60%	32%	37.49	3.03	3.26	0.10
DIM	minE.5B0_HR20	78%	58%	26%	73.54	3.42	1.48	0.05
conM	NoFish_FSC	100%	97%	76%	0.00	0.14	–	–
conM	HS30-60_HR05	100%	96%	71%	46.71	1.89	1.21	0.04
conM	HS50-60_HR20_cap2.5	100%	96%	70%	28.55	1.96	1.56	0.05
conM	HS30-60_HR10_cap2.5	98%	94%	68%	29.25	2.10	2.42	0.08
conM	minE.5B0_HR10	98%	91%	57%	41.62	3.64	1.48	0.05
conM	minE0.3B0_HR10	97%	88%	51%	29.37	4.20	3.26	0.10
conM	minE.5B0_HR20	94%	82%	41%	56.35	5.74	1.48	0.05

Table 30. Central Coast SAR: management procedure performance for the Pacific Herring statistical catch-age model. 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	2022	
OM	**MP**	$SB_t > 0.3SB_0$	$\geq 0.4SB_0$	$\geq 0.6SB_0$	AAV	$\overline{C}$	**TAC**	**HR**
DDM	NoFish_FSC	94%	88%	68%	0.00	0.14	–	–
DDM	HS30-60_HR05	94%	85%	65%	43.16	1.90	1.28	0.04
DDM	HS30-60_HR10_cap5	93%	82%	59%	40.11	3.29	2.55	0.09
DDM	minE0.5B0_HR10	92%	84%	57%	54.13	3.09	2.68	0.10
DIM	NoFish_FSC	88%	78%	52%	0.00	0.14	–	–
DIM	HS30-60_HR05	87%	75%	51%	50.16	1.41	1.28	0.04
DIM	HS30-60_HR10_cap5	85%	72%	46%	53.36	2.48	2.55	0.09
DIM	minE.5B0_HR10	84%	70%	40%	68.76	2.22	2.68	0.10
conM	NoFish_FSC	100%	98%	84%	0.00	0.14	–	–
conM	HS30-60_HR05	100%	97%	79%	42.38	2.69	1.28	0.04
conM	HS30-60_HR10_cap5	99%	95%	74%	30.65	3.88	2.55	0.09
conM	minE.5B0_HR10	98%	92%	67%	45.91	4.82	2.68	0.10

Table 31. Strait of Georgia SAR: management procedure performance for the Pacific Herring statistical catch-age model. 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	2022	
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_HR10	85%	71%	45%	50.73	6.16	6.83	0.09
DDM	minE0.3B0_HR10	83%	69%	43%	38.21	7.24	7.85	0.10
DDM	HS30-60_HR15	83%	68%	39%	48.59	8.51	10.25	0.13
DDM	HS30-60_HR20	82%	64%	33%	49.67	10.62	13.66	0.18
DDM	minE0.3B0_HR20	77%	60%	30%	43.51	12.60	15.67	0.20
DIM	NoFish_FSC	85%	74%	55%	0.00	0.14	–	–
DIM	HS30-60_HR10	82%	70%	46%	50.16	6.14	6.83	0.09
DIM	minE0.3B0_HR10	81%	69%	45%	39.53	7.06	7.85	0.10
DIM	HS30-60_HR15	80%	67%	40%	48.34	8.54	10.25	0.13
DIM	HS30-60_HR20	78%	64%	35%	50.93	10.65	13.66	0.18
DIM	minE0.3B0_HR20	75%	61%	33%	42.84	12.38	15.67	0.20
conM	NoFish_FSC	100%	100%	93%	0.00	0.14	–	–
conM	HS30-60_HR10	100%	99%	82%	36.74	10.76	6.83	0.09
conM	minE0.3B0_HR10	100%	98%	81%	30.37	11.25	7.85	0.10
conM	HS30-60_HR15	100%	97%	75%	37.62	15.30	10.25	0.13
conM	HS30-60_HR20	99%	94%	66%	38.95	19.42	13.66	0.18
conM	minE0.3B0_HR20	98%	93%	63%	32.79	20.31	15.67	0.20

Table 32. Strait of Georgia SAR: management procedure (MP) performance for roe seine and roe gillnet allocation for Pacific Herring. For this analysis, simulations use the most recent spawn index as a biomass estimate and MP 'HS30-60_HR20' with two alternative roe allocations to explore the movement of total allowable catch (TAC) between the roe seine and roe gillnet fleets. The 'MP and allocation' column indicates the harvest control rule and allocation scenario (i.e., proportion of TAC for roe seine and roe gillnet fleets, respectively). The 'no adjust' MP represents the status quo allocation based on average catches from the past 20 years. Final allocation indicates the proportion of TAC for the food and bait (FB), roe seine, and roe gillnet fleets. Performance metrics for objectives are given for the density-dependent natural mortality operating model scenarios only. Legend: C_t is catch in year t. See Table 29 for description.

	Objectives					**Final allocation**		
	Conservation	**Biomass**	**Yield**					
MP and allocation	$P(SB_t > 0.3SB_0)$	$P(SB_t > 0.6SB_0)$	AAV	$\overline{C}$	$P(C_t < 650\,\text{t})$	**FB**	**Seine**	**Gillnet**
NoFish_FSC	0.81	0.45	0.00	0.14	1.00	-	-	-
HS30-60_HR20_alloc (no adjust)	0.72	0.26	79.18	10.26	0.33	0.21	0.40	0.39
HS30-60_HR20_alloc (0.1, 0.9)	0.72	0.26	79.44	10.35	0.33	0.21	0.08	0.71
HS30-60_HR20_alloc (0.9, 0.1)	0.72	0.26	78.93	10.20	0.33	0.21	0.71	0.08

Table 33. West Coast of Vancouver Island SAR: management procedure (MP) performance for the Pacific Herring statistical catch-age model. 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 $SB_t >= SB_{AVE}$ are proposed by the Nuu-chah-nulth Nations (NCN) as biomass targets at $P >= 50\%$ and $P >= 75\%$ levels.

		Conservation	Biomass					Yield			
Scenario		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	2022	
OM	**MP**	$SB_t > 0.3SB_0$	$\geq 0.4SB_0$	$\geq 0.6SB_0$	$\geq 0.65SB_0$	$\geq 0.75SB_0$	$\geq SB_{AVE}$	AAV	$\overline{C}$	**TAC**	**HR**
DDM	NoFish_FSC	92%	86%	67%	63%	52%	64%	0.00	0.14	–	–
DDM	minE0.3B0_HR05	92%	82%	61%	56%	45%	56%	43.83	1.59	0.96	0.05
DDM	HS50-60_HR10	92%	83%	58%	52%	40%	48%	55.74	2.47	0.00	0.00
DDM	HS30-60_HR10_cap2	91%	83%	62%	55%	45%	55%	34.71	1.60	0.77	0.04
DDM	HS30-60_HR15_cap2	91%	83%	61%	55%	45%	55%	26.38	1.74	1.16	0.06
DDM	HS50-60_HR15	91%	81%	53%	47%	34%	42%	60.80	3.38	0.00	0.00
DDM	consTAC1	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	minE0.3B0_HR05	83%	71%	47%	41%	32%	29%	48.76	1.39	0.96	0.05
DIM	HS30-60_HR10_cap2	83%	70%	46%	41%	31%	29%	46.91	1.46	0.77	0.04
DIM	HS50-60_HR10	83%	70%	45%	39%	28%	26%	64.52	1.83	0.00	0.00
DIM	HS30-60_HR15_cap2	82%	70%	47%	41%	32%	29%	44.24	1.40	1.16	0.06
DIM	HS50-60_HR15	82%	69%	40%	35%	23%	21%	67.62	2.54	0.00	0.00
DIM	consTAC1	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	93%	81%	56%	49%	39%	96%	6.67	1.26	0.00	0.00
conM	HS30-60_HR10_cap2	93%	81%	54%	48%	38%	95%	24.51	1.85	0.77	0.04
conM	HS30-60_HR15_cap2	93%	80%	54%	48%	38%	95%	21.03	1.92	1.16	0.06
conM	minE0.3B0_HR05	93%	80%	53%	46%	37%	95%	45.12	2.76	0.96	0.05
conM	HS50-60_HR10	91%	77%	47%	40%	31%	92%	49.69	5.01	0.00	0.00
conM	HS50-60_HR15	89%	74%	41%	36%	26%	89%	51.66	7.29	0.00	0.00

Figures

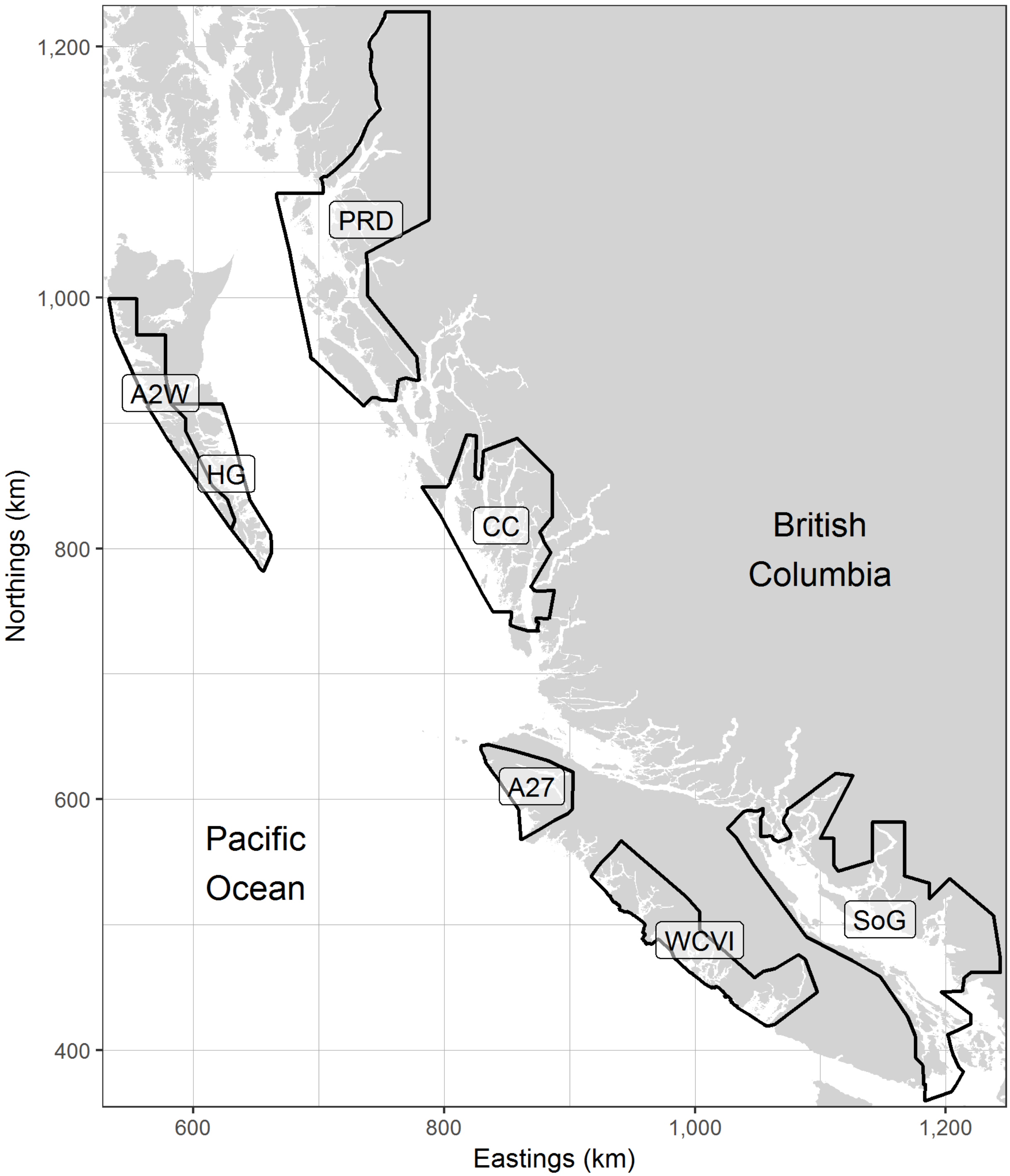

Figure 1. Boundaries for Pacific Herring SARs in British Columbia. The major SARs are Haida Gwaii (HG), Prince Rupert District (PRD), Central Coast (CC), Strait of Georgia (SoG), and West Coast of Vancouver Island (WCVI). The minor SARs are Area 27 (A27) and Area 2 West (A2W). Units: kilometres (km).

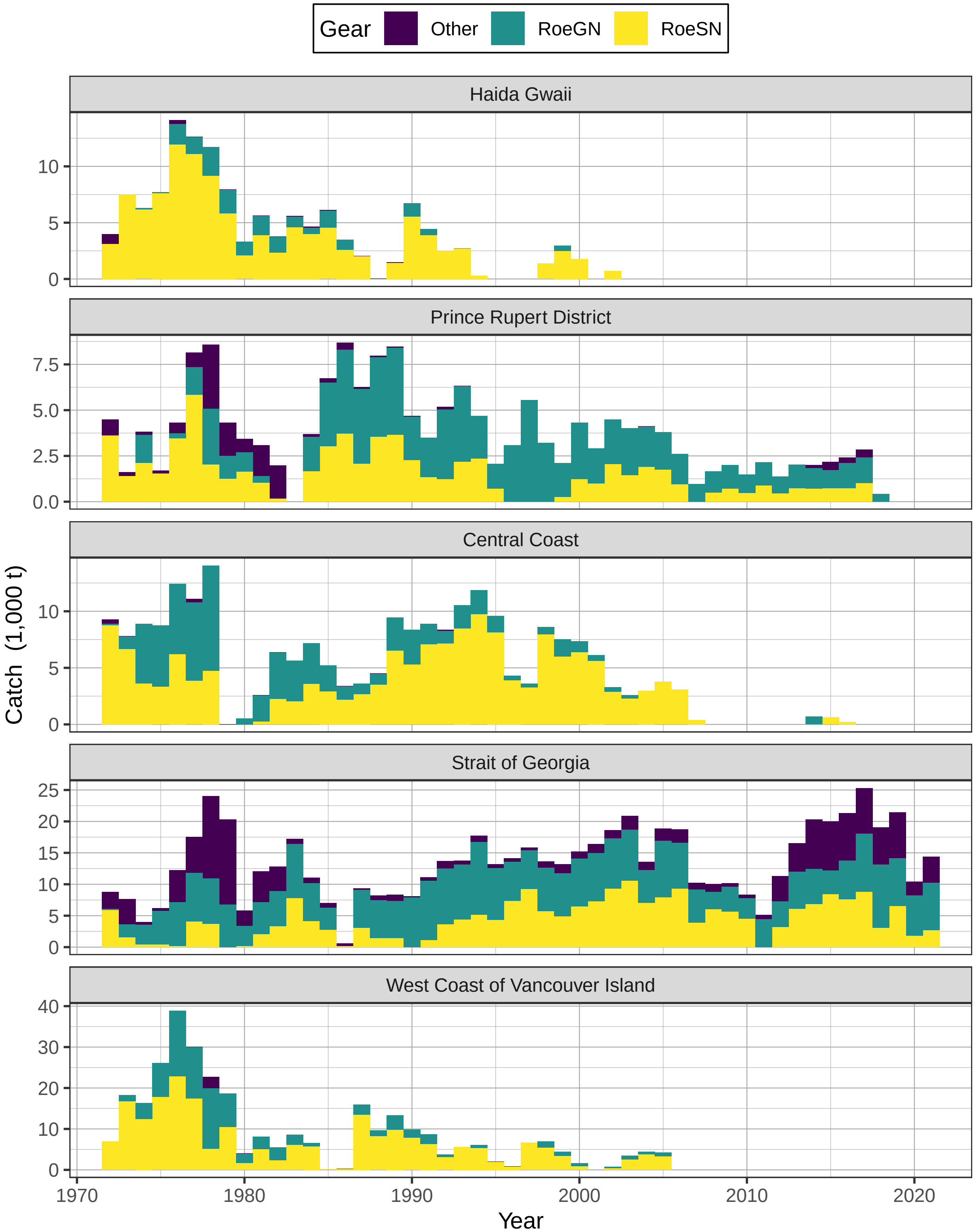

Figure 2. Total landed Pacific Herring catch in thousands of tonnes (t) from 1972 to 2021 in the major SARs. See Figures 7 to 12 for catches during the reduction period (1951 to 1971). Legend: 'Other' represents the reduction, the food and bait, as well as the special use fishery; 'RoeGN' represents the roe gillnet fishery; and 'RoeSN' represents the roe seine fishery.

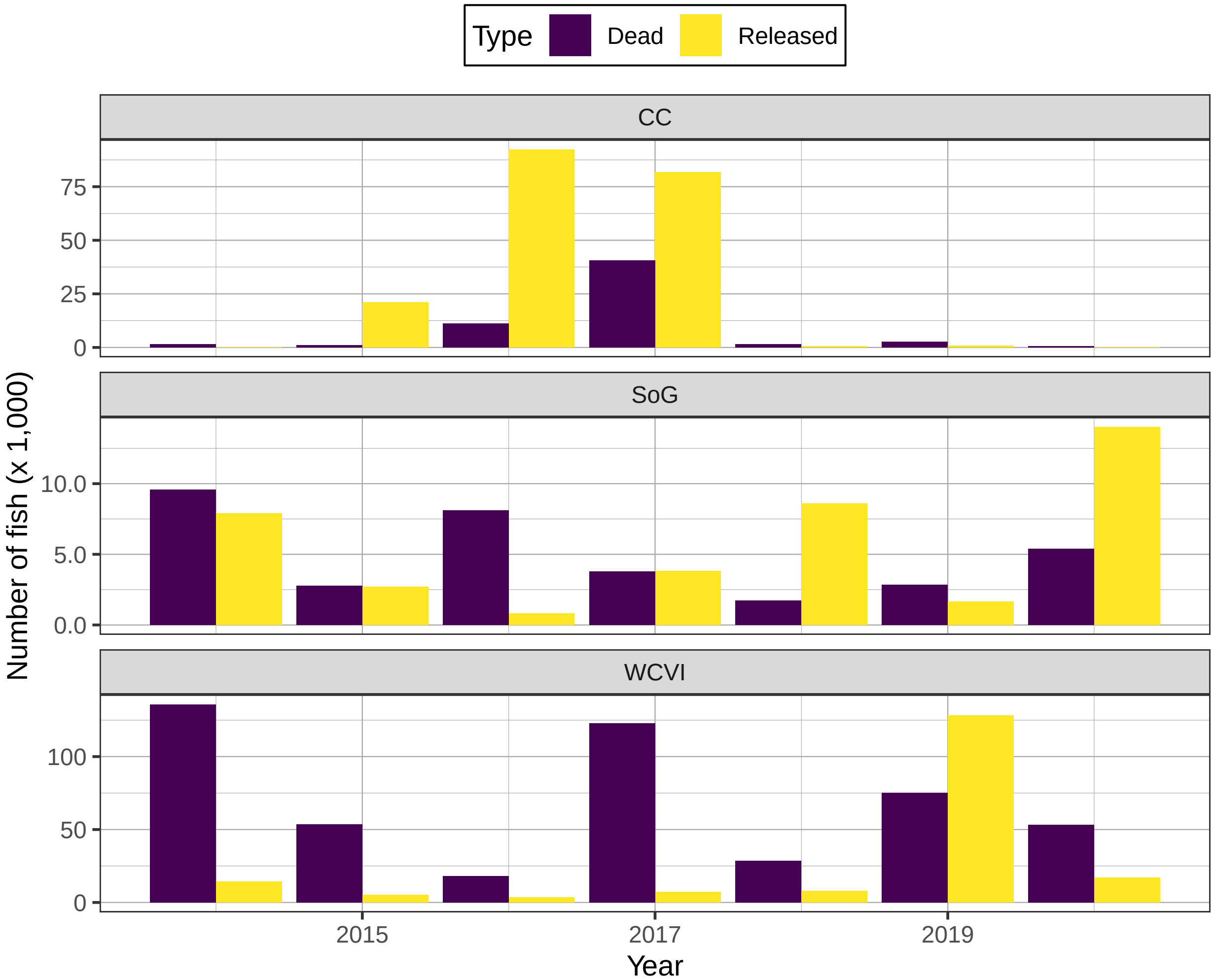

Figure 3. Incidental Pacific Herring mortality in aquaculture activities in thousands of fish from 2014 to 2020 in the major SARs. Notes: data for 2020 may be incomplete, figure may include data outside SAR boundaries, and figure excludes SARs with no reported incidental mortality

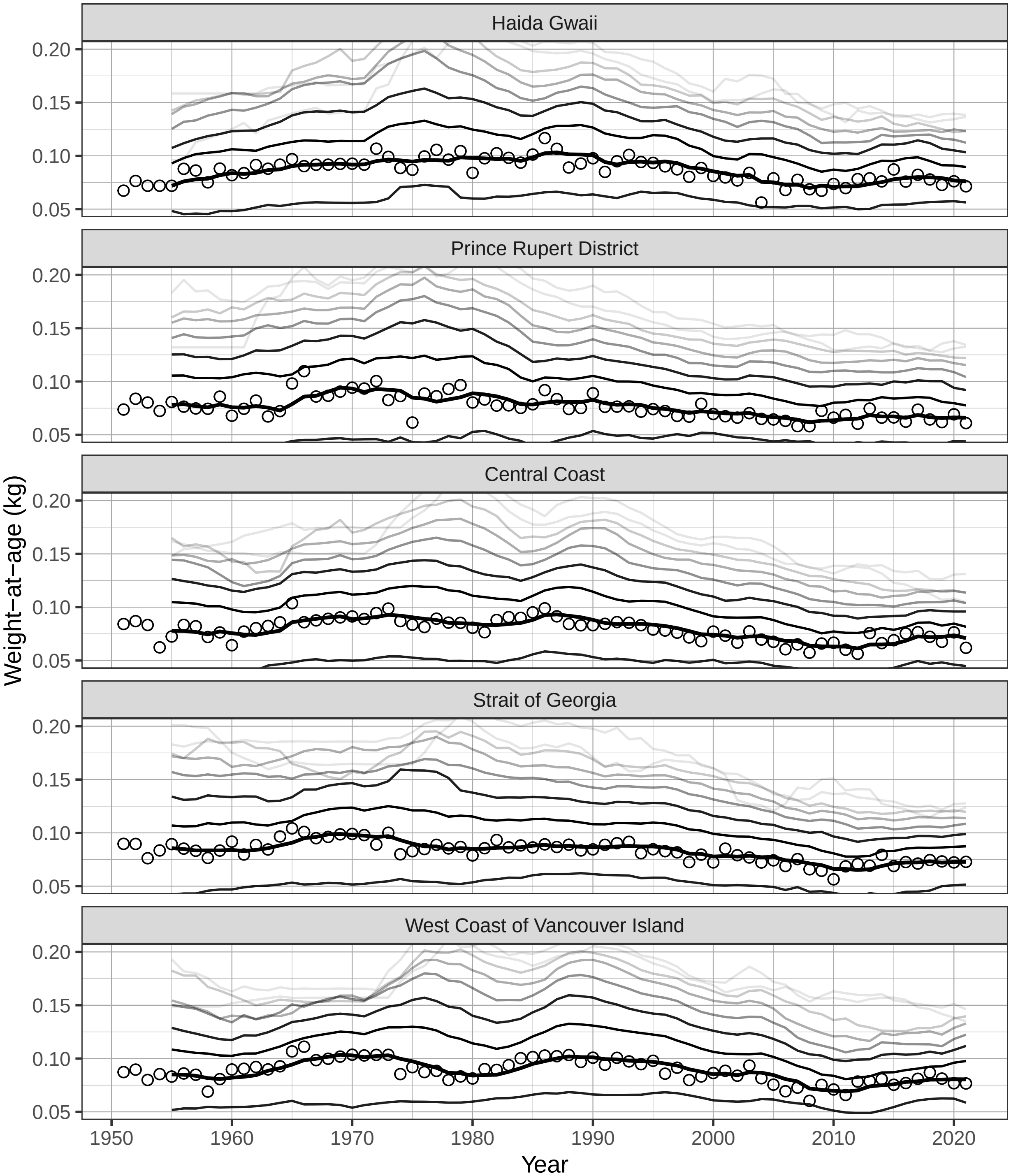

Figure 4. Mean weight-at-age for Pacific Herring in kilograms (kg) from 1951 to 2021 in the major SARs. Lines show 5-year running means for age-2 to age-10 herring, incrementing up from bottom line and shaded from darker to lighter, except thickest line shows age-3 herring. Circles show mean for age-3 herring. In years where there are no biological samples for an age class, values are imputed as the mean of the previous 5 years, except for the beginning of the time series which are imputed by extending the first non-missing value backwards. 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 includes fish ages 10 and older. Vertical axes are cropped at 0.05 to 0.20 kg.

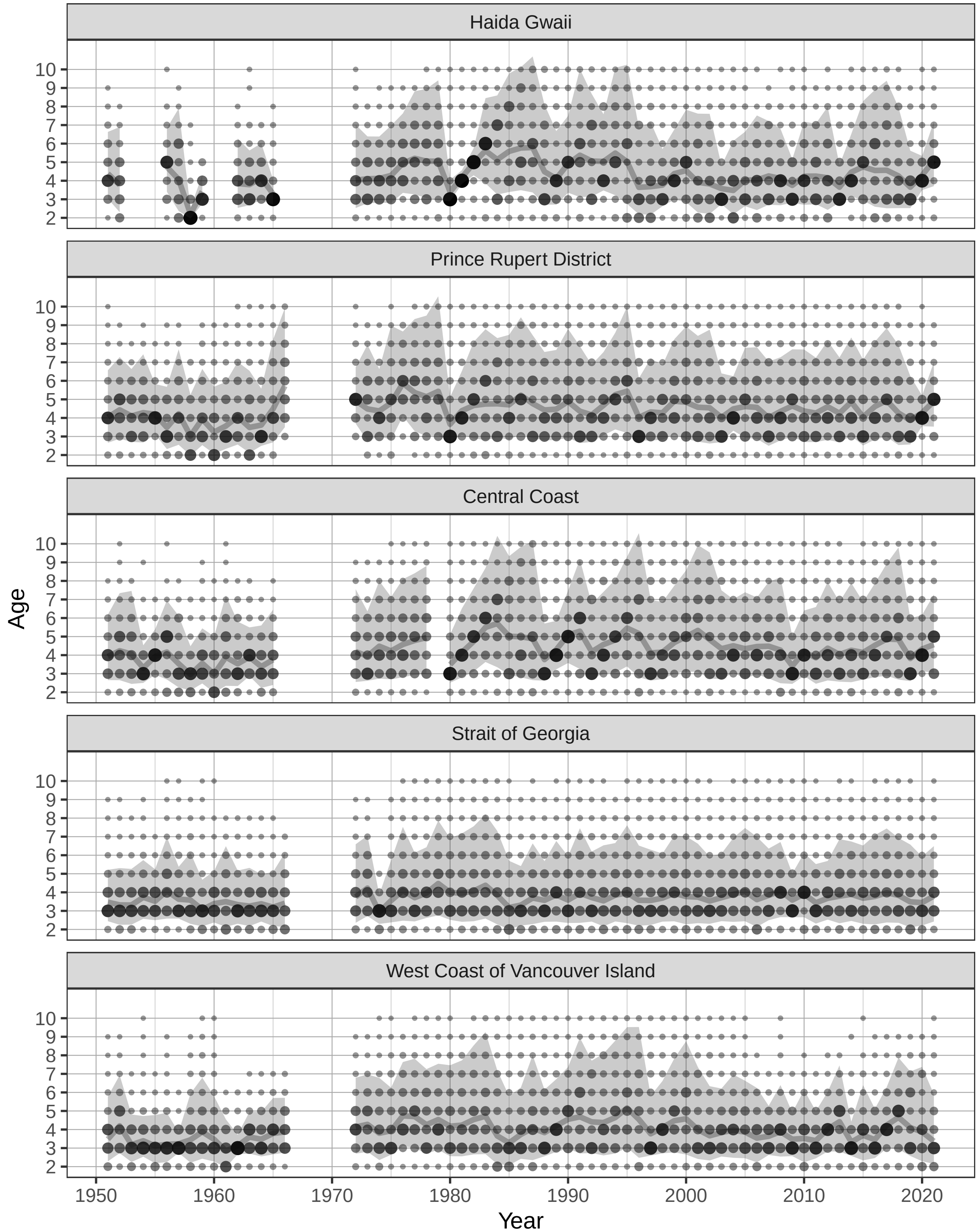

Figure 5. Proportion-at-age for Pacific Herring from 1951 to 2021 in the major SARs. Dot size and colour indicates age class proportion for the year; each year adds up to 1.0. The gray line is the mean age, and the shaded area is the approximate 90% distribution. Biological summaries only include samples collected using seine nets (commercial and test) due to size-selectivity of other gear types such as gillnet. The age-10 plus class includes fish ages 10 and older.

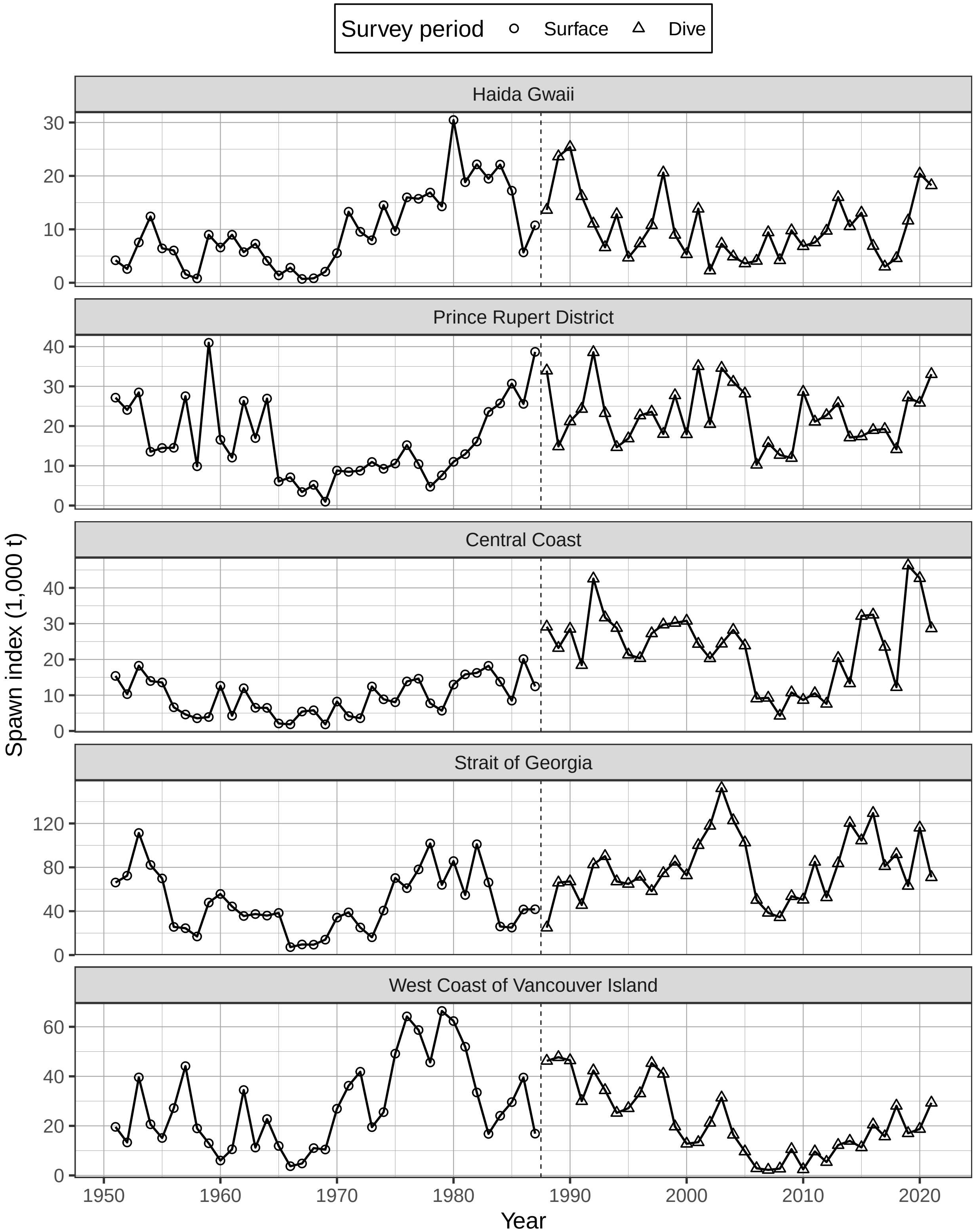

Figure 6. Spawn index in thousands of tonnes (t) for Pacific Herring from 1951 to 2021 in the major SARs. The dashed vertical line delineates between two periods defined by the dominant survey method: surface surveys (1951 to 1987), and dive surveys (1988 to 2021). Note: the 'spawn index' is not scaled by the spawn survey scaling parameter q.

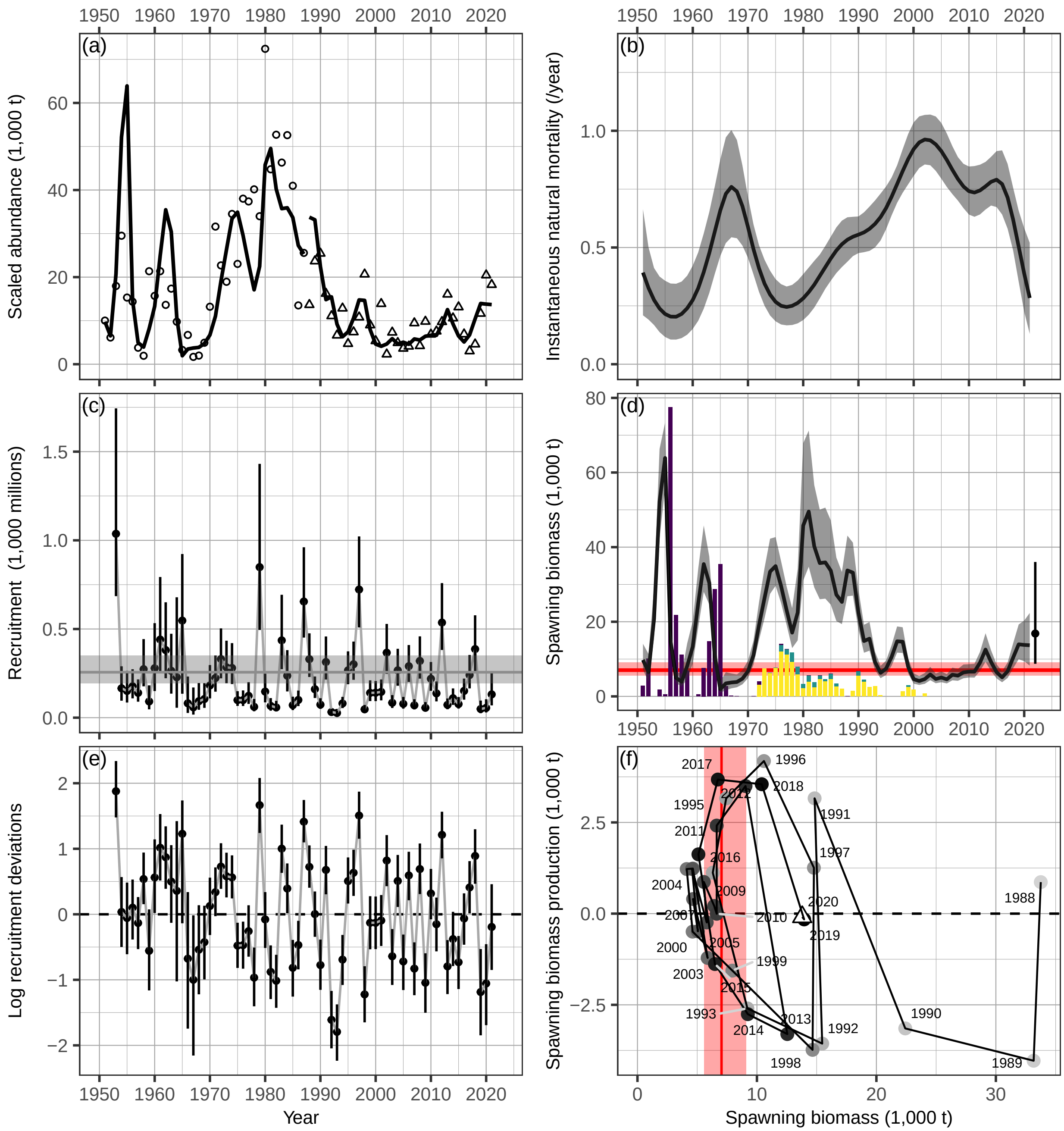

*Figure 7. Haida Gwaii SAR: statistical catch-age model output for Pacific Herring from 1951 to 2021. **Panel (a)**: Model fit (lines) to scaled abundance (points; Figure 6). Spawn index is scaled to abundance by the spawn index scaling parameter q. **Panel (b)**: Instantaneous natural mortality rate (year^{-1}). **Panel (c)**: Reconstructed number of age-2 recruits in thousands of millions from 1953 to 2021. Horizontal line indicates unfished age-2 recruitment R_0. **Panel (d)**: Spawning biomass (line), and forecast spawning biomass in 2022 in the absence of fishing (point). Coloured vertical bars indicate commercial catch (Figure 2). **Panel (e)**: Log recruitment deviations from 1953 to 2021. **Panel (f)**: Phase plot of spawning biomass production for the dive survey period (1988 to 2020). Points are chronologically shaded light to dark; triangle indicates 2020. Legend: biomass and catch are in thousands of tonnes (t), points and time-series lines are median posterior estimates, bands and error bars are 90% credible intervals, dashed horizontal lines indicate zero, and red lines indicate the median limit reference point $0.3SB_0$, where SB_0 is the estimated unfished spawning biomass.*

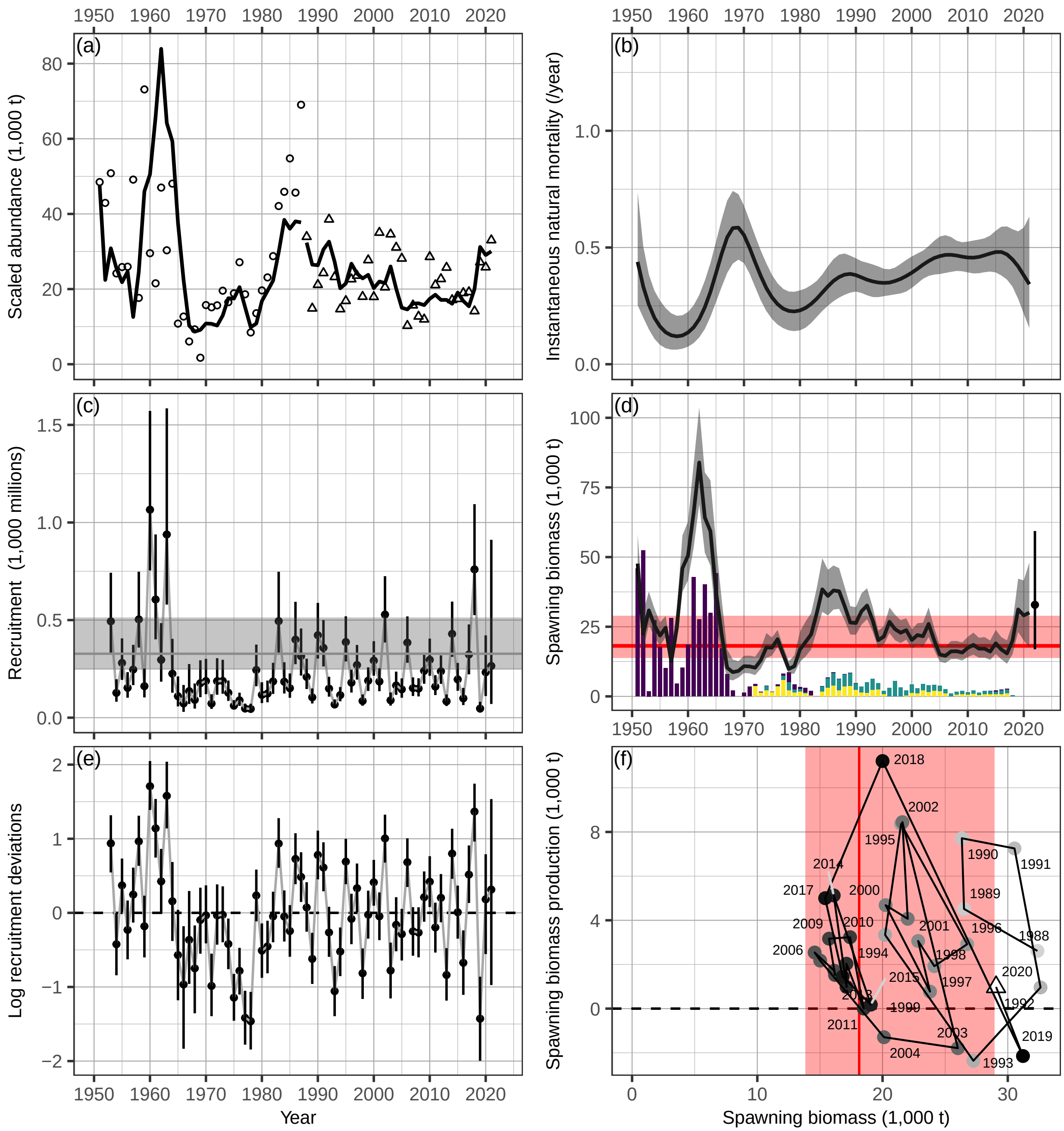

*Figure 8. Prince Rupert District SAR: statistical catch-age model output for Pacific Herring from 1951 to 2021. **Panel (a)**: Model fit (lines) to scaled abundance (points; Figure 6). Spawn index is scaled to abundance by the spawn index scaling parameter q. **Panel (b)**: Instantaneous natural mortality rate (year^{-1}). **Panel (c)**: Reconstructed number of age-2 recruits in thousands of millions from 1953 to 2021. Horizontal line indicates unfished age-2 recruitment R_0. **Panel (d)**: Spawning biomass (line), and forecast spawning biomass in 2022 in the absence of fishing (point). Coloured vertical bars indicate commercial catch (Figure 2). **Panel (e)**: Log recruitment deviations from 1953 to 2021. **Panel (f)**: Phase plot of spawning biomass production for the dive survey period (1988 to 2020). Points are chronologically shaded light to dark; triangle indicates 2020. Legend: biomass and catch are in thousands of tonnes (t), points and time-series lines are median posterior estimates, bands and error bars are 90% credible intervals, dashed horizontal lines indicate zero, and red lines indicate the median limit reference point $0.3SB_0$, where SB_0 is the estimated unfished spawning biomass.*

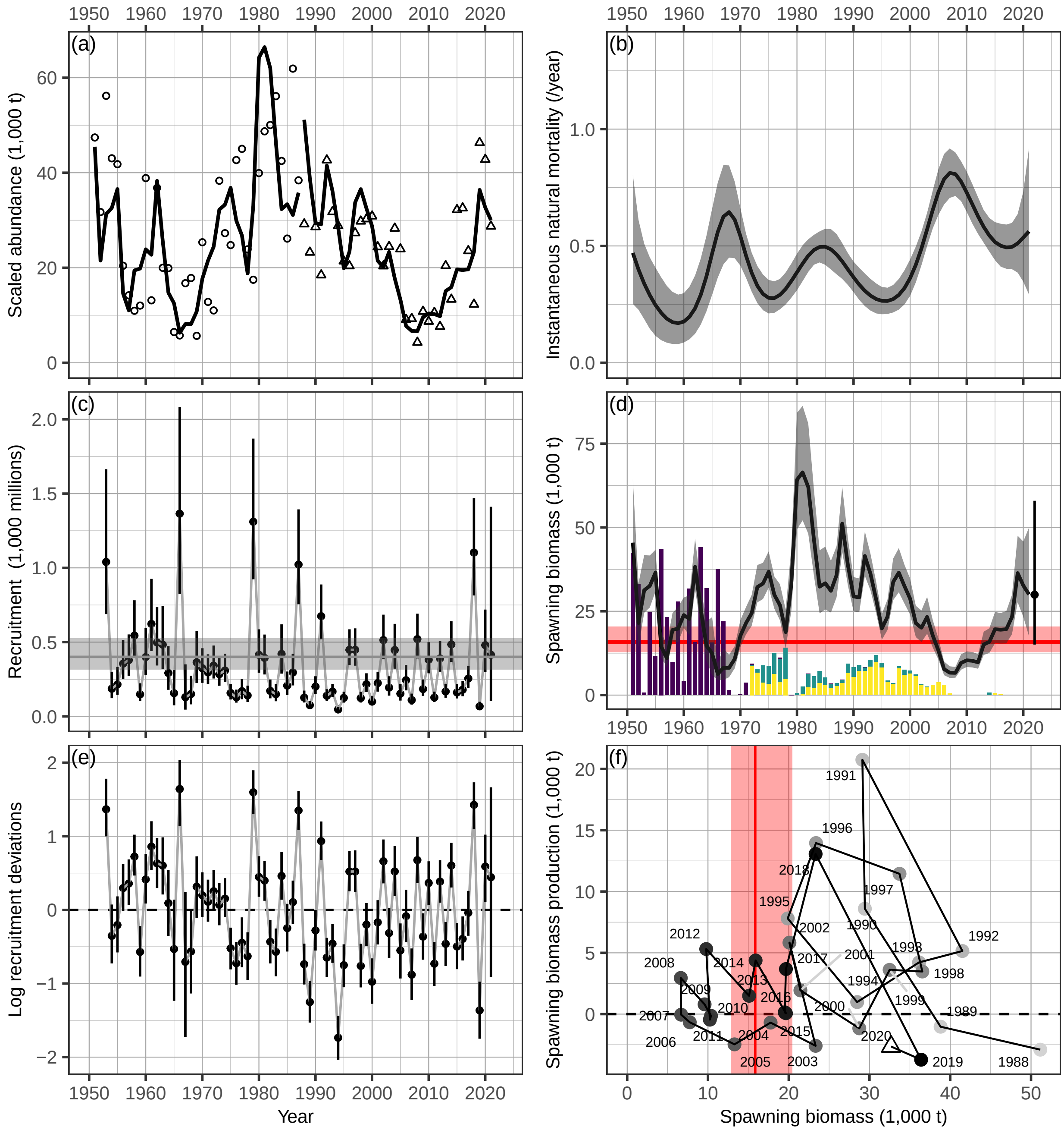

Figure 9. Central Coast SAR: statistical catch-age model output for Pacific Herring from 1951 to 2021. ***Panel (a)****: Model fit (lines) to scaled abundance (points; Figure 6). Spawn index is scaled to abundance by the spawn index scaling parameter q.* ***Panel (b)****: Instantaneous natural mortality rate (year^{-1}).* ***Panel (c)****: Reconstructed number of age-2 recruits in thousands of millions from 1953 to 2021. Horizontal line indicates unfished age-2 recruitment R_0.* ***Panel (d)****: Spawning biomass (line), and forecast spawning biomass in 2022 in the absence of fishing (point). Coloured vertical bars indicate commercial catch (Figure 2).* ***Panel (e)****: Log recruitment deviations from 1953 to 2021.* ***Panel (f)****: Phase plot of spawning biomass production for the dive survey period (1988 to 2020). Points are chronologically shaded light to dark; triangle indicates 2020. Legend: biomass and catch are in thousands of tonnes (t), points and time-series lines are median posterior estimates, bands and error bars are 90% credible intervals, dashed horizontal lines indicate zero, and red lines indicate the median limit reference point $0.3SB_0$, where SB_0 is the estimated unfished spawning biomass.*

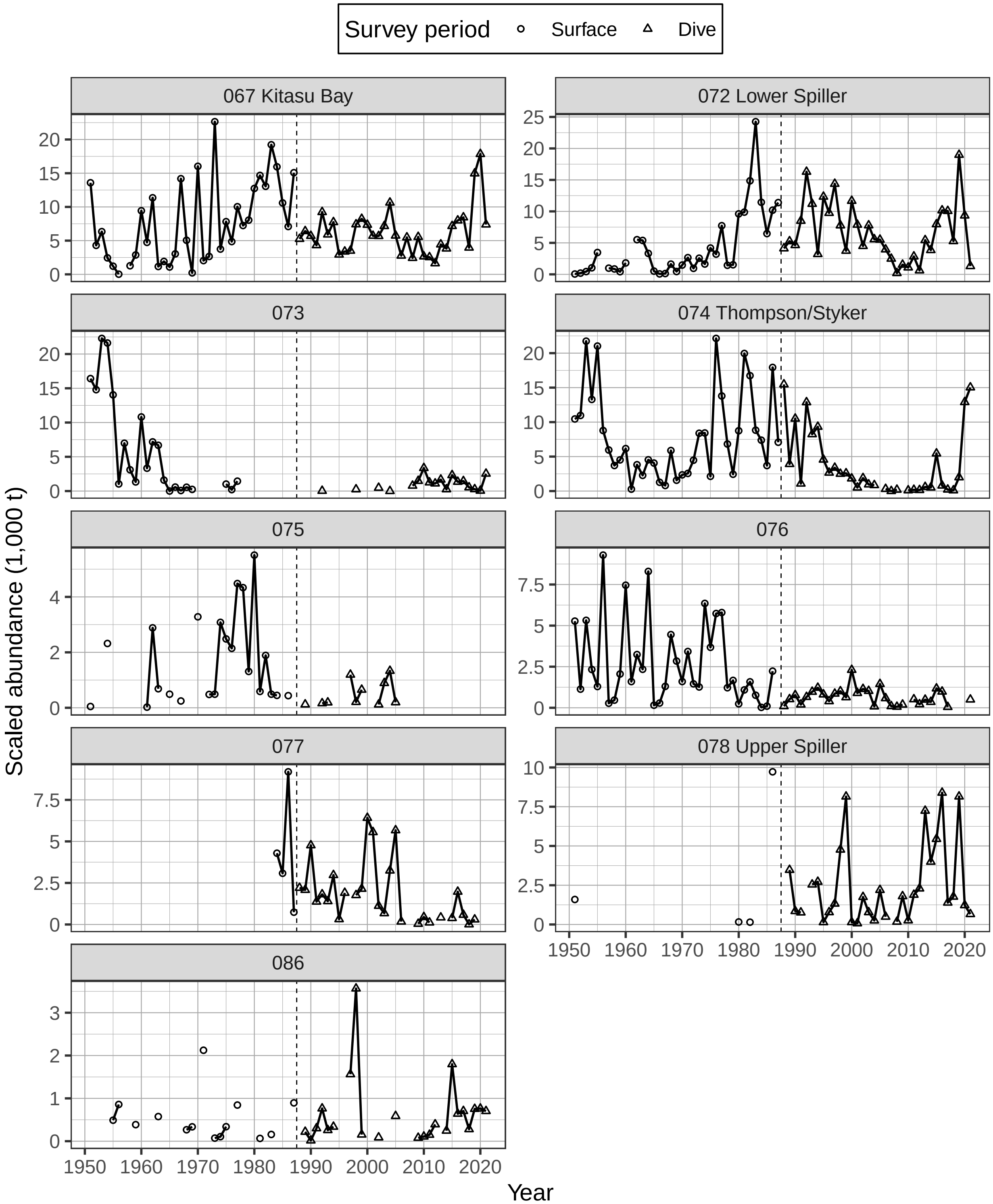

Figure 10. Central Coast SAR: scaled abundance in thousands of tonnes (t) of Pacific Herring in selected Sections from 1951 to 2021. The spawn index is scaled to abundance by the spawn survey scaling parameter q (median posterior estimate). The dashed vertical line delineates between two periods defined by the dominant survey method: surface surveys (1951 to 1987), and dive surveys (1988 to 2021).

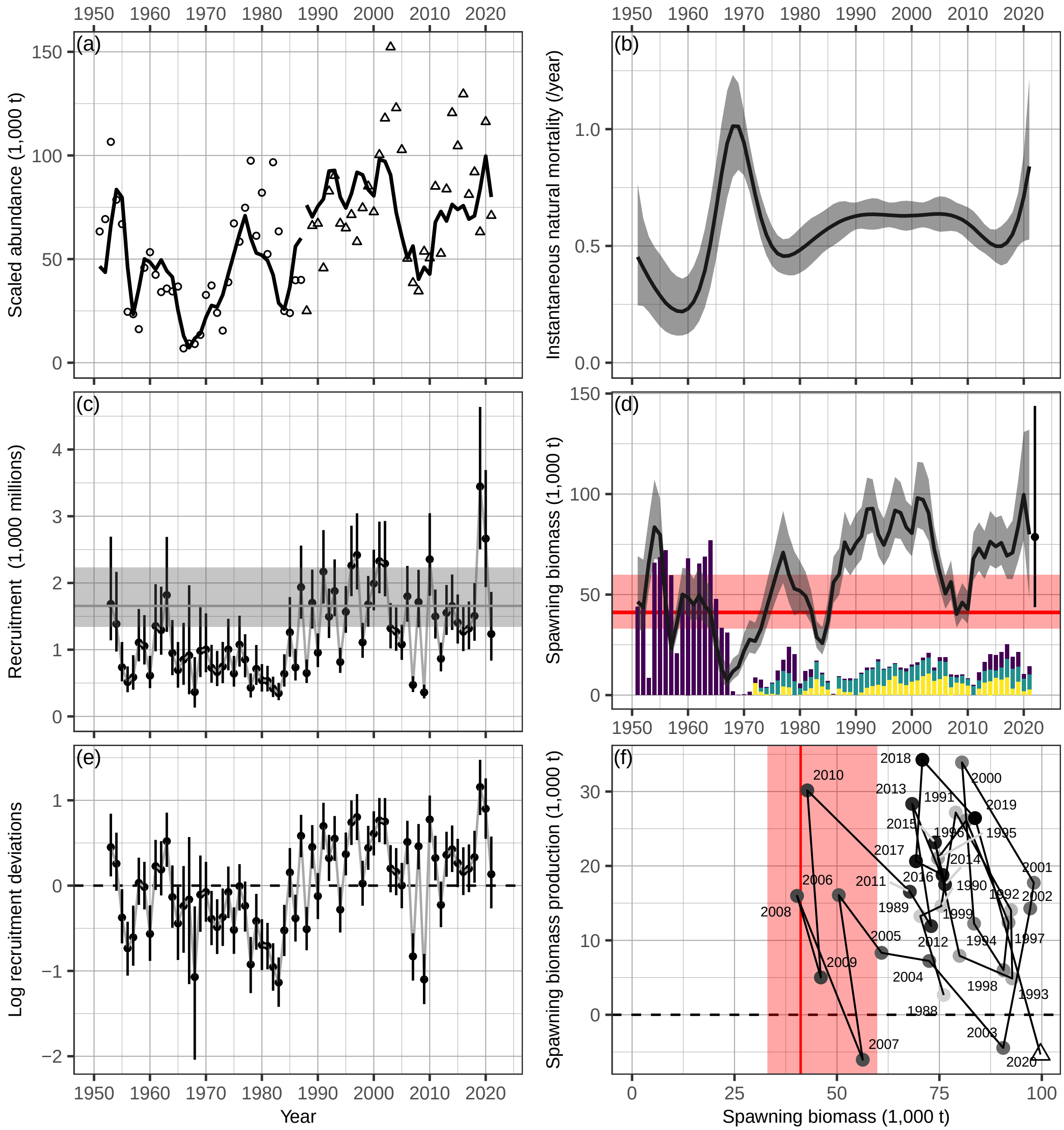

Figure 11. Strait of Georgia SAR: statistical catch-age model output for Pacific Herring from 1951 to 2021. ***Panel (a)****: Model fit (lines) to scaled abundance (points; Figure 6). Spawn index is scaled to abundance by the spawn index scaling parameter q.* ***Panel (b)****: Instantaneous natural mortality rate (year^{-1}).* ***Panel (c)****: Reconstructed number of age-2 recruits in thousands of millions from 1953 to 2021. Horizontal line indicates unfished age-2 recruitment R_0.* ***Panel (d)****: Spawning biomass (line), and forecast spawning biomass in 2022 in the absence of fishing (point). Coloured vertical bars indicate commercial catch (Figure 2).* ***Panel (e)****: Log recruitment deviations from 1953 to 2021.* ***Panel (f)****: Phase plot of spawning biomass production for the dive survey period (1988 to 2020). Points are chronologically shaded light to dark; triangle indicates 2020. Legend: biomass and catch are in thousands of tonnes (t), points and time-series lines are median posterior estimates, bands and error bars are 90% credible intervals, dashed horizontal lines indicate zero, and red lines indicate the median limit reference point $0.3SB_0$, where SB_0 is the estimated unfished spawning biomass.*

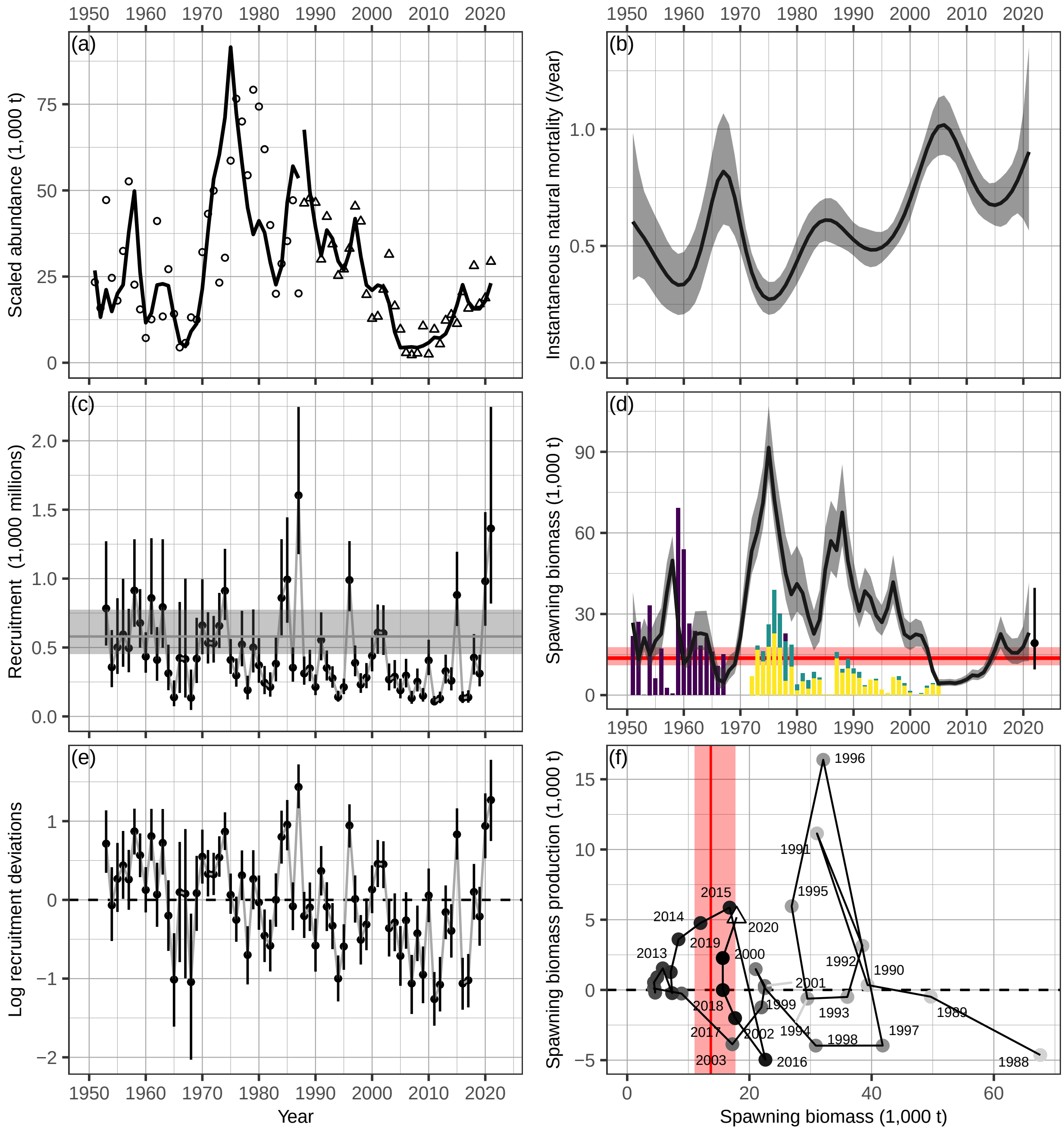

*Figure 12. West Coast of Vancouver Island SAR: statistical catch-age model output for Pacific Herring from 1951 to 2021. **Panel (a)**: Model fit (lines) to scaled abundance (points; Figure 6). Spawn index is scaled to abundance by the spawn index scaling parameter q. **Panel (b)**: Instantaneous natural mortality rate (year^{-1}). **Panel (c)**: Reconstructed number of age-2 recruits in thousands of millions from 1953 to 2021. Horizontal line indicates unfished age-2 recruitment R_0. **Panel (d)**: Spawning biomass (line), and forecast spawning biomass in 2022 in the absence of fishing (point). Coloured vertical bars indicate commercial catch (Figure 2). **Panel (e)**: Log recruitment deviations from 1953 to 2021. **Panel (f)**: Phase plot of spawning biomass production for the dive survey period (1988 to 2020). Points are chronologically shaded light to dark; triangle indicates 2020. Legend: biomass and catch are in thousands of tonnes (t), points and time-series lines are median posterior estimates, bands and error bars are 90% credible intervals, dashed horizontal lines indicate zero, and red lines indicate the median limit reference point $0.3SB_0$, where SB_0 is the estimated unfished spawning biomass.*

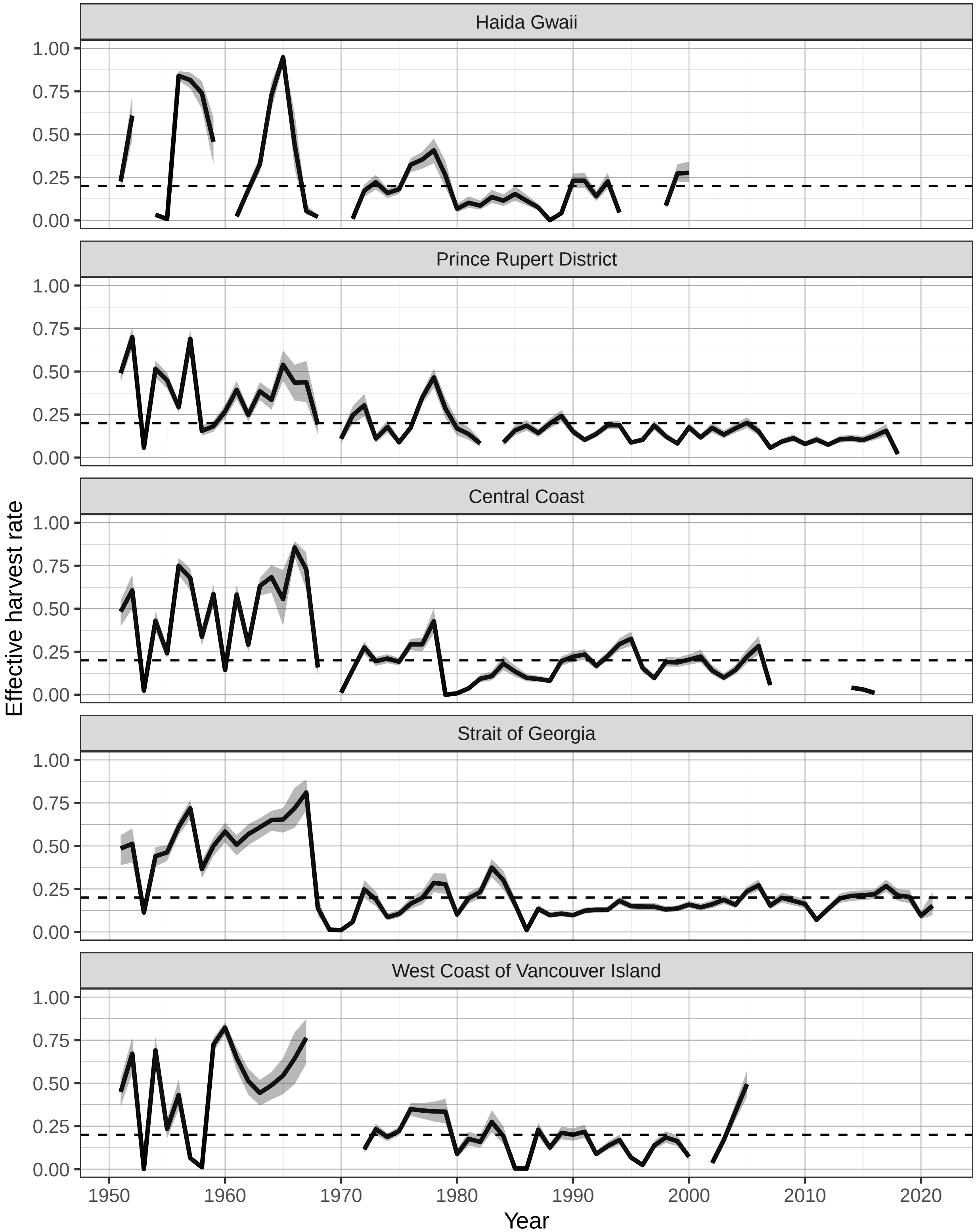

Figure 13. Effective harvest rate U_t for Pacific Herring from 1951 to 2021 in the major SARs. Effective harvest rate is $U_t = C_t/(C_t + SB_t)$ where C_t is catch in year t, and SB_t is estimated spawning biomass in year t. Black lines and shaded ribbons indicate medians and 90% credible intervals for U_t, respectively. Horizontal dashed lines indicate $U_t = 0.2$.

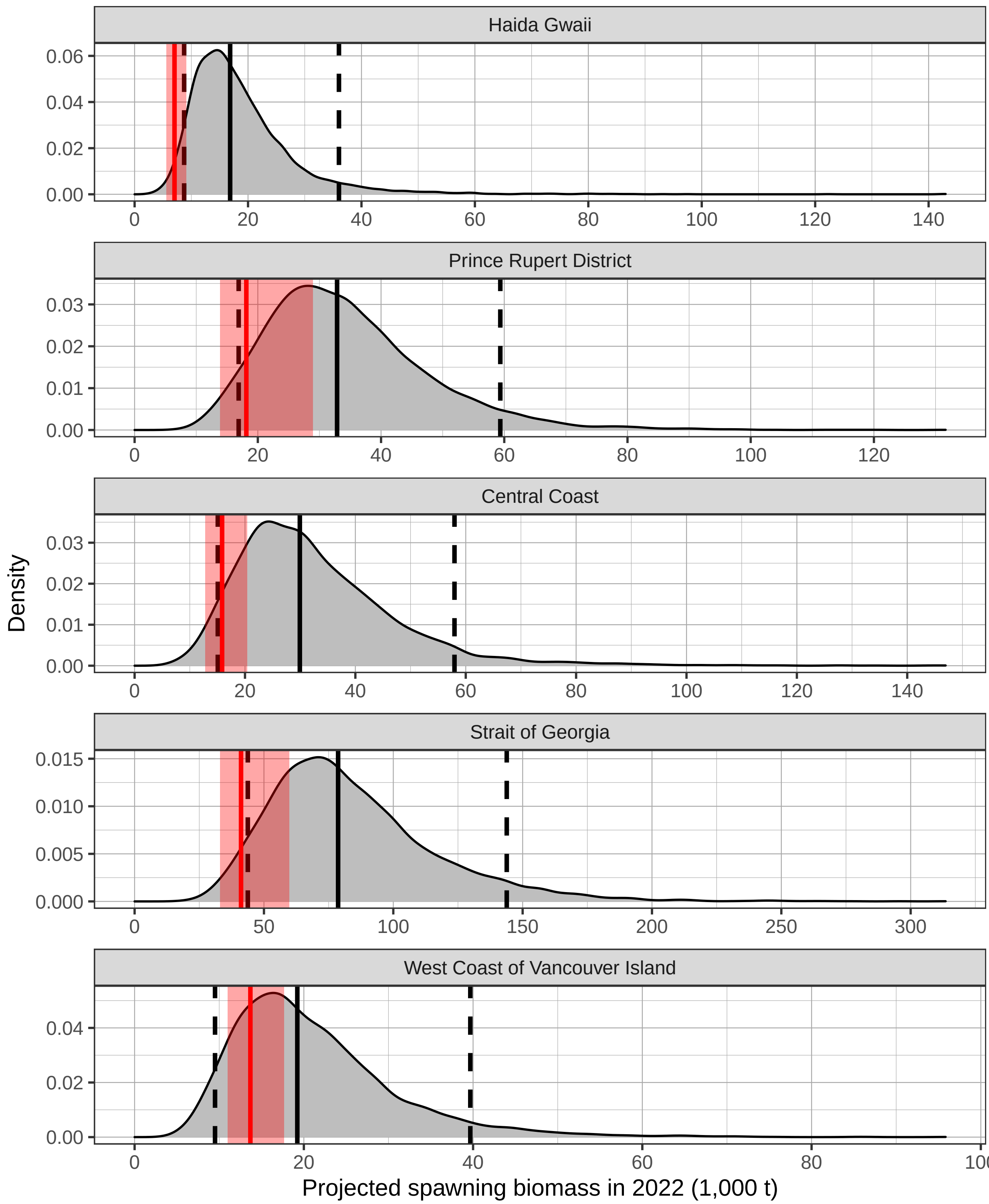

Figure 14. Projected spawning biomass of Pacific Herring assuming no fishing in 2022 SB_{2022} in thousands of tonnes (t) in the major SARs. Solid and dashed black lines indicate median posterior estimate and 90% credible intervals for SB_{2022}, respectively. Vertical red lines and shaded red areas indicate medians and 90% credible intervals for the limit reference point $0.3SB_0$, respectively, where SB_0 is estimated unfished spawning biomass.

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September 23, 2021

Sources of information

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Appendix

Minor stock assessment regions

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 and proportion of spawn index by Section from 2012 to 2021 for A27 and A2W (Tables 35 and 36, respectively). For Area 27, we provide the time series of spawn index by Section from 1978 to 2021 (Figure 15). We also provide time series of landed commercial catch (Figure 16), incidental catch (Figure 17), biological data including weight-at-age (Figure 18) and proportion-at-age (Figure 19), as well as spawn index (Figure 20) from 1978 to 2021.

Special areas

We do not conduct formal analyses of stock trend information for the Pacific Herring special area, Area 10 (A10; Figure 21). Note that special areas are not SARs; therefore they are excluded from regular monitoring and analyses. In addition, note that Area 10 is a subset of the Central Coast Sections that are outside the SAR boundary. As with the minor SARs, we provide the spawn index and proportion of spawn index by Section from 2012 to 2021 (Table 37). Note that 2021 spawn data may be incomplete; data for 2021 are from the DFO dive survey on 14 April 2021, and do not include data collected by the Gwa'sala-'Nakwaxda'xw Nation. We also provide time series of biological data including weight-at-age (Figure 22) and proportion-at-age (Figure 23), as well as the spawn index (Figure 24) from 1978 to 2021. Note that there is no commercial catch or incidental catch in Area 10 from 1978 to 2021.

Tables

Table 35. Area 27 SAR: spawn index in tonnes for Pacific Herring, and proportion of spawn index by Section from 2012 to 2021. See Table 4 for description.

		Proportion			
Year	**Spawn index**	**271**	**272**	**273**	**274**
2012	744	0.000	0.000	1.000	0.000
2013	914	0.000	0.000	1.000	0.000
2014	1,307	0.000	0.000	1.000	0.000
2015	2,169	0.000	0.000	1.000	0.000
2016	814	0.000	0.000	1.000	0.000
2017	26	0.000	0.000	1.000	0.000
2018	1,045	0.000	0.000	1.000	0.000
2019	192	0.000	0.000	1.000	0.000
2020	NA	0.000	0.000	0.000	0.000
2021	1,653	0.000	0.000	1.000	0.000

Table 36. Area 2 West SAR: spawn index in tonnes for Pacific Herring, and proportion of spawn index by Section from 2012 to 2021. See Table 4 for description.

		Proportion				
Year	**Spawn index**	**001**	**002**	**003**	**004**	**005**
2012	2,416	0.000	0.965	0.035	0.000	0.000
2013	2,076	0.000	0.983	0.017	0.000	0.000
2014	1,368	0.000	1.000	0.000	0.000	0.000
2015	NA	0.000	0.000	0.000	0.000	0.000
2016	3,001	0.000	1.000	0.000	0.000	0.000
2017	NA	0.000	0.000	0.000	0.000	0.000
2018	617	0.000	0.269	0.000	0.000	0.731
2019	2,884	0.000	1.000	0.000	0.000	0.000
2020	6,834	0.000	1.000	0.000	0.000	0.000
2021	1,377	0.000	1.000	0.000	0.000	0.000

Table 37. Area 10 special area: spawn index in tonnes for Pacific Herring, and proportion of spawn index by Section from 2012 to 2021. See Table 4 for description.

		Proportion		
Year	**Spawn index**	**101**	**102**	**103**
2012	NA	0.000	0.000	0.000
2013	267	0.000	1.000	0.000
2014	493	0.000	1.000	0.000
2015	NA	0.000	0.000	0.000
2016	588	0.000	0.967	0.033
2017	2,206	0.000	1.000	0.000
2018	477	0.000	1.000	0.000
2019	570	0.000	1.000	0.000
2020	888	0.000	1.000	0.000
2021	155	0.000	1.000	0.000

Figures

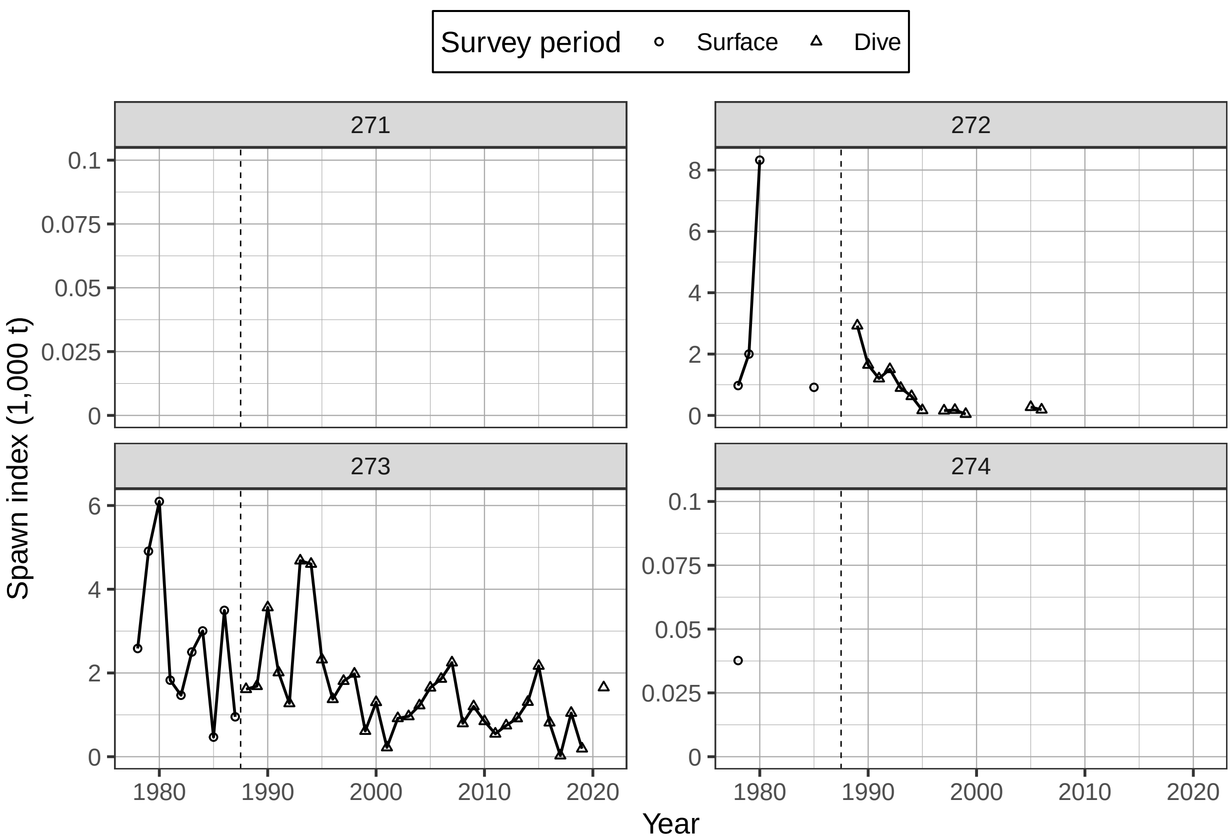

Figure 15. Area 27 SAR: spawn index in thousands of tonnes (t) of Pacific Herring by Section from 1978 to 2021. The dashed vertical line delineates between two periods defined by the dominant survey method: surface surveys (1951 to 1987), and dive surveys (1988 to 2021). Note: the 'spawn index' is not scaled by the spawn survey scaling parameter q.

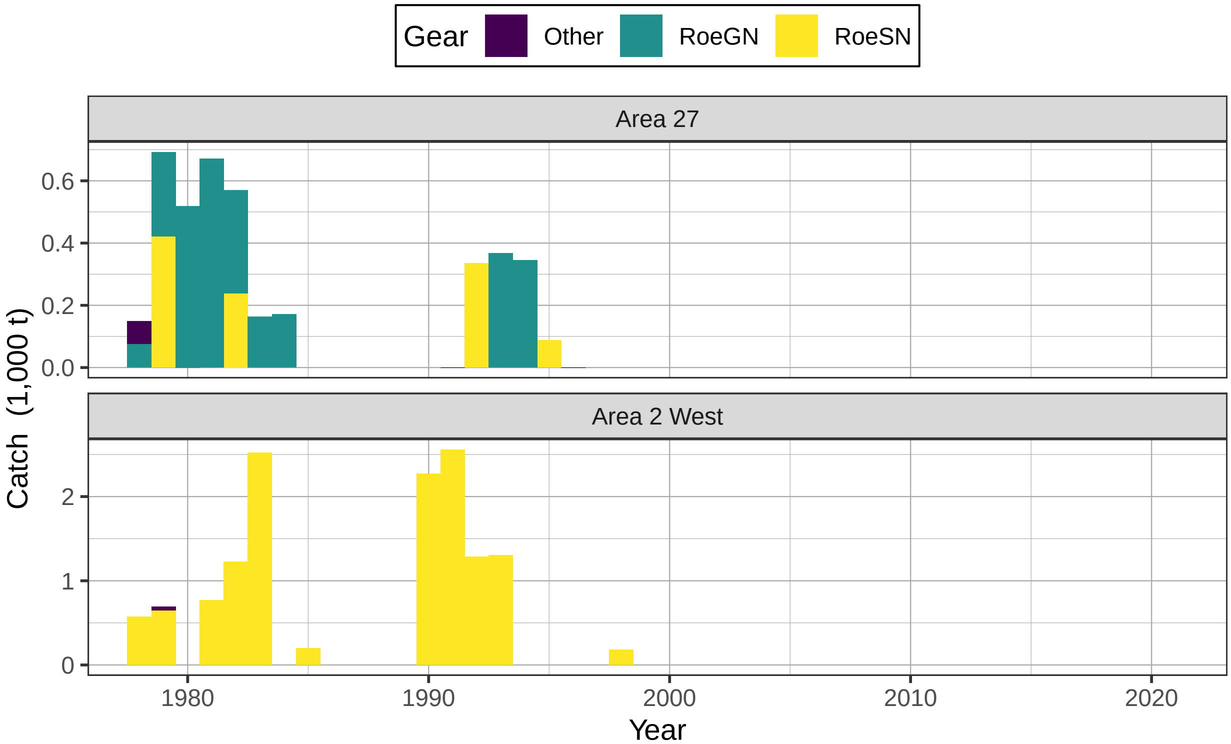

Figure 16. Total landed Pacific Herring catch in thousands of tonnes (t) from 1978 to 2021 in the minor SARs. See Figure 2 for description.

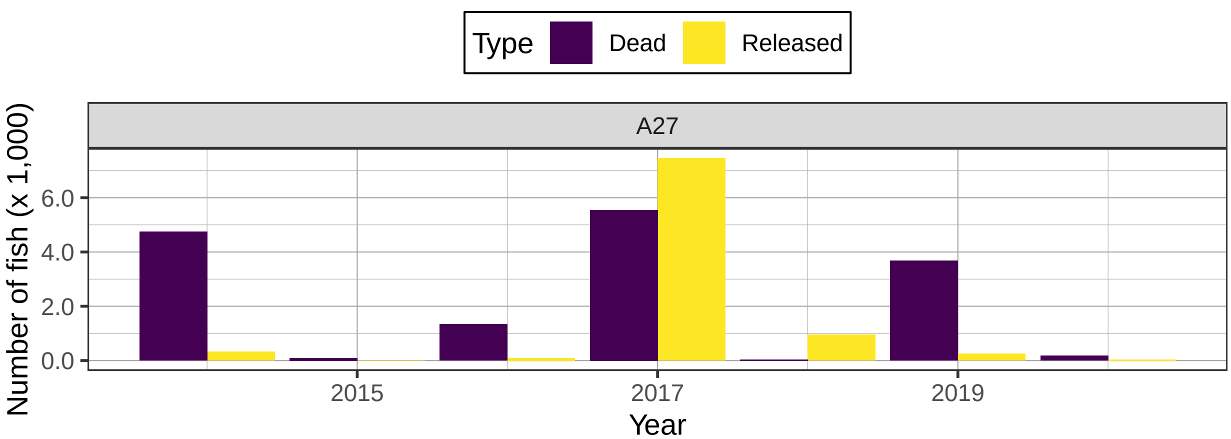

Figure 17. Incidental Pacific Herring mortality in aquaculture activities in thousands of fish from 2014 to 2020 in the minor SARs. See Figure 3 for description.

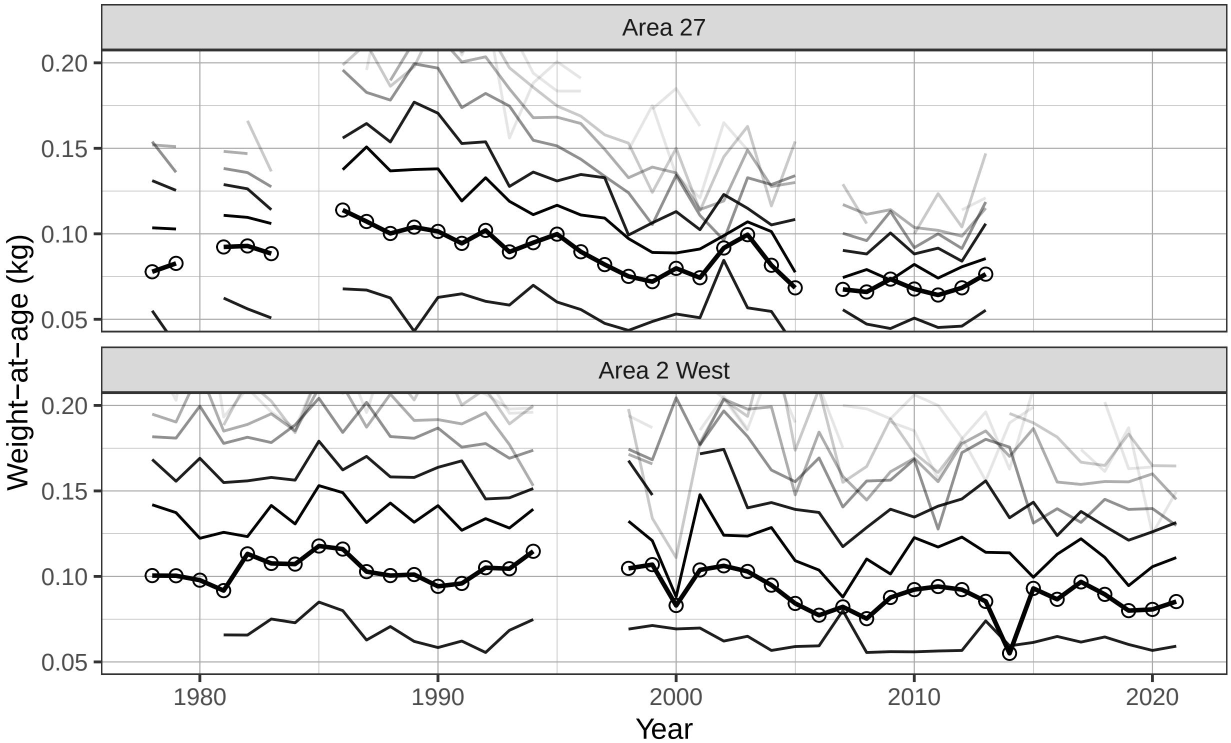

Figure 18. Mean weight-at-age for Pacific Herring in kilograms (kg) from 1978 to 2021 in the minor SARs. Circles show mean for age-3 herring. Lines show means for age-2 to age-10 herring, incrementing up from bottom line and shaded from darker to lighter. The thick line shows age-3 herring. Biological 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 includes fish ages 10 and older. Note: vertical axes are cropped at 0.05 to 0.20 kg.

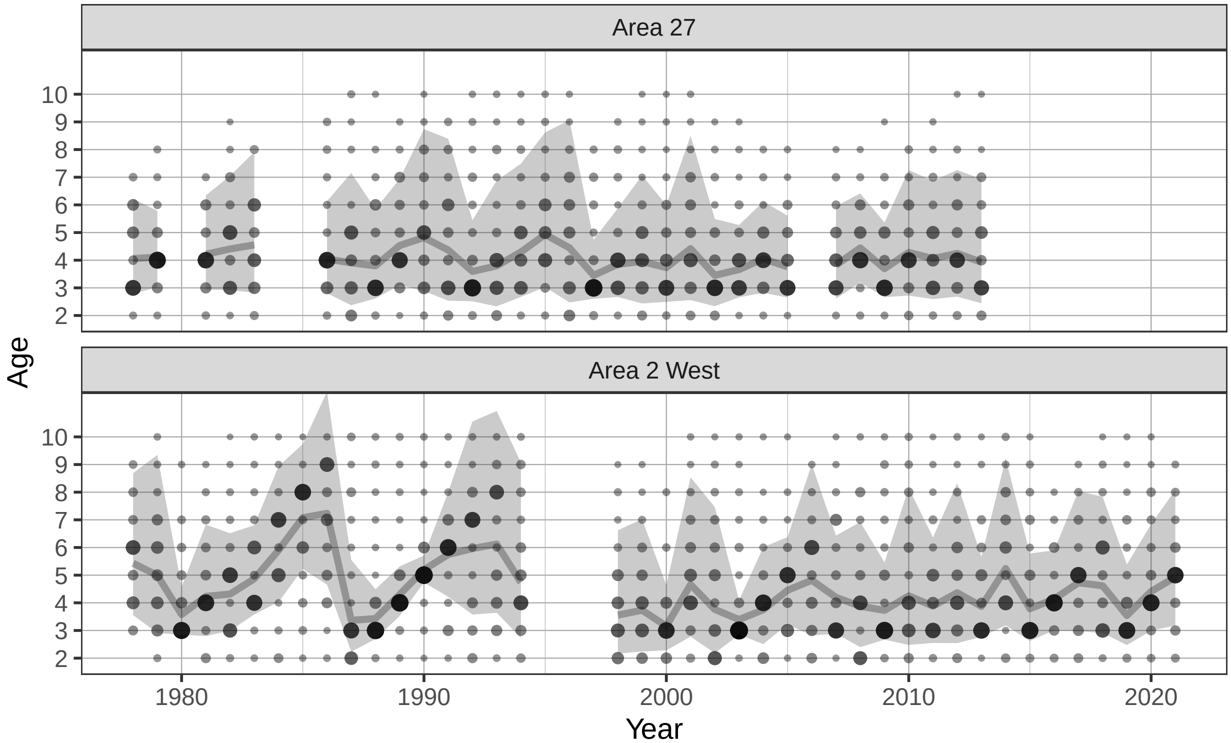

Figure 19. Proportion-at-age for Pacific Herring from 1978 to 2021 in the minor SARs. See Figure 5 for description.

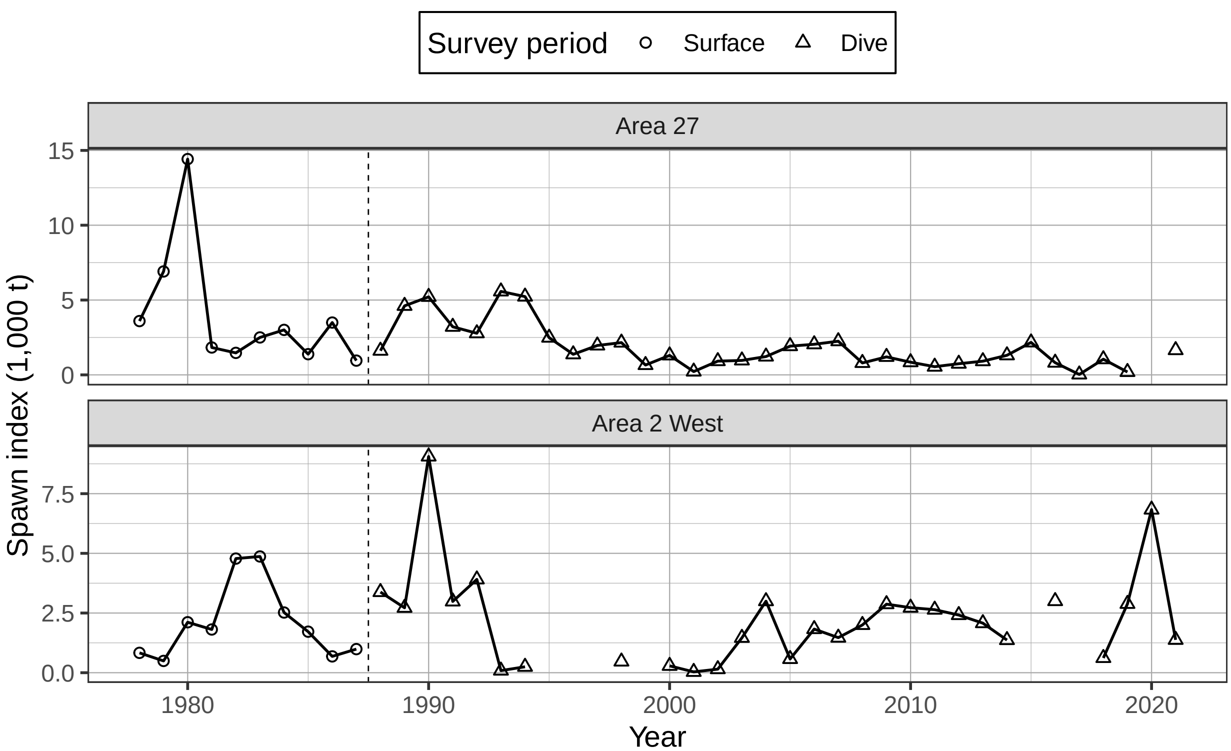

Figure 20. Spawn index in thousands of tonnes (t) for Pacific Herring from 1978 to 2021 in the minor SARs. See Figure 6 for description.

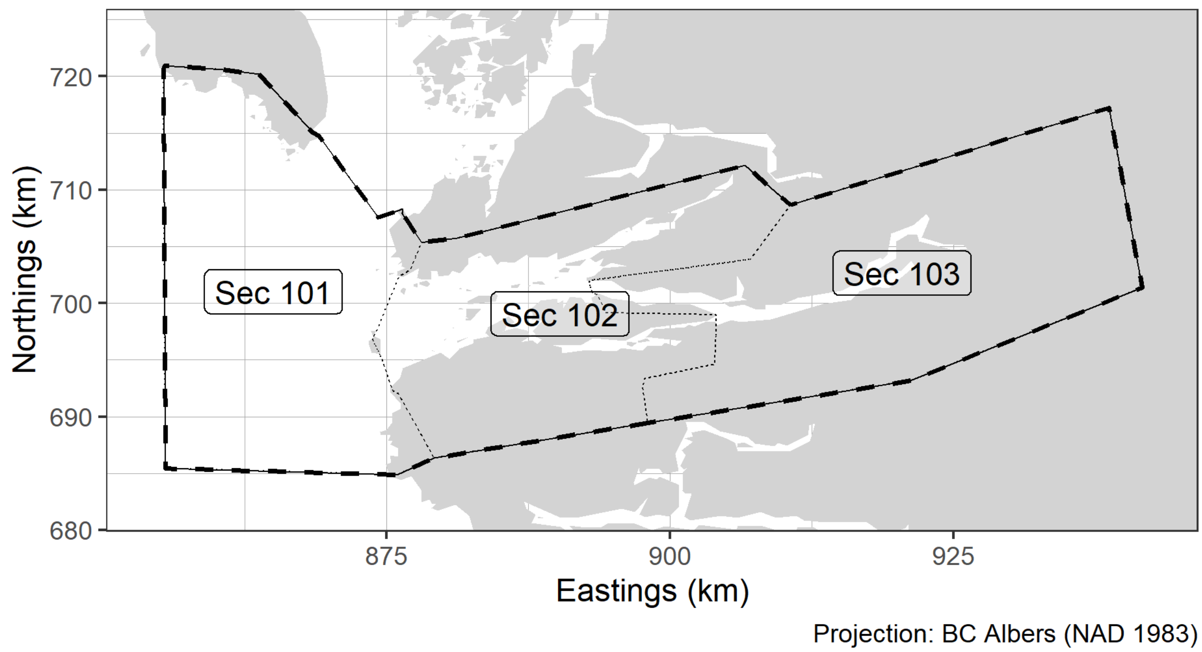

Figure 21. Sections (Sec) included in the Pacific Herring special area, Area 10 (A10). Note that special areas are not stock assessment regions (SARs); therefore they are excluded from regular monitoring and analyses. In addition, note that A10 is a subset of the Central Coast Sections that are outside the SAR boundary. Units: kilometres (km).

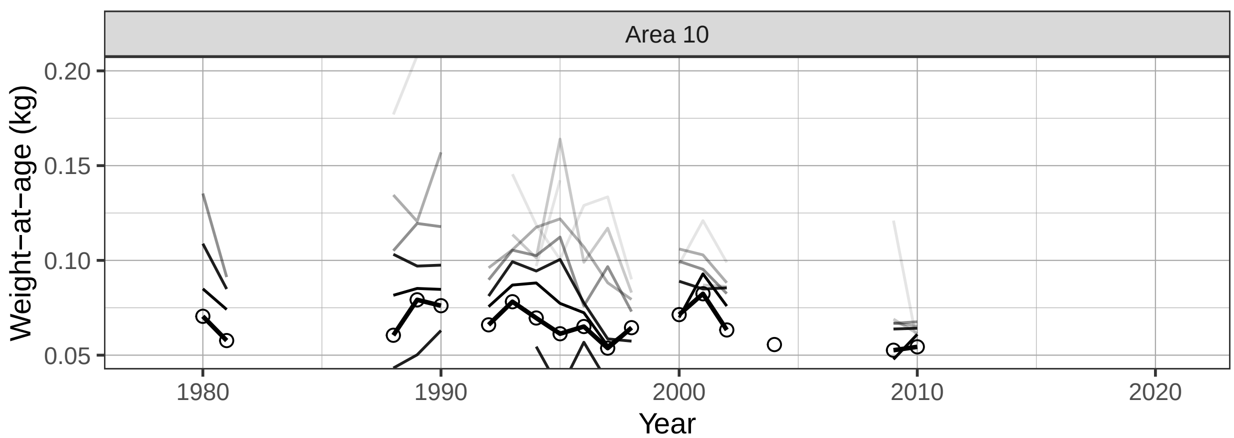

Figure 22. Mean weight-at-age for Pacific Herring in kilograms (kg) from 1978 to 2021 in the special area, Area 10. See Figure 18 for description.

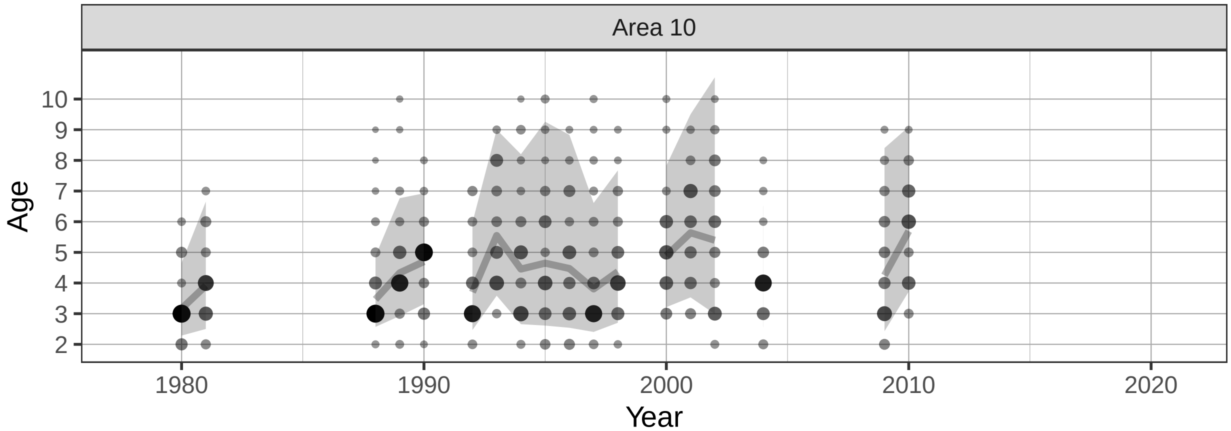

Figure 23. Proportion-at-age for Pacific Herring from 1978 to 2021 in the special area, Area 10. See Figure 5 for description.

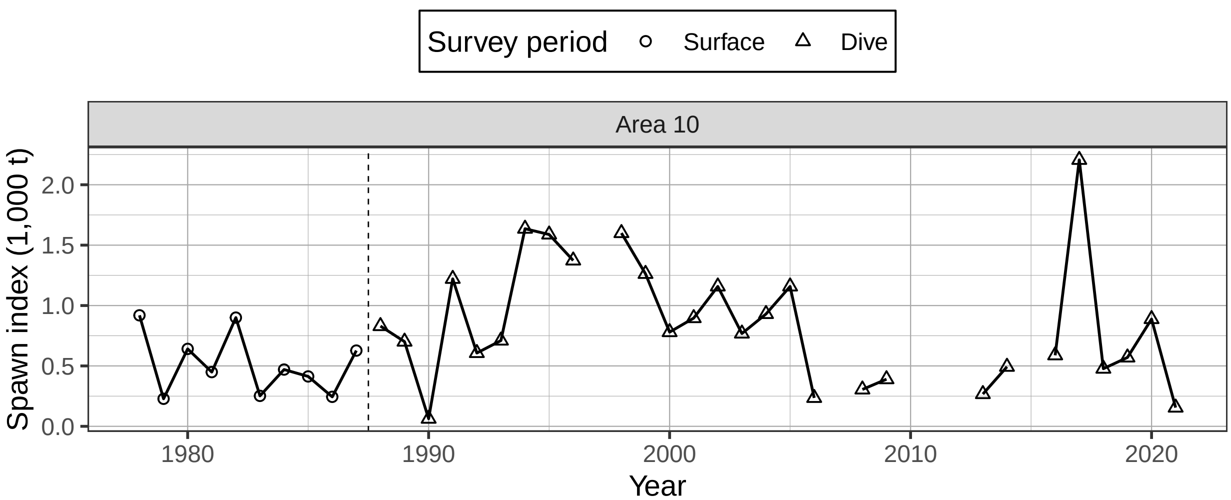

Figure 24. Spawn index in thousands of tonnes (t) for Pacific Herring from 1978 to 2021 in the special area, Area 10. See Figure 6 for description.

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