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STATUS OF PACIFIC HERRING (*CLUPEA PALLASII*) IN 2018 AND FORECAST FOR 2019

Context

Pacific Herring abundance is assessed using a statistical catch-age (SCA) model. The 2017 assessment included updates to the model (Integrated Statistical Catch-Age Model; Martell et al., 2012), and a bridging analysis to support these changes (Cleary et al., 2018). Also new to the 2017 assessment was the estimation of stock productivity and current stock status relative to the new limit reference point (LRP) of $0.3SB_0$ (Kronlund et al., 2017). The structure of the 2017 model was not changed for the 2018 stock assessment.

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 conducting a Management Strategy Evaluation (MSE) process to evaluate the performance of candidate management procedures against a range of hypotheses about uncertain stock and fishery dynamics. As part of the MSE process, a CSAS regional peer review occurred July 25 and 26, 2018, where performance of Pacific Herring management procedures were assessed against conservation objectives for Strait of Georgia and West Coast of Vancouver Island stock assessment regions (DFO, 2018).

Estimated stock trajectories, current status of stocks for 2018, and harvest advice recommendations for 2019 reflect methods of Cleary et al. (2018) and, where applicable, recommendations from the aforementioned July 2018 regional peer review. These recommendations are described in the section “Harvest recommendations for 2019”.

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 2018 and recommend harvest advice for 2019 to inform the development of the 2018/2019 Integrated Fisheries Management Plan.

This Science Response Report results from the Science Response Process of September 2019 on the Status of Pacific Herring (*Clupea pallasii*) in 2018 and forecast for 2019.

Background

Pacific Herring in BC are managed as five major and two minor stock assessment regions (SARs; Figure 1). The major SARs are Haida Gwaii (HG), Prince Rupert District (PRD), Central Coast (CC), Strait of Georgia (SoG), and West Coast of Vancouver Island (WCVI). The minor SARs are Area 27 (A27) and Area 2 West (A2W). We conduct formal analyses of stock trend information for the Pacific Herring major SARs. For the minor SARs, we present catch data, biological data, and spawn survey data (Appendix).

Description of the fishery

At present, Pacific Herring fisheries in BC consist of commercial fishing opportunities for food and bait (FB), spawn-on-kelp (SOK) products, and roe herring. There are also opportunities for First Nations food, social, and ceremonial (FSC) fisheries, as well as recreational fishing.

In 2017/2018, the primary Pacific Herring fisheries were seine roe and gillnet roe fisheries, with a combined coast wide catch in 2017/2018 of 13,577 tonnes (t), and the FB seine fishery with a coast wide catch of 5,907 t. The roe fishery was operational in SoG and PRD. The spawn-on-kelp (SOK) fishery was operational in PRD and CC, and special use (SU) minor fishery was operational in SoG only.

A complete dockside monitoring program exists for all Pacific Herring commercial fisheries and the resulting validated catch data are included in the annual stock assessment process for all fisheries, except SOK. The SOK fishery is licenced based on validated pounds of SOK product (eggs on kelp) however these landings are not easily combined with catches of whole herring and are not currently incorporated in the stock assessment process.

The exclusion of SOK fishery data from the annual stock assessment process was identified as a key uncertainty in the most recent CSAS review of the stock assessment framework (Cleary et al., 2018). Recommendations for addressing this uncertainty will require quantifying ponding mortality and removals (eggs) associated with the SOK fishery. Consideration of these uncertainties will occur at a future stage in the MSE process.

First Nations fish for whole herring, herring roe, and herring eggs for FSC purposes. Whole herring are fished by seine, gillnet, rake, dip net, and jig. Herring eggs are collected as spawn on seaweed such as kelp, or spawn on set tree boughs. Opportunities are provided in a manner that allows for harvest activity in all assessment areas. In addition, Treaty and aboriginal commercial fisheries may occur in some specific management areas.

Description of the stock assessment process

The SCA model is fitted to commercial catch data, fishery and survey proportions-at-age data and a fishery-independent spawning biomass index to estimate total and spawning biomass, natural mortality, and recruitment. Observed annual weight-at-age is estimated external to the model, and maturity-at-age is a fixed input parameter. In 2017, an updated version of the SCA model was applied to assess each of the five major Pacific Herring stocks (Cleary et al., 2018). The main change from the SCA model used from 2011 to 2016 was the partitioning of variance between observation and process error to improve the estimation of the variance structure (Cleary et al., 2018). A bridging analysis was used to validate the updated model: this showed parameter estimates and biomass trajectories associated with the structural adjustments to be nearly identical to results from previous versions of the model, supporting the adoption of the revised structure (Cleary et al., 2018). Other adjustments were made to improve computational efficiency and update input data.

A Bayesian framework was used to estimate time series of spawning biomass, instantaneous natural mortality, and age-2 recruitment from 1951 to 2018. Advice to managers for the major stock areas includes posterior estimates of current stock status (SB_{2018}), spawning biomass in 2019 assuming no catch (SB_{2019}), and stock status relative to the LRP of $0.3SB_0$. The Markov chain Monte Carlo (MCMC) sampling procedure follows the same method implemented by Cleary et al. (2018).

Cleary et al. (2018) reported results from two SCA model fits that differed in assumptions about dive survey (from 1988 to 2018) catchability (i.e., AM1 where q_2 is estimated with a prior distribution assumed, and 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 HG, CC, SoG, and WCVI SARs and the estimated value reflects the prior mean (Cleary et al., 2018, Appendix D). Assuming $q_2 = 1$ at least produces a "minimum" biomass estimate so that any other assessment errors and management implementation errors are buffered (see Martell et al., 2012 and DFO, 2012). Application of the AM1 model 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, 2018). Simulations to quantify the risks associated with continued application of a management procedure where $q_2 = 1$ were conducted because fisheries management quota decisions since 2015 have been based on the AM2 model. Scaling the assessment with values of $q_2 < 1$ is likely to result in larger absolute assessment errors than those estimated when $q_2 = 1$. For these reasons, advice presented here is based on the AM2 stock assessment model parameterization, supported also by comparisons presented in DFO (2016, Table A1) and Cleary et al. (2018, Appendix D).

Analysis and response

Input data

Input data to the stock assessment are summarized in Table 1. Relative to last year's assessment, the only change made to input data was updating the time series to include data from the 2017/2018 herring season (July 1 to June 30).

Catch data

For the purposes of stock assessment, catch data are summarized by gear type and fishing category as described in Table 1 and presented in Figure 2.

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

Combined commercial removals from 2010 to 2018 from the roe, food and bait, and special use fisheries are presented for the major stocks in Table 2. The proportion of coast-wide catch that comes from the SoG was 22% in 1990, and has increased to greater than 95% in 2018. Total SOK harvest is presented for the major SARs in Table 3.

Biological data

Biological samples are collected as described in Cleary et al. (2018) and Table 1. The biological data inputs to the stock assessment are annual weight-at-age (Figure 3) and annual numbers-at-age, shown as proportions-at-age (Figure 4).

Significant declines in weight-at-age are evident for all major herring stocks, from the mid-1980s to 2010. Declining weight-at-age may be attributed to any number of factors, including fishing effects (i.e., gear selectivity) and environmental effects (e.g., changes in ocean productivity), or it may be attributed to changes in sampling protocols (e.g., shorter time frame over which samples are collected). An increasing trend in weight-at-age is now apparent for all major stocks from 2012 to 2018, although to a lesser degree for PRD.

Abundance data

The surface (1951 to 1987) and dive (1988 to 2018) spawn survey methods involve collecting information on spawn length (parallel to shore), spawn width (perpendicular to shore), and number of egg layers by vegetation type. These data are used to calculate egg densities per spawn. Ultimately, the estimated weight of mature spawners required to produce the egg deposition is calculated and referred to as the spawn index. Execution of the 2018 spawn survey followed all standard protocols as described in Cleary et al. (2018). Time series of spawn index by major stock area, from 1951 to 2018 are summarized in Figure 5. In 2018, there was an increase in survey biomass in WCVI and SoG (Figure 5 and Tables 8 and 7) and a decrease in survey biomass in PRD and CC (Figure 5 and Tables 5 and 6). HG survey biomass has remained at historical low levels since 2016.

Spatial spawn distribution

Tables 4 to 8 summarize the spatial distribution of survey spawn biomass (i.e., the spawn index) and proportions over years for the major SARs. We summarise HG, PRD, CC, and WCVI by Statistical Area, and SoG by Group, where 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. Sections and Groups are not intended to represent sub-stock structure or ‘known’ stocklets.

Tables 4 to 8 also present annual proportions of survey spawn index expressed as biomass by Statistical Area or Group for the last five years, and average proportions by Statistical Area or Group for 1 to 5 years. To facilitate comparisons, these tables also include spawn index by year.

First Nations observations

First Nations observations are provided by First Nations representatives to describe their perspective in their respective local areas.

Haida Gwaii

The 2018 herring spawn survey on Haida Gwaii was conducted from April 7 to 21 within Area 2 East. Haida traditional harvest of spawn on kelp observed in the major stock area was low.

Prince Rupert District

This year in the Prince Rupert District, Lax Kw’alaams had several fishermen out on the water. One of the members was on the water for a full eight days. He and his crew observed lots of herring, at least 10,000 fish, swimming in the region for several days. After four to five days of observation, they disappeared. It should be noted that there were whales feeding on these fish over the observation period. It is possible that these fish felt there was too much predation and they moved to deeper water to spawn or they were eaten by the whales. Some spawning was observed, but it was not as much as expected based on the herring observed.

Lax Kw'alaams gill net fishermen reported that the use of nets with a smaller mesh size yielded better catches. The fish obtained were smaller than normal. Most of the gill net fishermen did not gather enough fish to satisfy FSC needs. For the SOK fishery in the Prince Rupert District, there was very little spawn obtained and with insufficient amounts needed to satisfy the FSC needs of the community. Many of the ponds that were established (four) were destroyed by sea lions preying on captive fish.

Lax Kw'alaams Fisheries Technicians spent four days during the harvest monitoring and recording herring. They found no schools of fish on any of the days they were out. Their correspondence with harvesters on the water confirmed the absence of herring.

Similar observations were reported by members of the Metlakatla First Nation. Metlakatla members were unsuccessful again in 2018 in achieving their Section 35(1) needs for herring spawn-on-kelp or -on-branches. The last catch reports were submitted from community members during the early 2000s, and this information is reflected in the catch reporting to the AFS Manager at that time. Although effort was made in 2018, with assistance from DFO staff, to obtain SOK from the fishery, it was not successful due to many circumstances, including very low herring biomass. Metlakatla technicians participated in field work with Lax Kw'alaams during one of their patrols, and the lack of fish, spawn, and wildlife indicated to our technician that the stocks are seriously depressed.

Central Coast

FSC fishermen and SOK fishermen from both the Heiltsuk and Kitasoo/Xai'xais Nations reported very challenging fishing seasons in 2018, resulting in less and overall lower-grade product than in previous years, due to a combination of low tonnage of spawners, high predator pressure, and unusual spawner behaviour.

Heiltsuk harvesters reported generally low spawner volume and a high incidence of spot spawning, exacerbated by seals and sea lions, which frequently disturbed spawning aggregations. The main spawn lasted only two days, which is shorter than usual. Although what appeared to be a strong spawning event occurred in Spiller Channel, spawning was too brief and/or deep to obtain any product. In general, harvesters found it more difficult than usual to predict the erratic spawner behaviour. Some harvesters would get only one or two layers on their kelp, not enough for merchantable product, while others reported that it took much longer than usual to cover the kelp with a sufficient number of layers (a week instead of a few days).

Kitasoo harvesters also observed that the tonnage of fish available had noticeably dropped from previous years. Sea lions continue to be a major problem for fishing, especially in the SOK fishery. Higgins Pass had very small tonnage in the area prior to spawning. Overall these observations signal a reduction in biomass in 2018. Spawn timing was similar to previous years, though it has been trending earlier over the past 8 to 10 years (18 days earlier than the 2010/2011 season). The fish held deeper than normal, and spawned very intensely over a shorter period than normal.

Strait of Georgia

Hul'q'umi'num Nations report that little to no spawn activity occurred south of Dodd Narrows in 2018. Additionally, there was limited predator activity observed, and a number of species/predators seemed to have moved from the area (predators were less numerous than previous years). FSC roe catch was gathered within the traditional fishing territory but outside of the immediate core territory. There was also an issue with cholera that required an extensive community outreach collaboration with the health department of Hul'q'umi'num, taking time that would have otherwise been spent continuing to look for spawn in the area.

West Coast of Vancouver Island

There were several observations from Nuu-chah-nulth harvesters and Fisheries Technicians regarding WCVI herring in 2018. Very early spawn was observed in Hesquiaht Harbour, and on the west side of Barkley Sound (January). A January spawn in Hesquiaht Harbour is a common event, but not in Barkley. There were small spawning events in February, primarily in Area 24. The main spawning events in Areas 23 to 25 were in mid to late March. Due to the distinct timing and relatively small spawn, the early Hesquiaht and Barkley spawns were not assessed by divers or included in the WCVI assessment. Marine vegetation from the early spawn collected by Hesquiaht residents corresponded to one to two layers of eggs.

For the main WCVI herring spawning, Nuu-chah-nulth harvesters set whole trees and lines of tree branches to harvest herring spawn-on-bough (SOB). Trees and boughs were set in both usual herring spawning locations and in active spawning locations in Barkley Sound (Area 23), Clayoquot Sound (Area 24), Nootka Sound, Esperanza Inlet, Nuchatlitz (Area 25), and Kyuquot Sound (Area 26, which is outside of DFO assessment area for WCVI herring). Herring SOB harvests were mixed. In both Areas 23 and 24 some harvesters succeeded with one or two trees acquiring four to six layers, whereas some trees had only one to two layers (a minimum of four to six layers of eggs are necessary to provide enough eggs to peel off branches for harvesting). Harvests in Areas 23 and 24 were well below community food needs. In Area 25 both SOB and SOK harvest occurred in the northern and southern areas. Although significantly less than observed in the mid to late 1990's, the SOK and SOB harvests in 2018 were the largest in over 10 years with many trees having over eight layers.

Stock status update

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

(a) Time series of maximum posterior density (MPD) estimates of the spawn survey data in thousands of tonnes (t $\times 10^3$). The spawn survey data (i.e., spawn index) is scaled to abundance via the spawn survey scaling parameter q. The spawn index has two distinct periods defined by the dominant survey method: surface surveys (1951 to 1987), and dive surveys (1988 to 2018). Two q parameters are implemented in the estimation procedure: q_1 with an uninformative prior and q_2 with an informative prior approximating 1.0.

(b) Time series of natural mortality (M) estimates;

(c) Time series reconstruction of number of age-2 recruits;

(d) Time series of total catch and estimated spawning biomass with reference line at model estimates of $0.3SB_0$;

(e) Time series of (log) deviations from the estimated Beverton-Holt recruitment function overlaid with a 3-year trailing moving average smoother; and

(f) Phase plot of spawning biomass production for the dive survey period (MPD estimates), with reference line at model estimates of $0.3SB_0$.

Reference points

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

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

Simulation results showed similar properties between USRs $0.6SB_0$ and SB_{ave} both within and among SARs, while the USR based on the average biomass in a productive period, $SB_{ave-prod}$, was found to be most variable among SARs. The simulation-evaluations did not select a single USR, however a USR of $0.6SB_0$ is included in this stock status update because this candidate is sufficiently above the LRP (2*LRP) and it is a repeatable calculation across all SARs. Stock status relative to the assessment model estimates $0.3SB_0$ (LRP) and $0.6SB_0$ (USR) are presented for each stock in Tables 9 to 13.

The LRP and the USR relate stock status to the DFO PA Framework (DFO, 2009) and in this assessment the same calculations are applied for each SAR. These reference points differ from operational control points (OCPs) which are the biomass levels where management action is taken (i.e., the inflection points of the harvest control rule; HCR). OCPs and HCRs differ among SARs, and are described below.

Haida Gwaii

Estimated spawning biomass declined to near historic lows in the mid-1990s and briefly increased through the late 1990s before falling to persistent historic lows from 2000 to 2010 (Figure 6d). A modest increase in estimated spawning biomass occurred during the early 2010s before falling once again to near historic lows over the most recent few years. The increase can be attributed to increases in the survey biomass index in 2012 and 2014 (Figure 6a) that were supported by above average recruitment of age-2 fish in 2012 (Figure 6c, d). An increasing trend in the estimated natural mortality rate since 1980 (Figure 6b) largely absorbed surplus production attributable to above average recruitment events (e.g., 1997 and 2012; Figure 6c, d). In particular, estimated natural mortality has increased sharply since the early 2010s following a decline from a peak rate in the early 2000s. In most years since 2000, including the most recent year between 2017 and 2018 spawning periods, the HG stock has persistently existed in a low productivity, low biomass state which has precluded stock growth (Figure 6f). Although an increasing trend in weight-at-age has been observed since 2012 (Figure 3), this increase in biomass per individual has not been sufficient to offset the lack of increased numbers of herring, which implies there are larger but fewer herring individuals per tonne of spawners.

Estimated spawning biomass in 2018 is 4,032 t (SB_{2018}, median posterior value) or 17.6% of SB_0 (Table 9). The 2018 spawning biomass is estimated to be at a historic low level, exceeded only by more severe depletion levels following the stock collapse of the 1960s (Figure 6d). Since 2000, the effective harvest rate, U_{t}, has been at or near zero (Figure 11), with the last commercial roe fishery in 2002 and the last commercial SOK fishery in 2004. Spawning biomass in 2018 is estimated to be less than the LRP of $0.3SB_0$ with a 89.8% probability (Table 9).

Prince Rupert District

Estimated spawning biomass recovered by the mid-1980s from historic low depletion levels following the collapse of the 1960s, to about 50% of the historic high biomass estimated in the early 1960s (Figure 7d). However, after the mid-1980s estimated spawning biomass steadily declined before stabilizing at a relatively low level (but above historic lows) by the mid-2000s. The estimated stock biomass has shown little trend from 2005 to 2018. Fluctuations in the trend in spawning biomass appear to be less than those observed in other SARs, possibly because some spawn index points are being under- or over-fit (e.g., 2001–2004, 2010, 2013) as shown in Figure 7a. Estimated natural mortality reached historic highs in the late 1960s, before declining through the late 1970s. Beginning in about 1980, estimated natural mortality increased through to 2018, roughly doubling from 0.25 to 0.5 yr^{-1} (Figure 7b). This trend in natural mortality coincides with the decline in spawning biomass (Figure 7d); recruitment deviations have fluctuated around 0 without any strong positive or negative trending (Figure 7e). An above average age-2+ recruitment in 2014 and modest recruitment in 2016 were not sufficient to raise the stock from a low biomass state (Figure 7f). Despite relatively low and stable levels of catch it appears the estimated increase in natural mortality has absorbed the potential for positive higher surplus production. An increasing trend in weight-at-age has been observed since about 2010, although the change does not appear to be as large as in the CC, HG, SoG and WCVI SARs.

The model estimates spawning biomass in 2018, SB_{2018}, at 16,635 t (posterior median), equal to 27.3% of SB_0 (Table 10). Commercial fisheries have occurred annually in PRD since the mid-1980s during which the effective harvest rate, U_{t}, is estimated to be at or below 20% (Figure 11), with the exception of 1989. Spawning biomass in 2018 is estimated to be less than the LRP of $0.3SB_0$ with a 60.4% probability (Table 10).

Central Coast

Estimated spawning biomass fluctuated around a strongly declining trend from a historic high around 1980 before reaching a historic low level in the late 2000s (Figure 8d). An increase in spawning stock biomass was estimated through the mid-2010s but remained below levels estimated prior to 2000, and then declining modestly through to 2018. The estimated biomass trend largely reflects the trend in the spawn index (Figure 8a), where fluctuations correspond in opposite phase to the fluctuations in estimated natural mortality (Figure 8b). For example, the decline in spawn index (and estimated spawning biomass) to the historic lows of the late 2000s followed a strongly increasing trend in estimated natural mortality through the same period. Estimated natural mortality moderated by the late 2000s, which was followed by the increase in spawn index (and estimated spawning biomass) until 2015 whereupon natural mortality again increased. Recruitment deviations have been slightly negative (lower than predicted by the stock-recruit function) on average since about 1990 (Figure 8e). Production has tended to be near zero or negative over recent years, although the stock does not appear to have lapsed back to the low production, low biomass state observed during the late 2000s/early 2010s (Figure 8f). However there is no evidence of strong production as observed, for example, during the 1990 to 1999 period.

Since implementing the current HCR in 1986, the effective harvest rate, U_{t}, is estimated to fluctuate above and below the 20% target rate, with median estimates exceeding 20% frequently Figure 11). Occurrences of U_{t} exceeding the 20% target rate are due in part to positive assessment model errors.

Following a commercial fishery closure from 2007 to 2013, the CC stock reopened to commercial fisheries in 2014 and small commercial roe fisheries occurred in 2014, 2015, and 2016. A commercial SOK fishery has operated yearly since 2014, however these removals are not included in the estimation of U_{t}.

The model estimates spawning biomass in 2018, SB_{2018}, at 16,454 t (posterior median), equal to 30.9% of SB_0 (Table 11). Spawning biomass in 2018 is estimated to be less than the LRP of $0.3SB_0$ with a 46.6% probability (Table 11).

Strait of Georgia

The SCA model fit to the SoG stock and fishery monitoring data shows that spawning biomass is at a historic high although uncertainty associated with the terminal spawning biomass estimate is large, as is the uncertainty associated with the forecast of SB_{2019} (Figure 9d). The increasing trend in estimated spawning biomass since about 2010 coincides with a decline in estimated natural mortality that began in the late 2000s (Figure 9b). Estimated natural mortality has now reached a level last estimated in the late 1970s as the stock recovered from the collapse of the late 1960s. The large uncertainty in both spawning biomass and natural mortality estimates in 2018 may be in part a function of the decline in the spawn index from 2016 to 2018 following the increase of the preceding few years (Figure 9a). The model fits an averaged trajectory through the spawn index values of the 2010s and has, to date, insufficient information to determine whether the decline from 2016 to 2018 represents a decline in spawning biomass. It may require a few more spawn index observations to resolve whether a change in spawning biomass trajectory has recently occurred. The model estimates above average recruitment in most years from 2010 to 2018 (Figure 9c) with the recruitment deviations showing larger recruitment of age-2 fish than expected from the stock-recruitment function (Figure 9e). The SoG is estimated to be in a high production, high biomass state (Figure 9f).

Commercial fisheries have occurred annually in SoG since the early-1970s (following the stock collapse of the late 1960s). Since implementing the current HCR in 1986, the effective harvest rate, U_{t}, is estimated to fluctuate above and below the 20% target rate, with median estimates exceeding 20% in 2005, 2006, 2013–2015, and 2017 (Figure 11). The model estimates spawning biomass in 2018, SB_{2018}, at 113,425 t (posterior median), equal to 82.3% of SB_0 (Table 12). Spawning biomass in 2018 is estimated to be greater than the LRP of $0.3SB_0$ with a 99.6% probability.

West coast of Vancouver Island

The time series of estimated spawning biomass shows a decline from the late 1980s through to a historic low in the 2000s (Figure 10d). The low estimated spawning biomass persisted through the 2006 to 2013 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 the spawn index values (Figure 10a). The increase in spawning biomass from 2013 coincides with a decline in estimated natural mortality from a historic high in the late 2000s (Figure 10b). Recruitment deviations have been negative (lower than predicted by the stock-recruit function) on average since about 2003 (Figure 10e), however the reduction in estimated natural mortality and absence of removals from a commercial fishery appears to be sufficient to offset this below average recruitment of age-2 fish. The absence of a commercial fishery since 2005 means the realized harvest rate has been near zero for the last 13 years (Figure 11). Recent production estimates are at a higher spawning biomass level than those estimated during the low production, low biomass period of the last half of the 2000s and early 2010s (Figure 10f).

The model estimates spawning biomass in 2018, SB_{2018}, at 23,335 t (posterior median), equal to 48.7% of SB_0, (Table 13). Spawning biomass in 2018 is estimated to be greater than the LRP of $0.3SB_0$ with a 91.2% probability (Table 13).

Management performance: effective harvest rate

Management procedure performance can be investigated using time series of effective harvest rate. U_t represents the estimated effective harvest rate in each year t, calculated as $U_\text{t} = \frac{C_\text{t}}{SB_\text{t}+C_\text{t}}$ where C_t is catch in year t, and SB_t is the estimated spawning biomass in year t. Times series of U_t relative to target harvest rate of 20% are presented in Figure 11.

Harvest recommendations for 2019

Harvest advice for the major stocks of Pacific Herring has been based on a 1-year forecast of pre-fishery spawning biomass and application of a harvest control rule that is a hybrid of fixed escapement and a target harvest rate (e.g., Hall et al., 1988). Although the target harvest rate has varied among areas in recent years (e.g., CC and PRD SARs; DFO, 2017), the “historical” practice was to apply a target harvest rate of 0.2 when the forecast is estimated to be above a fixed commercial fishery cutoff of $0.25SB_0$ defined in the 1996 stock assessment (DFO, 2016).

Provision of harvest advice was changed to a decision table format in 2012, providing probabilistic advice to managers for consultation and decision-making. Decision tables report the probability of being above (or below) management parameters of interest for a range of catch levels using one-year-ahead projections. In Cleary et al. (2018) projected spawning biomass in 2018 relative to the LRP ($0.3SB_0$) was added to decision tables for the five major Pacific Herring stocks. The 2018 decision tables report the probability that spawning biomass in 2019 will be below the LRP (P($SB_{2019} < 0.3SB_0$)), the probability that spawning biomass in 2019 will be below the USR (P($SB_{2019} < 0.6SB_0$)), and the probabilities of the harvest rate in 2019 exceeding 20% or 10% (P($U_{2019} > 20\%$), and P($U_{2019} > 10\%$), respectively) for a range of commercial catch levels including 0 tonnes.

Renewal of the Pacific Herring management framework included a commitment to simulation-evaluation of the performance of the historical and alternative management procedures using management strategy evaluation (MSE), and the first cycle of the MSE process was completed for the WCVI and SoG SARs in July 2018 (DFO, 2018). These two areas were selected for evaluation because they exhibit contrasting stock and fishery states that encompass the range of stock conditions observed elsewhere in BC.

Several lessons were learned from the analysis:

1. The catch-at-age stock assessment model can produce large (positive) assessment errors. Such assessment errors cause over-estimation of spawning biomass and result in recommended catch limits such that the realized harvest rate exceeds the intended target specified by a harvest control rule (HCR; e.g., over-harvest).
2. Reduction in harvest rate from 20% to 10% was the most effective means of mitigating stock assessment errors by reducing the absolute size of the catch. The use of a catch cap, implemented as a maximum annual catch level, was an effective model-free way to further mitigate assessment errors. Simulation analyses additionally showed that outcomes are insensitive to the choice of operational control points (OCPs) in the HCR when a low harvest rate (HR) and catch cap are applied. This occurs because low biomass levels (associated with the lower OCP) are avoided for these management procedures (MPs).
3. Differences in specification of Pacific Herring MPs, including the HCR components, are expected a priori among SARs. The reasons relate to differences in objectives deemed important by resource users, differences in historical and current stock and fishery dynamics, and differences in the magnitude and direction of assessment model errors in each area. Conservation objectives such as those based on avoiding a threshold to serious harm (i.e., a limit reference point) in alignment with the DFO PA Framework (DFO, 2009) are held constant among SARs based on the analyses of Kronlund et al. (2017).

Harvest advice in 2019 for the SoG and WCVI SARs is guided by the results and lessons learned from the simulation-evaluation completed in the first MSE cycle (DFO, 2018). In the absence of area-specific simulation-evaluation analyses for the CC, HG and PRD SARs, harvest advice for these areas is provided in the form of decision tables following Cleary et al. (2018). Details of harvest advice are provided below for each of the major SARs.

Haida Gwaii

The HG stock has persisted in a low biomass, low productivity state in since 2000, remaining below the LRP for much of that period and shows little evidence of sustained stock growth despite the absence of commercial fisheries since 2002 (2004 for the SOK fishery). In the absence of fishing, spawning biomass in 2019 is forecast at 4,966 t. The projected spawning biomass in 2019 is forecast to be below $0.3SB_0$ with 72.7% probability in the absence of fishing (Table 9 and Figure 12).

DFO has committed to developing and implementing a rebuilding plan for Haida Gwaii Pacific Herring by the end of fiscal year 2020/21.[1] Guidance for the Development of Rebuilding Plans under the Precautionary Approach Framework: Growing Stocks out of the Critical Zone (DFO, 2013) states the primary objective of any rebuilding plan is to promote stock growth out of the

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

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.

As such, the harvest recommendation for the HG stock in 2019 is 0 t.

Prince Rupert District

Harvest options for 2019 are presented as probabilistic decision tables and include total allowable catch (TAC) options relative to 10% and 20% target harvest rates, as well as projected spawning biomass relative to the assessment model estimate of the LRP (for each TAC level) (Table 14). Effective harvest rates for the past 10-years average ~12% (Figure 11), during which the stock showed no sign of growth, and is estimated to fluctuate at or near $0.3SB_0$ (Figure 7d). Furthermore, adjacent SARs (HG and CC) show evidence of recent prolonged periods of low biomass and low productivity: states that were entered rapidly and were preceded by high biomass levels (Kronlund et al., 2017).

In the absence of fishing, spawning biomass in 2019 is forecast to increase from 16,635 t in 2018 to an estimated 19,347 t (posterior medians). The forecast spawning biomass in 2019 is estimated to be below the LRP of $0.3SB_0$ with 43.3% probability in the absence of fishing (Table 10).

For PRD, the 2019 decision table includes the following columns, with TAC ranging from 0 to 3,000 t (Table 14):

1. 2019 TAC (t),
2. P($SB_{2019} < 0.3SB_0$),
3. Med($SB_{2019}/0.3SB_0$),
4. P($SB_{2019} < 0.6SB_0$),
5. P($U_{2019} > 20\%$),
6. P($U_{2019} > 10\%$), and
7. Med(U_{2019}).

The following modification from Cleary et al. (2018) is made:

1. Removal of SB_{2019} relative to fixed 1996 cutoffs.

The fixed cutoff values are removed from the 2018 decision table because they were calculated outside of the current assessment model, last updated in 1996, and therefore ignore 22 years of stock and fishery monitoring data, as well as substantial changes to the structural form of the assessment model.

Central Coast

Due to the absence of CC-specific simulation testing of HCRs, options for CC SAR follow the same steps as PRD. Harvest recommendations for CC stock are presented as a probabilistic decision table (Table 15) following the description and caveats presented above for PRD. The decision table for CC includes a catch stream from 0 t to 3,000 t, showing the probability of SB_{2019} falling below the LRP to increase with increasing catches.

In the absence of fishing, spawning biomass in 2019 is forecast at 18,267 t (posterior median), increasing from 16,454 t in 2018 (Table 11). The 2019 spawning biomass is forecast to be below the LRP of $0.3SB_0$ with 37.1% probability in the absence of fishing.

Strait of Georgia

Closed-loop feedback simulations for the SoG evaluated alternative MPs that differed only in the configuration of the HCR and application of a fixed catch cap (DFO, 2018). Results showed that all tested MPs could maintain the spawning biomass above the LRP with 91% probability or higher, including the historical HCR which applied a constant escapement of 21,200 t based on the 1996 stock assessment and 20% harvest rate. A 30,000 t catch cap was evaluated for the SoG; this cap was not often triggered, and thus did not limit the commercial fishery very often in simulations. Management procedures that included a 30,000 t catch cap were able to maintain spawning biomass above a biomass level of $0.6SB_0$ with 60% probability or higher. The purpose of the catch cap is to provide a model-free means of mitigating the effects of large positive assessment errors that lead to a higher realized harvest rate than intended (i.e., harvest rates that exceed 20%). Simulations showed that such assessment errors can occur when fitting the SCA model to SoG stock assessment data. Meeting the conservation objective of maintaining a high probability of exceeding the LRP does not mean the SoG is immune to stock decline. Future simulation-evaluation may suggest adjustment of the catch cap is necessary to acceptably meet additional stock and fishery objectives.

Management procedures evaluated included segmented HCRs of the form indicated in the DFO PA Framework with a lower operational control point (OCP) at the assessment model estimate of $0.3SB_0$ and an upper control point at the assessment model estimate of $0.6SB_0$. Discontinuing the use of fixed cutoffs and adopting a HCR with two OCPs is recommended for these reasons:

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

Harvest recommendations for SoG stock are provided by application of a management procedure that utilizes stock assessment estimates of forecast spawning biomass and operational control points at (0.3, 0.6) of SB_0 with a 20% target harvest rate, and a maximum catch cap of 30,000 t (DFO, 2018, Figure 4). The 2019 recommended catch calculated by applying the MP is 25,791 t.

West Coast of Vancouver Island

Closed-loop feedback simulations for WCVI evaluated alternative MPs that differed only in the configuration of the HCR and application of a fixed catch cap (DFO, 2018). Results showed that no tested management procedure could meet the conservation objective of maintaining spawning biomass above the LRP with high probability (at least 75%)[2] across the three future natural

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

mortality (M) scenarios. In addition, for the scenario where M is most similar to the last 10 years (density-independent-M), the historical HCR can only meet the conservation objective 56% of the time.

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

Using a HCR with OCPs at (0.5, 0.6) of SB_0, a 10% target harvest rate, and a maximum catch cap of 2,000 t, the 2019 catch calculation is 671 t.

Given the best performing MP for the WCVI did not meet the minimum “high” probability of 75%, further simulation-testing of HCRs that include additional measures to ensure persistent stock growth away from the critical zone and towards identified biomass targets may be required. For example, for a rebuilding stock a "slow-up" MP could be designed to delay fishery openings for an additional predefined number of years (e.g., 3 to 5) when the spawning biomass is estimated to be above the lower OCP in order to provide higher confidence of stock growth. The WCVI survey data and model estimates of spawning biomass (Figure 10a, d) show the increasing trajectory for WCVI herring as both gradual and erratic. The 2018 assessment estimates WCVI spawning biomass to be above the LRP from 2015 to 2018 (based on posterior medians), however this perspective based on stock assessment model estimates does not take into consideration positive assessment model errors. Thus simulation-evaluation of a "slow-up" MP is needed to identify the number of closure years needed to support continual stock growth.

MPs designed to delay reopening of commercial fisheries following prolonged low biomass states will allow evidence of persistent stock growth to accrue, reducing the potential for assessment errors or underlying population dynamics (i.e., increasing natural mortality) to cause the spawning biomass to lapse back to a low production, low biomass state.

Such MPs could also be evaluated for the HG stock during development of the rebuilding plan.

Conclusions

The 2018 Science Response includes a formal analyses of stock trend information for the Pacific Herring major SARs using the stock assessment framework reviewed in 2017 (Cleary et al., 2018). Harvest recommendations for 2019 for PRD and CC include updated probabilistic decision tables relating forecast spawning biomass to the LRP of $0.3SB_0$, and a candidate USR of $0.6SB_0$. Harvest recommendations for SoG and WCVI adopt recommendations from simulation analyses conducted as part of the Management Strategy Evaluation (DFO, 2018). DFO has committed to developing and implementing a rebuilding plan for Pacific Herring in HG by the end of fiscal year 2020/21, thus a commercial closure is recommended for this SAR.

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

Tables

Table 1. Input data for the 2018 Pacific Herring stock assessment. The spawn index has two distinct periods defined by the dominant survey method: surface surveys (1951 to 1987), and dive surveys (1988 to 2018). The 'spawn index' represents the raw survey data only, and is not scaled by the spawn survey scaling parameter, q.

Source	Data	Years
Roe gillnet fishery	Catch	1972 to 2018
Roe seine fishery	Catch	1972 to 2018
Other fisheries	Catch	1951 to 2018
Test fishery (seine)	Biological: number-at-age	1975 to 2018
Test fishery (seine)	Biological: weight-at-age	1975 to 2018
Roe seine fishery	Biological: number-at-age	1972 to 2018
Roe seine fishery	Biological: weight-at-age	1972 to 2018
Roe gillnet fishery	Biological: number-at-age	1972 to 2018
Other fisheries	Biological: number-at-age	1951 to 2018
Other fisheries	Biological: weight-at-age	1951 to 2018
Surface survey	Abundance: spawn index	1951 to 1987
Dive survey	Abundance: spawn index	1988 to 2018

Table 2. Total landed catch in tonnes of Pacific Herring in the major stock assessment areas. 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.

Year	HG	PRD	CC	SoG	WCVI
2009	0	1,999	0	10,169	0
2010	0	1,485	0	8,323	0
2011	0	2,147	0	5,128	0
2012	0	1,383	0	11,339	0
2013	0	2,027	0	16,547	0
2014	0	2,003	687	20,310	0
2015	0	2,163	626	19,968	0
2016	0	2,425	213	21,310	0
2017	0	2,849	0	25,279	0
2018	0	417	0	19,067	0

Table 3. Total spawn-on-kelp harvest in pounds of Pacific Herring in the major stock assessment areas. 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.

Year	HG	PRD	CC	SoG	WCVI
2009	0	158,198	0	0	0
2010	0	108,834	0	0	0
2011	0	123,626	0	0	0
2012	0	87,494	0	0	0
2013	0	72,895	0	0	0
2014	0	113,269	239,861	0	0
2015	0	84,066	169,470	0	0
2016	0	WP	351,952	0	0
2017	0	82,597	392,746	0	0
2018	0	20,832	286,108	0	0

Table 4. Spawn index in tonnes (t), and proportion of the spawn index by Section within Statistical Area 02 for Pacific Herring in the Haida Gwaii major stock assessment region. The spawn index is the annual total for the earliest year indicated in the 'Year(s)' column. Proportions indicate the proportion by year, or mean proportion over years, where year(s) are specified in the 'Year(s)' column. The 'spawn index' represents the raw survey data only, and is not scaled by the spawn survey scaling parameter, q.

Year(s)	Spawn index (t)	006	021&025	023	024
2018	4,588	0.000	0.766	0.000	0.234
2017	3,016	0.000	0.982	0.000	0.018
2016	6,888	0.000	0.947	0.000	0.053
2015	13,102	0.000	0.940	0.000	0.060
2014	10,566	0.000	0.932	0.000	0.068
2013 to 2018	16,025	0.013	0.905	0.001	0.080
2012 to 2018	9,720	0.014	0.893	0.001	0.091
2011 to 2018	7,554	0.016	0.875	0.001	0.108
2010 to 2018	6,845	0.016	0.851	0.001	0.132
2009 to 2018	9,794	0.015	0.855	0.001	0.130

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

Year(s)	Spawn index (t)	03	04	05
2018	14,155	0.057	0.667	0.277
2017	19,235	0.052	0.632	0.317
2016	18,985	0.007	0.808	0.185
2015	17,407	0.056	0.756	0.188
2014	17,125	0.148	0.595	0.257
2013 to 2018	25,755	0.058	0.701	0.241
2012 to 2018	22,716	0.055	0.712	0.234
2011 to 2018	21,097	0.051	0.717	0.232
2010 to 2018	28,607	0.049	0.720	0.231
2009 to 2018	11,961	0.045	0.740	0.215

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

Year(s)	Spawn index (t)	06	07	08
2018	12,264	0.322	0.626	0.052
2017	23,517	0.359	0.584	0.057
2016	32,508	0.245	0.726	0.028
2015	32,146	0.223	0.706	0.072
2014	13,309	0.287	0.673	0.040
2013 to 2018	20,369	0.276	0.682	0.042
2012 to 2018	7,592	0.267	0.667	0.066
2011 to 2018	10,534	0.264	0.664	0.072
2010 to 2018	8,671	0.268	0.657	0.074
2009 to 2018	10,771	0.293	0.638	0.068

Table 7. Spawn index in tonnes (t), and proportion of the spawn index by Group for Pacific Herring in the Strait of Georgia major stock assessment region. Legend: '14&17' is Statistical Areas 14 and 17 (excluding Section 173); 'ESoG' is eastern Strait of Georgia; 'Lazo' is above Cape Lazo; and 'SDodd' is South of Dodd Narrows. See Table 4 for description.

Year(s)	Spawn index (t)	14&17	ESoG	Lazo	SDodd
2018	91,939	0.984	0.001	0.014	0.000
2017	81,064	0.806	0.000	0.194	0.000
2016	129,502	0.902	0.000	0.090	0.009
2015	104,481	0.525	0.014	0.354	0.106
2014	120,468	0.758	0.020	0.212	0.010
2013 to 2018	83,693	0.817	0.006	0.153	0.023
2012 to 2018	52,636	0.823	0.006	0.143	0.028
2011 to 2018	85,001	0.843	0.006	0.126	0.026
2010 to 2018	50,454	0.848	0.005	0.112	0.036
2009 to 2018	53,652	0.855	0.004	0.101	0.040

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

Year(s)	Spawn index (t)	23	24	25
2018	28,107	0.331	0.194	0.475
2017	15,734	0.335	0.097	0.568
2016	20,528	0.577	0.266	0.157
2015	11,323	0.372	0.185	0.442
2014	13,937	0.631	0.093	0.276
2013 to 2018	12,258	0.431	0.150	0.420
2012 to 2018	5,407	0.379	0.181	0.440
2011 to 2018	9,663	0.365	0.195	0.440
2010 to 2018	2,464	0.374	0.183	0.443
2009 to 2018	10,607	0.391	0.177	0.432

Table 9. Posterior (5th percentile, Median, and 95th percentile) estimates of proposed reference points for the Haida Gwaii model. SB_{2019} represents prefishery spawning biomass, and all biomass numbers are in thousands of tonnes. Probability of $SB_{2019} < 0.3SB_0$ is based on zero catch.

Reference point	5%	50%	95%
SB_0	17.997	22.594	29.521
$0.3SB_0$	5.399	6.778	8.856
SB_{2018}	2.043	4.032	7.877
SB_{2018}/SB_0	0.088	0.176	0.347
$SB_{2018}/0.3SB_0$	0.294	0.588	1.156
$P(SB_{2018} < 0.3SB_0)$	0.898	0.898	0.898
SB_{2019}	2.098	4.966	12.195
SB_{2019}/SB_0	0.091	0.217	0.540
$SB_{2019}/0.3SB_0$	0.304	0.723	1.800
$P(SB_{2019} < 0.3SB_0)$	0.727	0.727	0.727
$P(SB_{2019} < 0.6SB_0)$	0.968	0.968	0.968
Proportion aged 3	0.09	0.33	0.70
Proportion aged 4-10	0.16	0.40	0.70

Table 10. Posterior (5th percentile, Median, and 95th percentile) estimates of proposed reference points for the Prince Rupert District model. See Table 9 for description.

Reference point	5%	50%	95%
SB_0	45.419	59.132	89.719
$0.3SB_0$	13.626	17.740	26.916
SB_{2018}	9.333	16.635	28.000
SB_{2018}/SB_0	0.144	0.273	0.478
$SB_{2018}/0.3SB_0$	0.480	0.910	1.594
$P(SB_{2018} < 0.3SB_0)$	0.604	0.604	0.604
SB_{2019}	10.038	19.347	37.116
SB_{2019}/SB_0	0.158	0.320	0.622
$SB_{2019}/0.3SB_0$	0.528	1.067	2.072
$P(SB_{2019} < 0.3SB_0)$	0.433	0.433	0.433
$P(SB_{2019} < 0.6SB_0)$	0.940	0.940	0.940
Proportion aged 3	0.07	0.24	0.55
Proportion aged 4-10	0.39	0.67	0.86

Table 11. Posterior (5th percentile, Median, and 95th percentile) estimates of proposed reference points for the Central Coast model. See Table 9 for description.

Reference point	5%	50%	95%
SB_0	42.279	52.880	68.518
$0.3SB_0$	12.684	15.864	20.555
SB_{2018}	9.204	16.454	28.193
SB_{2018}/SB_0	0.169	0.309	0.529
$SB_{2018}/0.3SB_0$	0.564	1.030	1.764
$P(SB_{2018} < 0.3SB_0)$	0.466	0.466	0.466
SB_{2019}	8.979	18.267	38.532
SB_{2019}/SB_0	0.169	0.344	0.707
$SB_{2019}/0.3SB_0$	0.565	1.147	2.356
$P(SB_{2019} < 0.3SB_0)$	0.371	0.371	0.371
$P(SB_{2019} < 0.6SB_0)$	0.898	0.898	0.898
Proportion aged 3	0.10	0.30	0.63
Proportion aged 4-10	0.28	0.56	0.79

Table 12. Posterior (5th percentile, Median, and 95th percentile) estimates of proposed reference points for the Strait of Georgia model. See Table 9 for description.

Reference point	5%	50%	95%
SB_0	110.671	136.279	183.399
$0.3SB_0$	33.201	40.884	55.020
SB_{2018}	67.802	113.425	184.015
SB_{2018}/SB_0	0.472	0.823	1.387
$SB_{2018}/0.3SB_0$	1.575	2.744	4.623
$P(SB_{2018} < 0.3SB_0)$	0.002	0.002	0.002
SB_{2019}	67.071	122.921	221.362
SB_{2019}/SB_0	0.479	0.882	1.640
$SB_{2019}/0.3SB_0$	1.597	2.939	5.466
$P(SB_{2019} < 0.3SB_0)$	0.004	0.004	0.004
$P(SB_{2019} < 0.6SB_0)$	0.148	0.148	0.148
Proportion aged 3	0.09	0.25	0.52
Proportion aged 4-10	0.41	0.66	0.84

Table 13. Posterior (5th percentile, Median, and 95th percentile) estimates of proposed reference points for the WCVI model. See Table 9 for description.

Reference point	5%	50%	95%
SB_0	38.204	47.633	61.412
$0.3SB_0$	11.461	14.290	18.424
SB_{2018}	12.970	23.335	39.330
SB_{2018}/SB_0	0.271	0.487	0.827
$SB_{2018}/0.3SB_0$	0.902	1.624	2.758
$P(SB_{2018} < 0.3SB_0)$	0.088	0.088	0.088
SB_{2019}	12.443	24.799	52.099
SB_{2019}/SB_0	0.262	0.519	1.073
$SB_{2019}/0.3SB_0$	0.875	1.731	3.578
$P(SB_{2019} < 0.3SB_0)$	0.096	0.096	0.096
$P(SB_{2019} < 0.6SB_0)$	0.640	0.640	0.640
Proportion aged 3	0.13	0.35	0.66
Proportion aged 4-10	0.24	0.48	0.72

Table 14. Probabilistic decision table for the Prince Rupert District, AM2 model.

2019 TAC (t)	$\mathbf{P(SB_{2019} < 0.3SB_0)}$	$\mathbf{Med(SB_{2019}/0.3SB_0)}$	$\mathbf{P(SB_{2019} < 0.6SB_0)}$	$\mathbf{P(U_{2019} > 20\%)}$	$\mathbf{P(U_{2019} > 10\%)}$	$\mathbf{Med(U_{2019})}$
0	0.433	1.067	0.940	0.000	0.000	0.000
500	0.455	1.045	0.943	0.000	0.001	0.026
1,000	0.480	1.024	0.946	0.001	0.042	0.051
1,500	0.498	1.003	0.949	0.008	0.233	0.076
2,000	0.522	0.981	0.953	0.037	0.509	0.101
2,500	0.542	0.961	0.956	0.101	0.728	0.125
3,000	0.562	0.941	0.958	0.211	0.862	0.149

Table 15. Probabilistic decision table for the Central Coast, AM2 model.

2019 TAC (t)	$\mathbf{P(SB_{2019} < 0.3SB_0)}$	$\mathbf{Med(SB_{2019}/0.3SB_0)}$	$\mathbf{P(SB_{2019} < 0.6SB_0)}$	$\mathbf{P(U_{2019} > 20\%)}$	$\mathbf{P(U_{2019} > 10\%)}$	$\mathbf{Med(U_{2019})}$
0	0.371	1.147	0.898	0.000	0.000	0.000
500	0.394	1.124	0.902	0.000	0.001	0.027
1,000	0.412	1.101	0.907	0.001	0.074	0.054
1,500	0.437	1.077	0.910	0.013	0.300	0.080
2,000	0.455	1.054	0.914	0.062	0.562	0.106
2,500	0.474	1.031	0.918	0.155	0.751	0.132
3,000	0.492	1.008	0.922	0.274	0.855	0.157

Figures

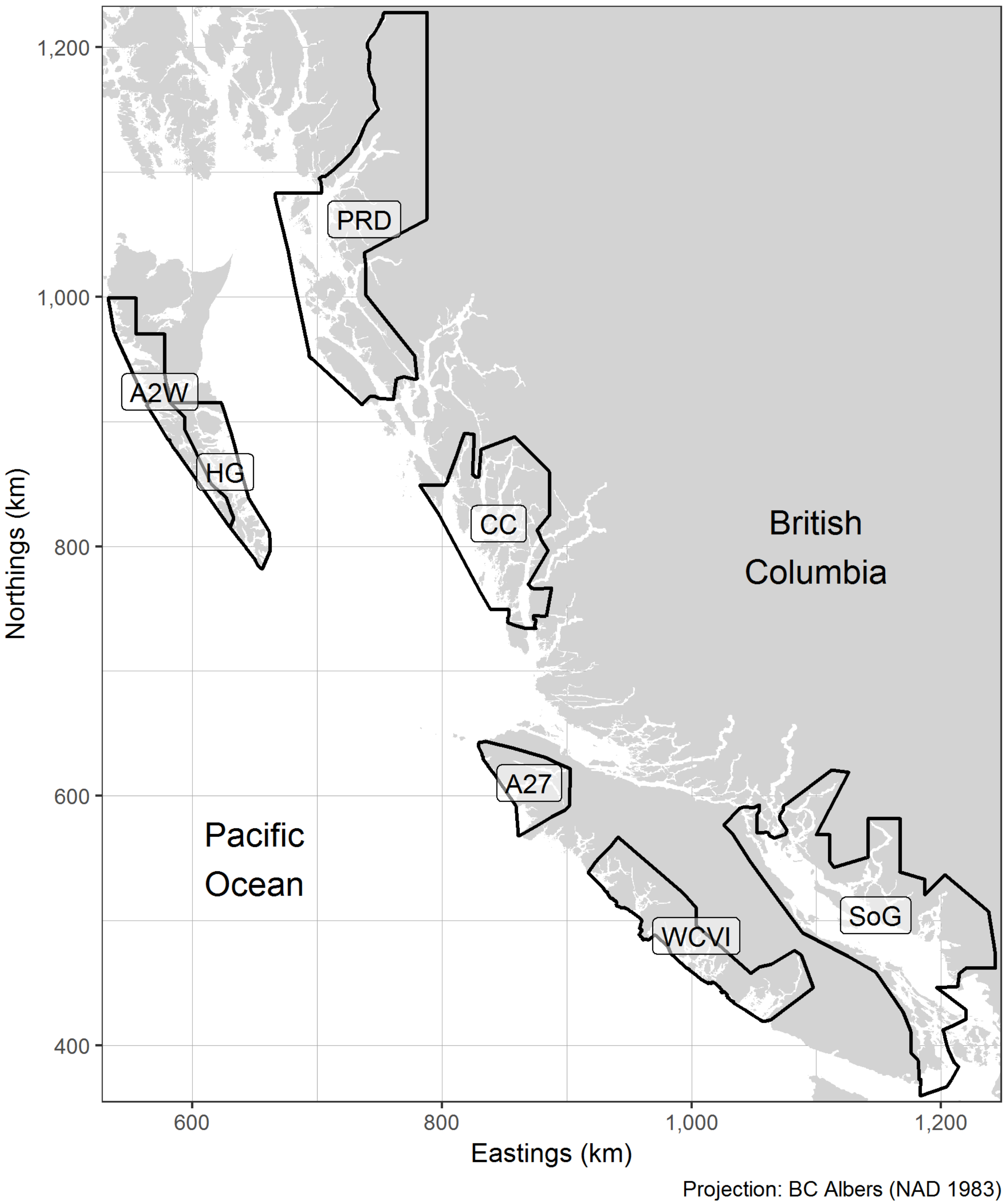

Figure 1. Boundaries for the Pacific Herring stock assessment regions (SARs) in BC. The major SARs are Haida Gwaii (HG), Prince Rupert District (PRD), Central Coast (CC), Strait of Georgia (SoG), and West Coast of Vancouver Island (WCVI). The minor SARs are Area 27 (A27) and Area 2 West (A2W). Units: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

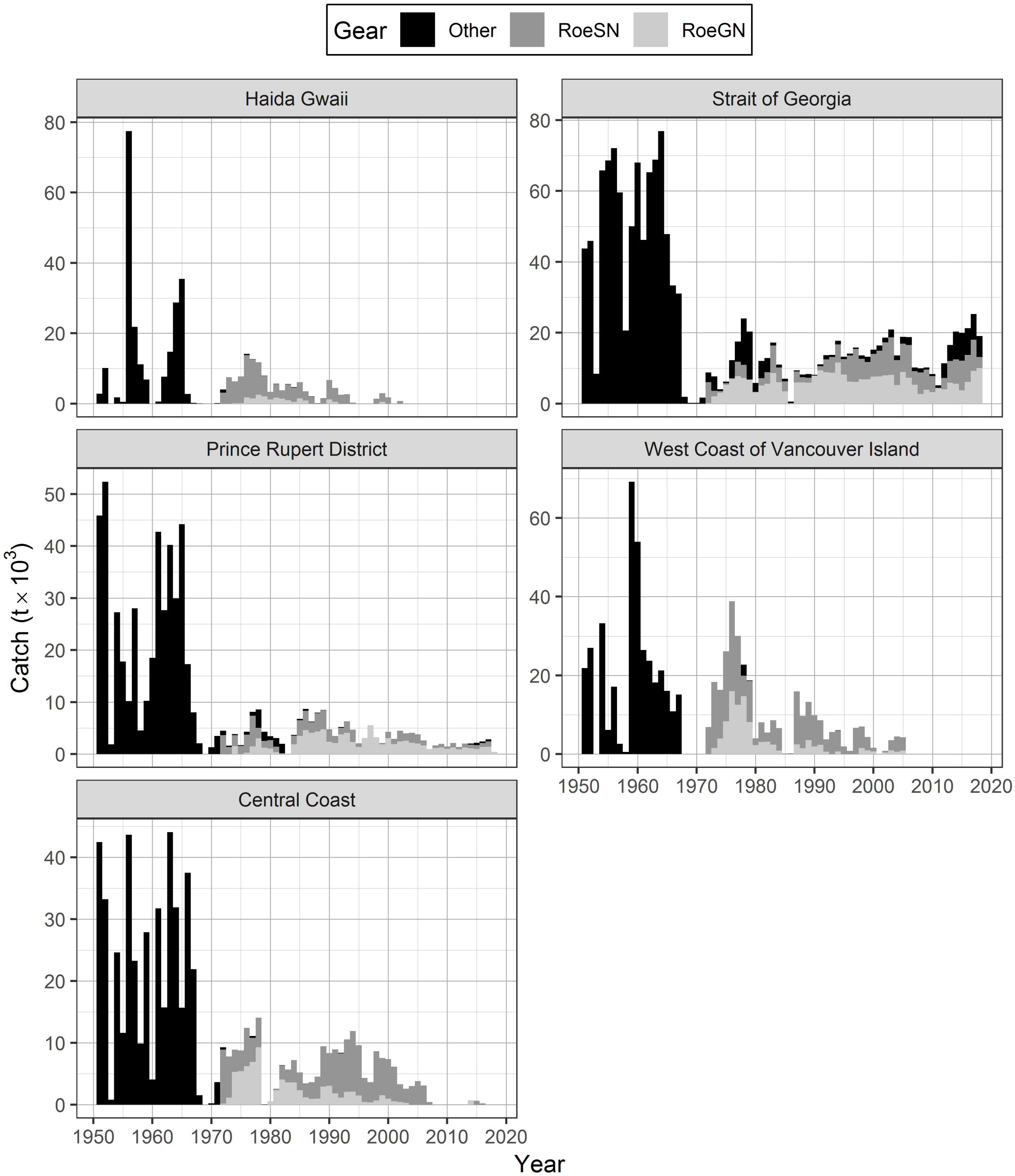

Figure 2. Time series of total landed catch in thousands of tonnes (t $\times 10^3$) of Pacific Herring from 1951 to 2018 in the major stock assessment regions. Legend: 'Other' represents the reduction, the food and bait, as well as the special use fishery; 'RoeGN' represents the roe gillnet fishery; and 'RoeSN' represents the roe seine fishery.

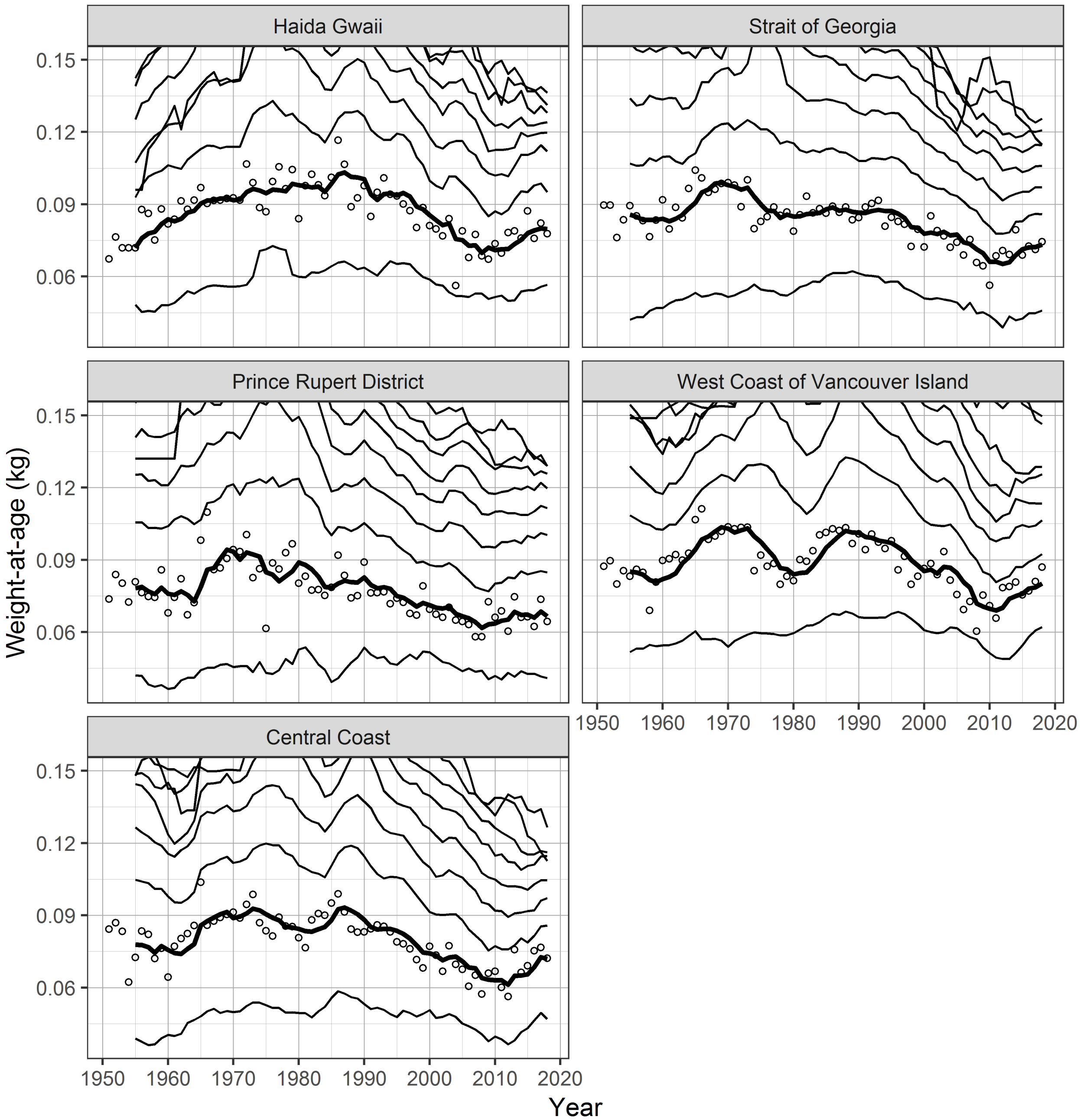

Figure 3. Time series of weight-at-age in kilograms (kg) for age-3 (circles) and 5-year running mean weight-at-age (lines) for Pacific Herring from 1951 to 2018 in the major stock assessment regions (SARs). Lines show 5-year running means for age-2 to age-10 herring (incrementing higher from the lowest line); the thick black line highlights age-3 herring. Missing weight-at-age values (i.e., years where there are no biological samples) are imputed using one of two methods: missing values at the beginning of the time series are imputed by extending the first non-missing value backwards; other missing values are imputed as the mean of the previous 5 years. Biological summaries only include samples collected using seine nets (commercial and test) due to size-selectivity of other gear types such as gillnet. The age-10 class is a 'plus group' which includes fish ages 10 and older. Note that vertical axes are cropped at 0.15 kg.

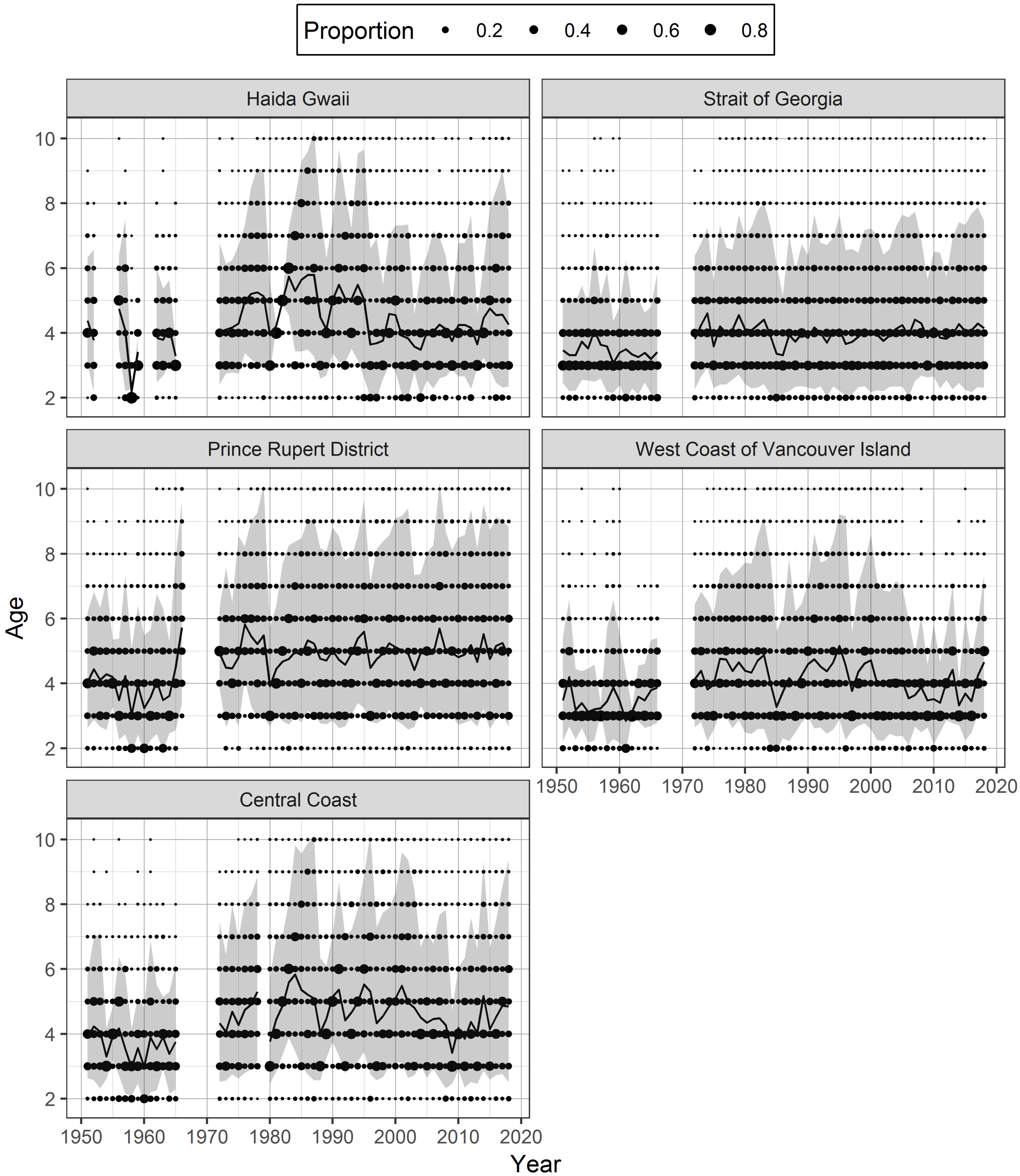

Figure 4. Time series of proportion-at-age for Pacific Herring from 1951 to 2018 in the major stock assessment regions (SARs). The black line is the mean age, and the shaded area is the approximate 90% distribution. Biological summaries only include samples collected using seine nets (commercial and test) due to size-selectivity of other gear types such as gillnet. The age-10 class is a 'plus group' which includes fish ages 10 and older.

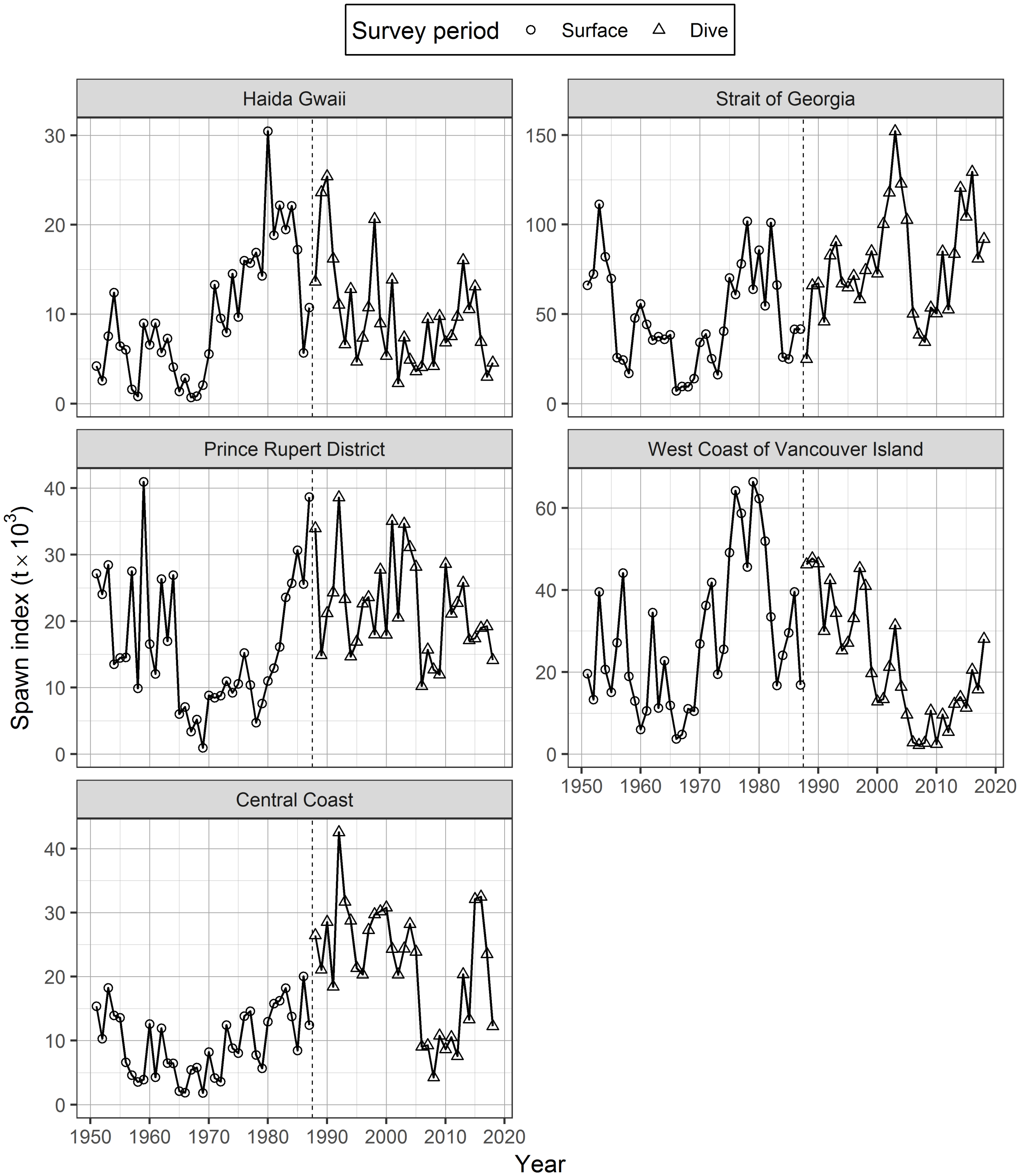

Figure 5. Time series of spawn index in thousands of tonnes ($t \times 10^3$) for Pacific Herring from 1951 to 2018 in the major stock assessment regions (SARs). The spawn index has two distinct periods defined by the dominant survey method: surface surveys (1951 to 1987), and dive surveys (1988 to 2018). The dashed vertical line is the boundary between these two periods. The 'spawn index' represents the raw survey data only, and is not scaled by the spawn survey scaling parameter, q.

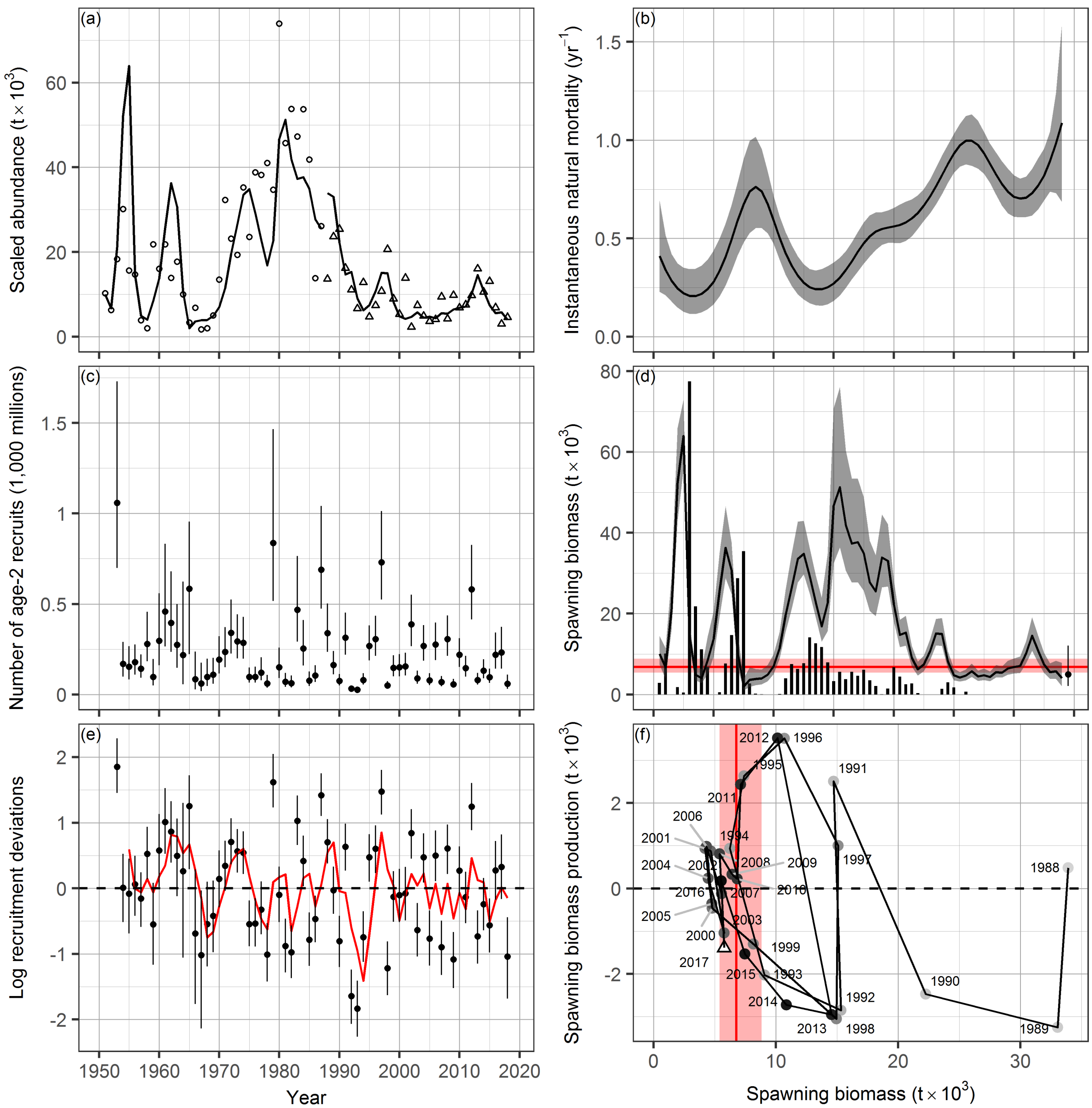

Figure 6. Model output for Pacific Herring in the Haida Gwaii major stock assessment region. Panel (a): model fit to scaled spawn survey data in thousands of tonnes (t $\times\ 10^3$). The spawn survey data (i.e., spawn index) is scaled to abundance via the spawn survey scaling parameter q. Panel (b): posterior estimates of instantaneous natural mortality rate (yr^{-1}). Panel (c): reconstructed number of age-2 recruits in thousands of millions. Panel (d): posterior estimate of spawning biomass (SB_t) for each year t in thousands of tonnes. Circle and vertical line indicate the median and 90% credible interval, respectively, of SB_{2019} (pre-fishery). Vertical bars indicate commercial catch, excluding spawn-on-kelp. Panels (b & d): lines and shaded areas indicate medians and 90% credible intervals, respectively. Panel (e): log recruitment deviations. The red line is the 3-year running mean of the median recruitment deviation. Panels (c & e): circles and vertical lines indicate medians and 90% credible intervals, respectively. Panel (f): phase plot of spawning biomass production for the dive survey period (1988 to 2018; maximum posterior density estimates). Grey shading becomes darker in chronological order; the triangle indicates 2017. Panels (d & f): red lines and shading indicate medians and 90% confidence intervals, respectively, for the limit reference point, $0.3SB_0$.

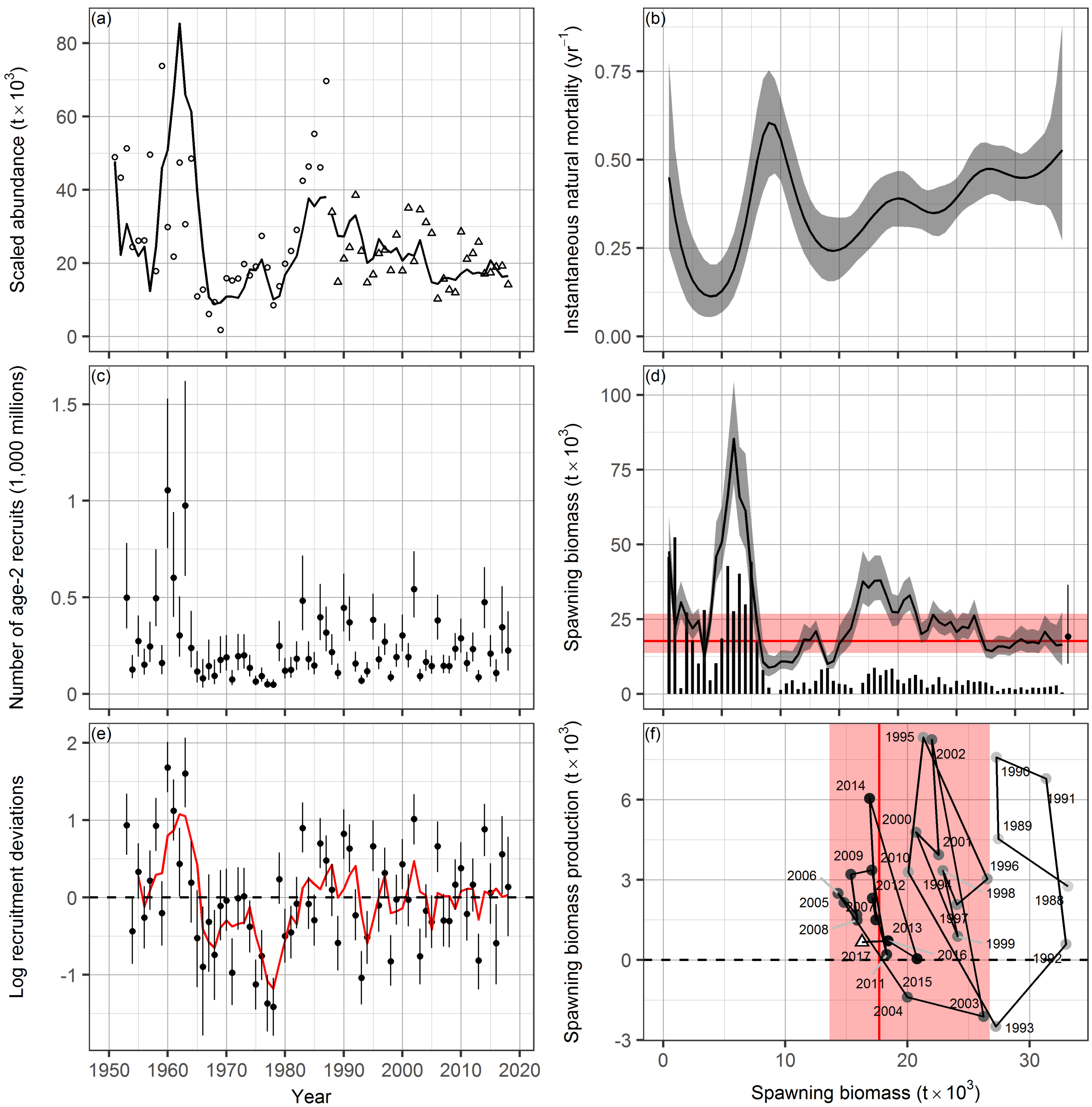

Figure 7. Model output for Pacific Herring in the Prince Rupert District major stock assessment region. See Figure 6 for description.

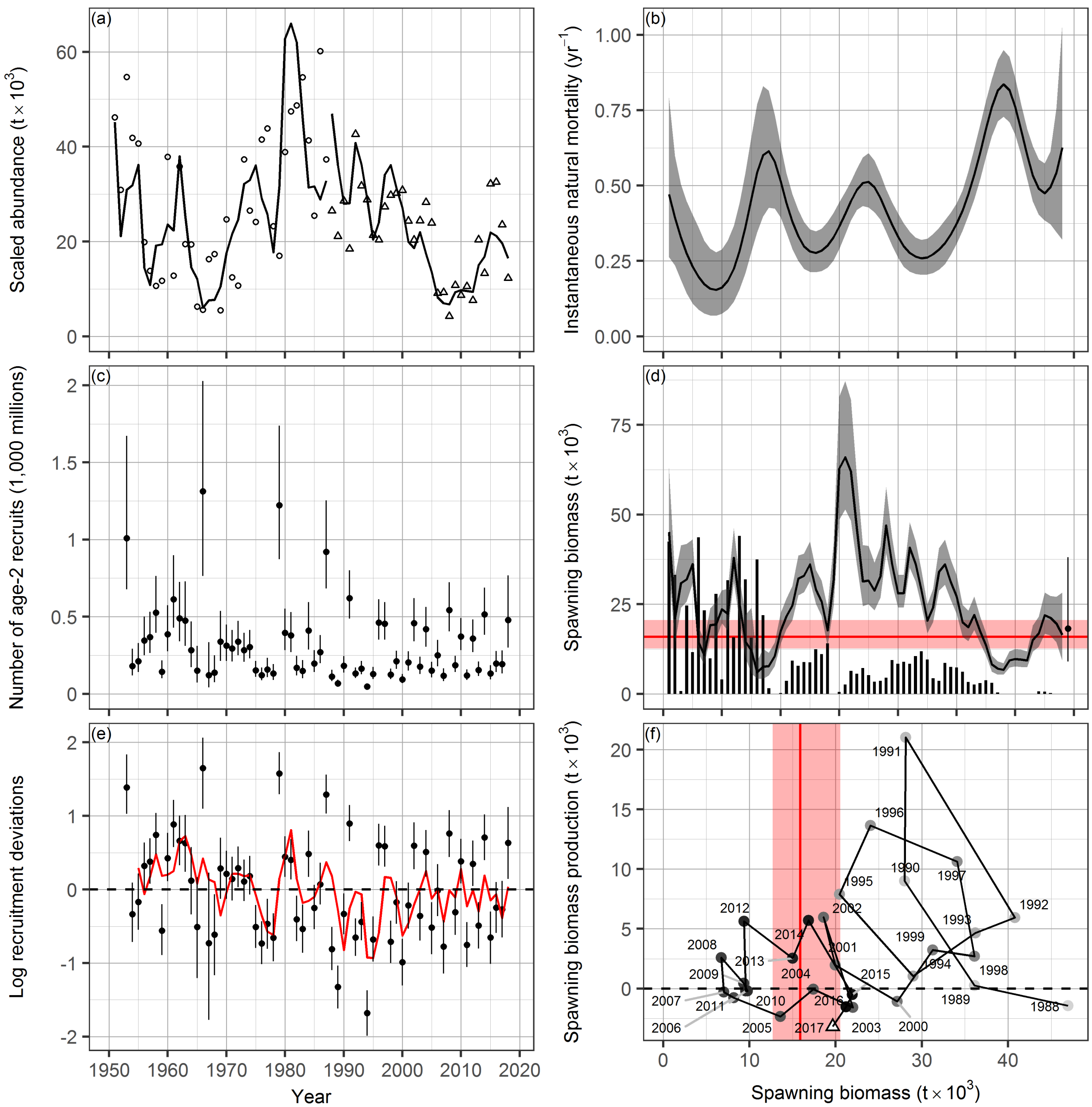

Figure 8. Model output for Pacific Herring in the Central Coast major stock assessment region. See Figure 6 for description.

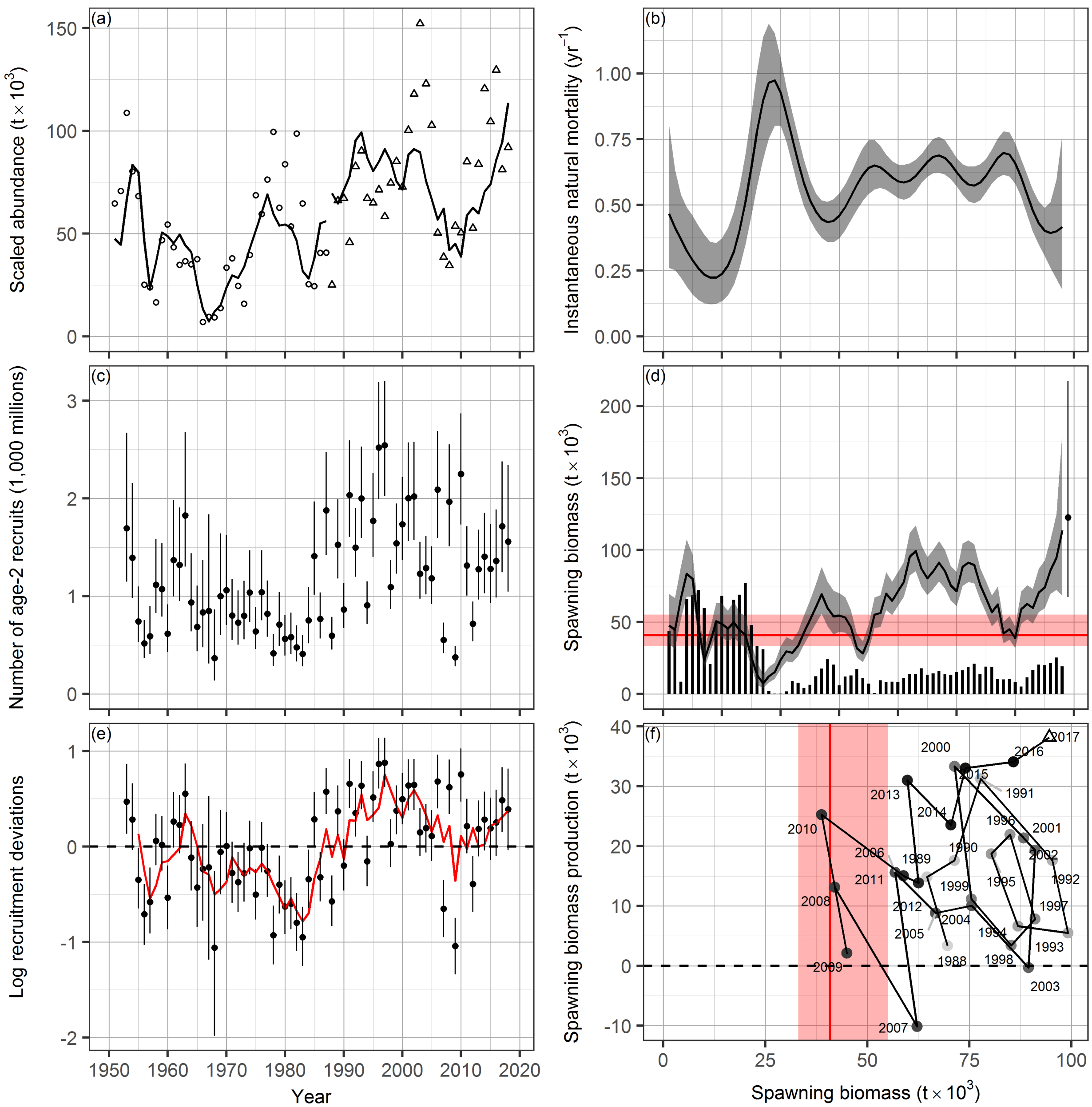

Figure 9. Model output for Pacific Herring in the Strait of Georgia major stock assessment region. See Figure 6 for description.

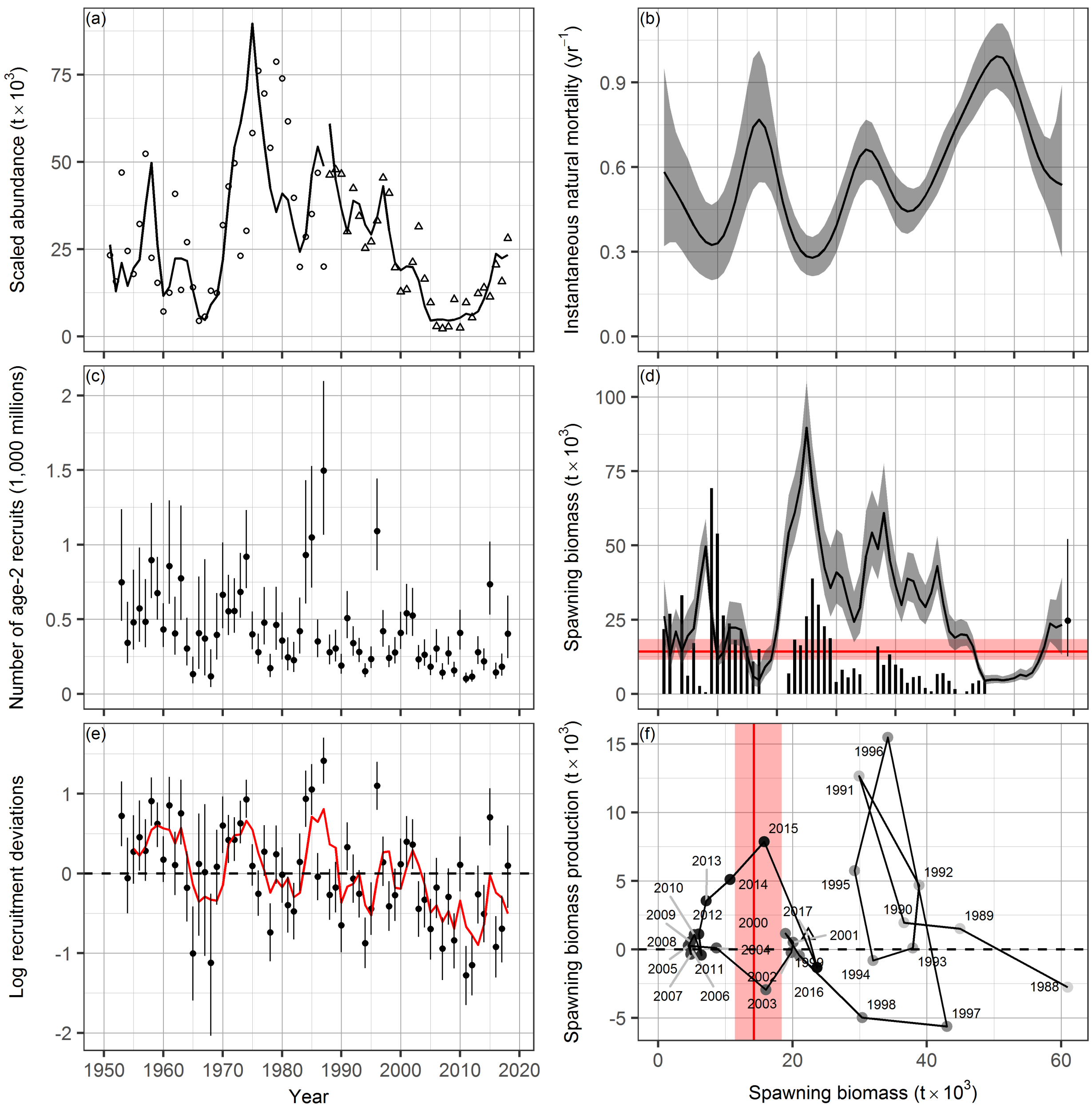

Figure 10. Model output for Pacific Herring in the West Coast of Vancouver Island major stock assessment region. See Figure 6 for description.

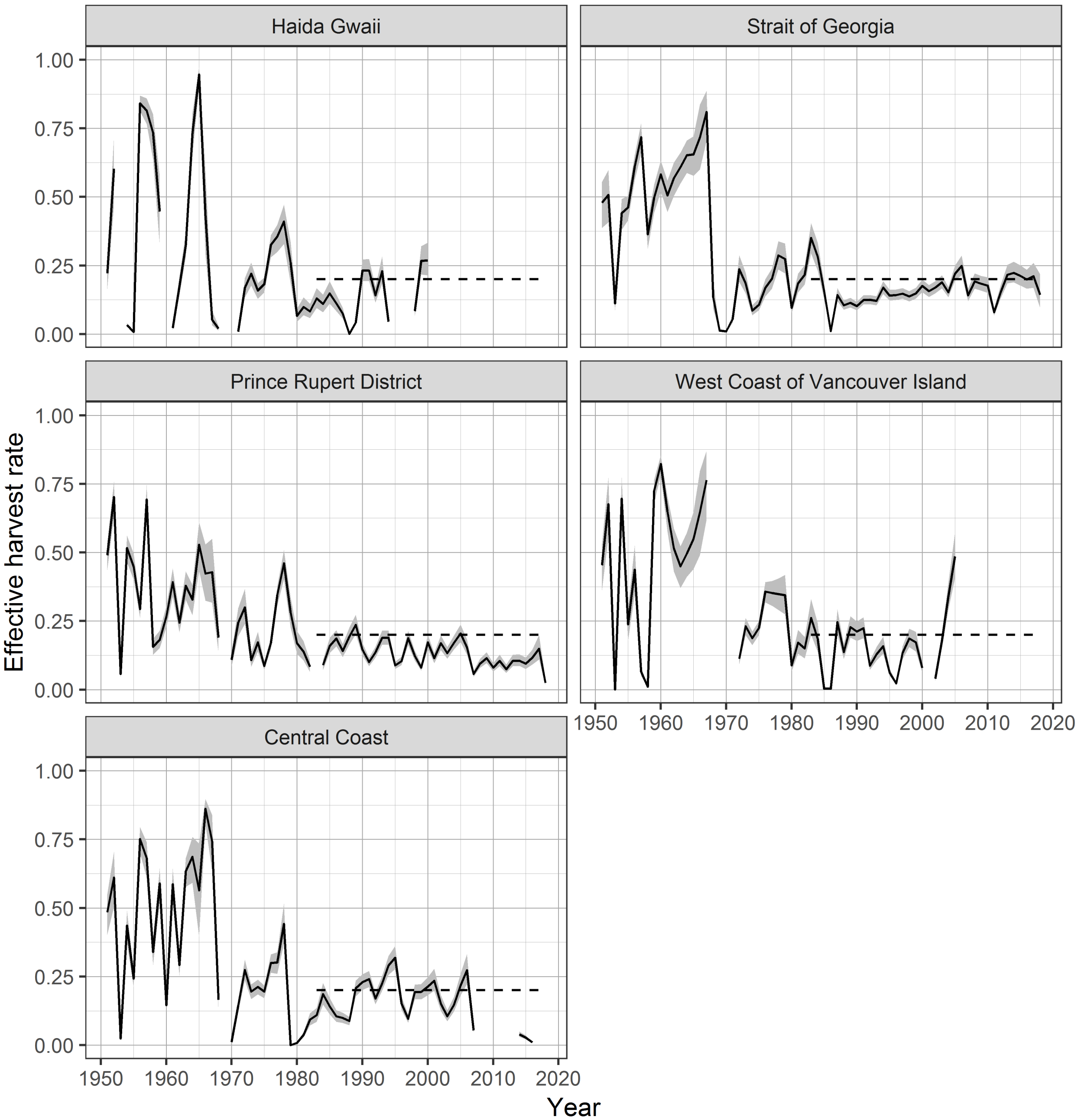

Figure 11. Time series of effective harvest rate for Pacific Herring from 1951 to 2018 in the major stock assessment regions. Effective harvest rate in year t, U_t is calculated as $U_t = \frac{C_t}{SB_t + C_t}$ where C_t is catch in year t, and SB_t is estimated spawning biomass in year t. Black lines indicate medians and shaded ribbons indicate 90% confidence intervals for spawning biomass, SB_t. Horizontal dashed lines indicate $U_t = 0.2$.

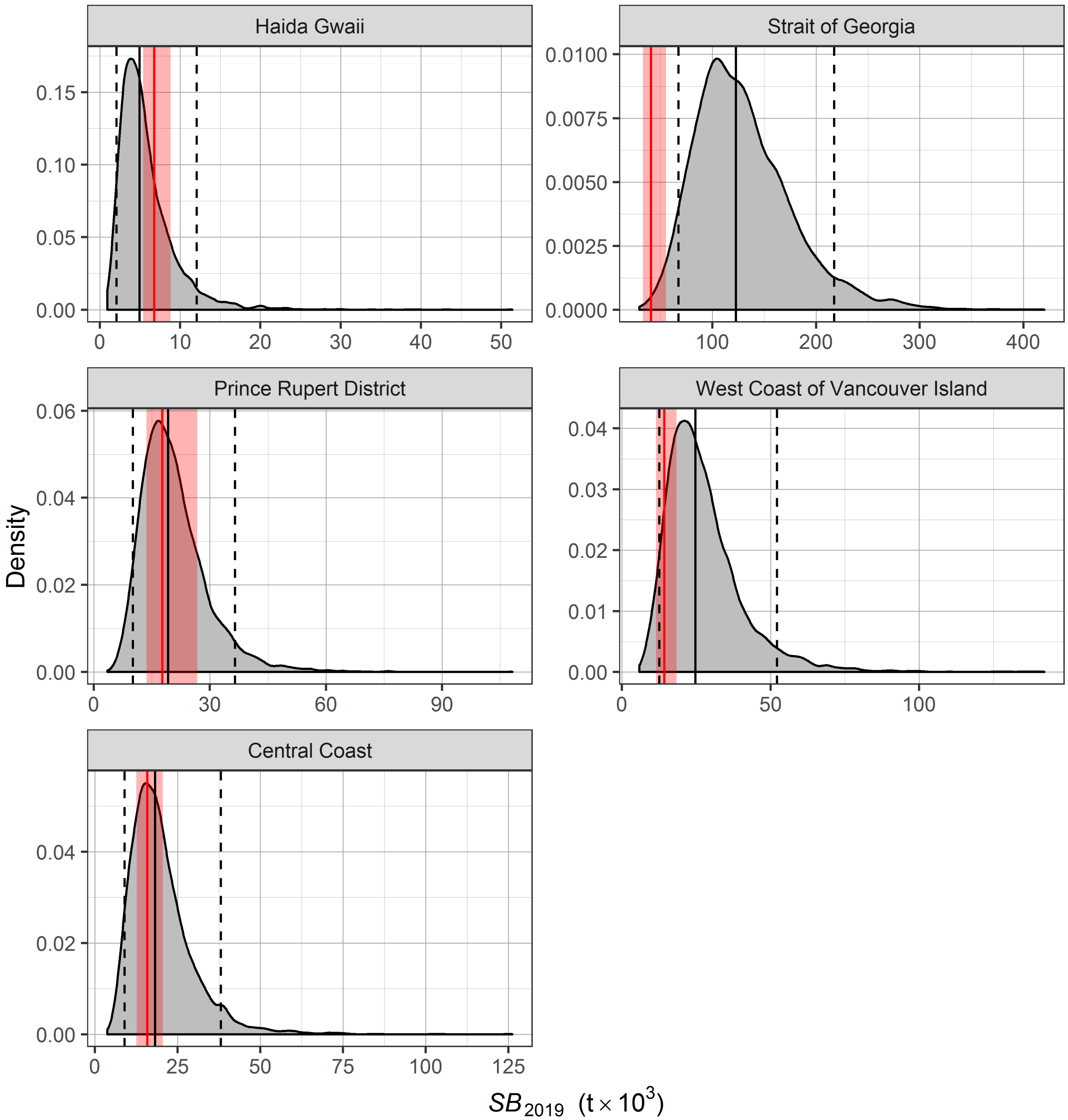

Figure 12. Projected spawning biomass assuming no fishing in 2019, SB_{2019} in thousands of tonnes (t $\times$ 10^3) for Pacific Herring in the major stock assessment regions. Vertical black lines indicate medians (solid) and 90% confidence intervals (dashed) for SB_{2019}. Vertical red lines indicate medians, and shaded red rectangles indicate 90% confidence intervals for the limit reference point, $0.3SB_0$, where SB_0 is estimated unfished biomass.

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Sources of information

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

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

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

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

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

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

DFO. 2018. Evaluation of management procedures for Pacific Herring (*Clupea pallasii*) in the Strait of Georgia and the West Coast of Vancouver Island management areas of British Columbia. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. In press.

Hall, D.L., Hilborn, R., Stocker, M. and Walters, C.J. 1988. Alternative harvest strategies for pacific herring (clupea harengus pallasi). Can. J. Fish. Aquat. Sci 45. 88S897.

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

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

Appendix

We do not conduct formal analyses of stock trend information for the two Pacific Herring minor SARs (Area 27 and Area 2 West). However, we do provide time series of landed commercial catch (Figure 13), biological data including weight-at-age (Figure 14) and proportion-at-age (Figure 15), as well as the spawn index (Figure 16) from 1978 to 2018.

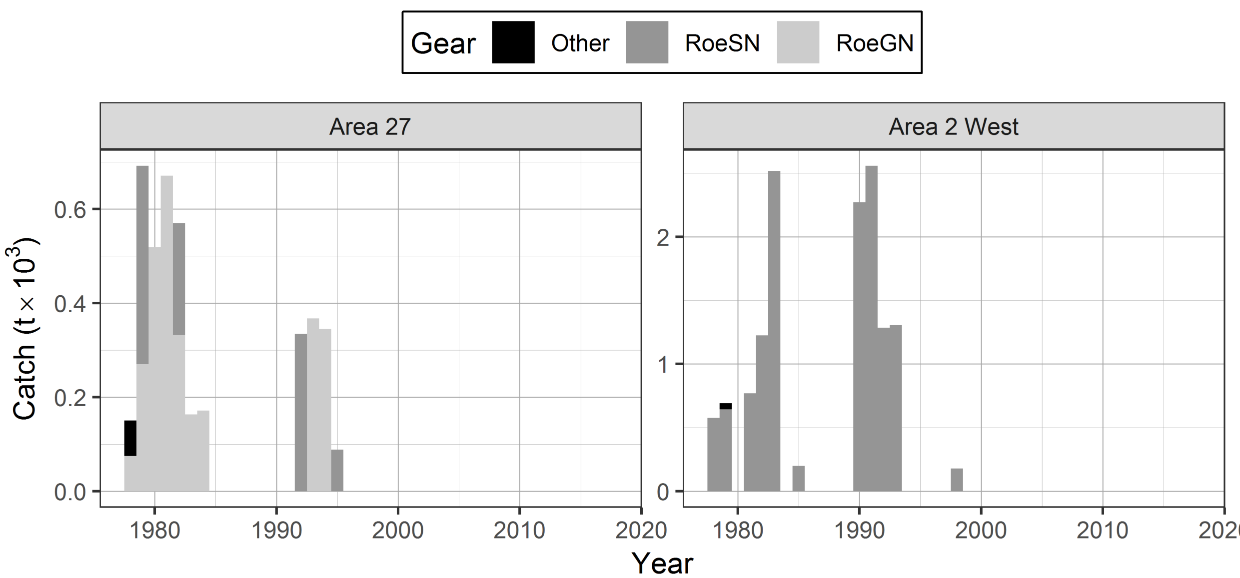

Figure 13. Time series of total landed catch in thousands of tonnes (t $\times 10^3$) of Pacific Herring from 1978 to 2018 in the minor stock assessment regions. Legend: 'Other' represents the reduction, the food and bait, as well as the special use fishery; 'RoeGN' represents the roe gillnet fishery; and 'RoeSN' represents the roe seine fishery.

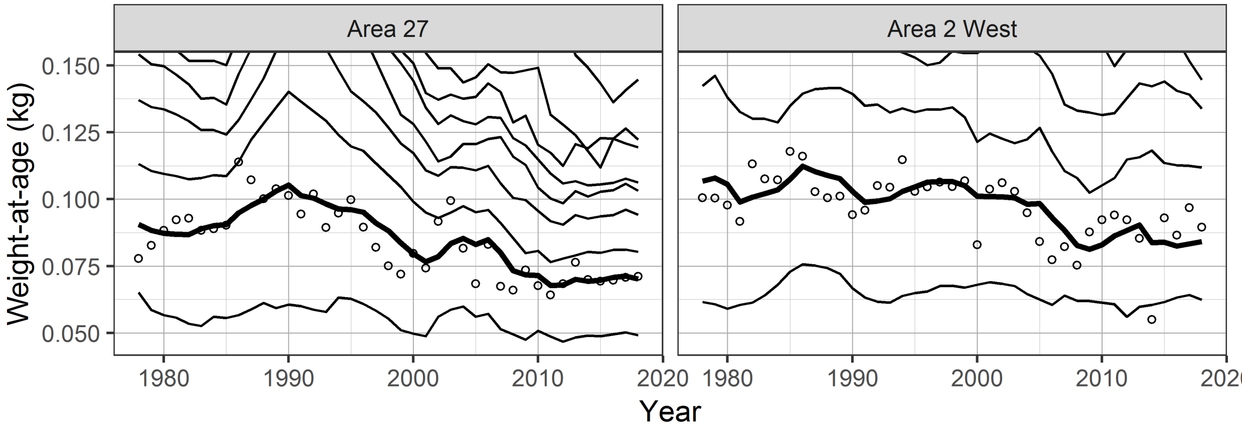

Figure 14. Time series of weight-at-age in kilograms (kg) for age-3 (circles) and 5-year running mean weight-at-age (lines) for Pacific Herring from 1978 to 2018 in the minor stock assessment regions. Lines show 5-year running means for age-2 to age-10 herring (incrementing higher from the lowest line); the thick black line highlights age-3 herring. Missing weight-at-age values (i.e., years where there are no biological samples) are imputed using one of two methods: missing values at the beginning of the time series are imputed by extending the first non-missing value backwards; other missing values are imputed as the mean of the previous 5 years. Biological summaries only include samples collected using seine nets (commercial and test) due to size-selectivity of other gear types such as gillnet. The age-10 class is a 'plus group' which includes fish ages 10 and older. Note that vertical axes are cropped at 0.15 kg.

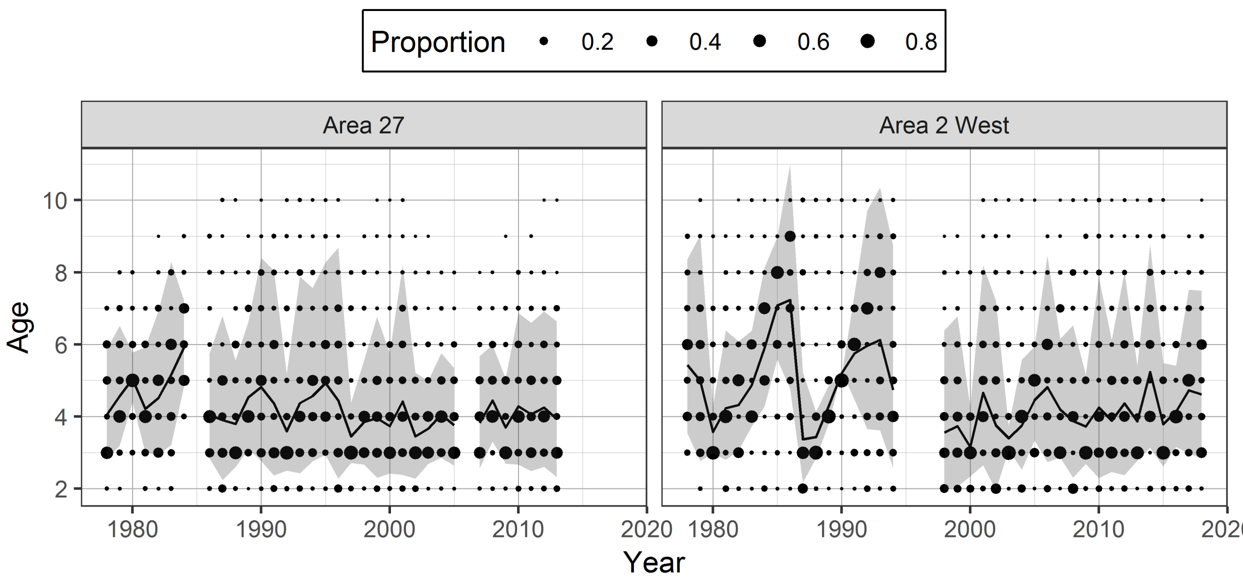

Figure 15. Time series of proportion-at-age for Pacific Herring from 1978 to 2018 in the minor stock assessment regions. The black line is the mean age, and the shaded area is the approximate 90% distribution. Biological summaries only include samples collected using seine nets (commercial and test) due to size-selectivity of other gear types such as gillnet. The age-10 class is a 'plus group' which includes fish ages 10 and older.

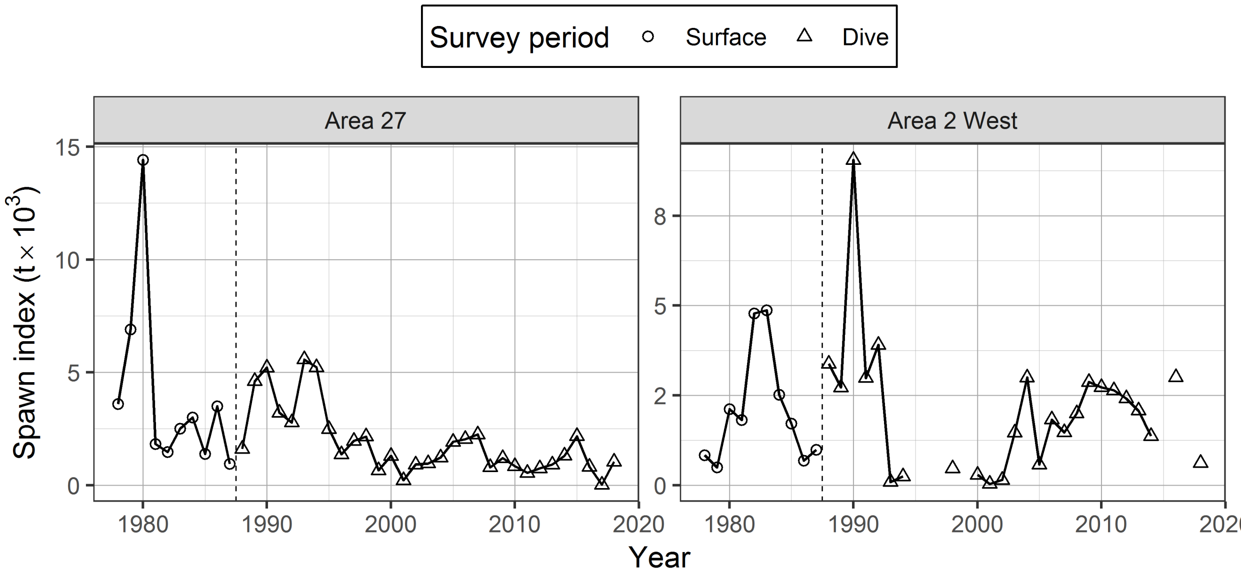

Figure 16. Time series of spawn index in thousands of tonnes (t $\times 10^3$) for Pacific Herring from 1978 to 2018 in the minor stock assessment regions. The spawn index has two distinct periods defined by the dominant survey method: surface surveys (1951 to 1987), and dive surveys (1988 to 2018). The dashed vertical line is the boundary between these two periods. The 'spawn index' represents the raw survey data only, and is not scaled by the spawn survey scaling parameter, q.

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