Fisheries and Oceans Canada / Pêches et Océans Canada
Ecosystems and Oceans Science / Sciences des écosystèmes et des océans

Pacific Region
Canadian Science Advisory Secretariat
Science Response 2019/XXX

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

Context

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

In 2016 DFO committed to renewing the current management framework to address a range of challenges facing Pacific Herring stocks and fisheries in BC. Renewal of the management framework includes engaging in a Management Strategy Evaluation (MSE) process to evaluate the performance of candidate management procedures against a range of hypotheses about future stock and fishery dynamics. As part of the MSE process, a CSAS regional peer review occurred July 25 and 26, 2018, where performance of Pacific Herring management procedures (MP) were assessed against conservation objectives for Strait of Georgia (SoG) and West Coast of Vancouver Island (WCVI) stock assessment regions (DFO 2018). Steps included operating model (OM) development, fitting the OM to Pacific Herring stock and fishery monitoring data, and closed-loop simulations of MP performance for alternative future natural mortality scenarios. The 2018 stock assessment included updated MP recommendations for SoG and WCVI management areas for 2019 (DFO 2019).

In the spring of 2019, the MSE process was initiated for the northern stock areas and performance evaluation of MPs for Haida Gwaii (HG), Prince Rupert District (PRD), and Central Coast (CC) is described in dfo2019b.

Estimated stock trajectories, current status of stocks for 2019, and harvest advice recommendations for 2020 reflect methods of Cleary et al. (2018) and, where applicable, recommendations from the aforementioned 2018 and 2019 MSE analyses. These recommendations are described in the section “Harvest recommendations for 2020”.

Fisheries and Oceans Canada (DFO) Pacific Fisheries Management Branch requested that DFO Pacific Science Branch assess the status of British Columbia (BC) Pacific Herring stocks in 2019 and recommend harvest advice for 2020 to inform the development of the 2019/2020 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 2019 and forecast for 2020.

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 in the 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 2018/2019, the primary Pacific Herring fisheries were seine roe and gillnet roe fisheries, with a combined coast wide catch in 2018/2019 of 179 tonnes (t), and the FB seine fishery with a coast wide catch of 0 t. The roe fishery was only operational in SoG. 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 2019. Advice to managers for the major stock areas includes posterior estimates of current stock status (SB_{2019}), spawning biomass in 2020 assuming no catch (SB_{2020}), 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 2019) 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 (Appendix D; Cleary et al. 2018). 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 Table A1, (DFO 2016) and Appendix D, (Cleary et al. 2018).

Analysis and response

Input data

Input data to the stock assessment are summarized in 1. Relative to last year's assessment, the only change made to input data was updating the time series to include data from the 2018/2019 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 100% in 2019. 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).

Signifcant 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). There has been an increasing trend in weight-at-age for all major stocks from 2012 to 2019, although to a lesser degree for PRD.

Abundance data

The surface (1951 to 1987) and dive (1988 to 2019) spawn survey methods involve collecting information on spawn length (parallel to shore), spawn width (perpendicular to shore), 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 2019 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 2019 are summarized in Figure 5. In 2019, there was a decrease in survey biomass in SoG and WCVI (Figure 5 and Tables 7 and 8) and an increase in survey biomass in HG, PRD, and CC (Figure 5 and Tables 4, 5 and 6).

Spatial spawn distribution

Tables 4- through 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 refects 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 through 8 also present annual proportions of survey spawn index expressed as biomass by Statistical Area or Group for the last fve 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.

Hadia Gwaii

Prince Rupert District

Central Coast

Strait of Georgia

West Coast Vancouver Island

Stock status update

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

a. Time series of maximum posterior density (MPD) estimates of the spawn survey data in thousands of tonnes. The spawn survey data (i.e., spawn index) is scaled to abundance via the spawn survey scaling parameter q. The spawn index has two distinct periods defined by the dominant survey method: surface surveys (1951 to 1987), and dive surveys (1988 to 2019). Two q parameters are implemented in the estimation procedure: q_1 with an uninformative prior and q_2 with an informative prior approximating 1.0.
b. Time series of natural mortality (M) estimates
c. Time series reconstruction of number of age-2 recruits
d. Time series of total catch and estimated spawning biomass with reference line at model estimates of $0.3SB_0$
e. Time series of (log) deviations from the estimated Beverton-Holt recruitment function overlaid with a 3-year trailing moving average smoother
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 defned for the major Pacific Herring SARs at $0.3SB_0$ (Kronlund et al. 2017). Candidate upper stock references (USR) were introduced in Cleary et al. (2018) and implemented as biomass objectives in the simulation analyses for WCVI and SoG in 2018 (DFO 2018) and HG, PRD, and CC in 2019 (DFO 2019). Candidate USRs are:

1. $0.4SB_0$,
2. $0.6SB_0$,

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

Simulation results showed similar properties between USRs $0.6SB_0$ and SB_{ave} both within and among SARs, while the USR based on the average biomass in a productive period, $SB_{ave-prod}$, was found to be most variable among SARs. The simulation-evaluations did not select a single USR, however a USR of $0.6SB_0$ is included in this stock status update because this candidate is suffciently 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 through 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 infection 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 briefy 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. This increase in biomass per individual combined with an increase in survey biomass index and above average recuitment seen in 2019 has only resulted in a very modest increase in estimated spawning biomass. Since 2000, the HG stock has persistently existed in a low biomass state, with many of these years also showing low productivity which has precluded stock growth (Figure 6f). In the most recent year between 2018 and 2019 spawning periods the HG stock appears to be out of a low productivity state but remains in a low biomass state.

Estimated spawning biomass in 2019 is 6,944 t (SB_{2019}, median posterior value) or 30.1% of SB_0 (Table 9). The 2019 spawning biomass continues to be estimated 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, Ut, 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 2019 is estimated to be less than the LRP of $0.3SB_0$ with a 49.9% 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-ft (e.g., 2001–2004, 2010, 2013) as shown in

Figure 7a. Estimated natural mortality reached historic highs in the late 1960s, before declining through the late 1970s. Beginning in about 1980, estimated natural mortality increased through to 2019, roughly doubling from 0.25 to 0.5 yr-1 (Figure 7b). This trend in natural mortality coincides with the decline in spawning biomass (Figure 7d); recruitment deviations have fuctuated around 0 without any strong positive or negative trending (Figure 7e). An above average age-2+ recruitment in 2014, 2017 and 2018 and an increase in the survey biomass index were still not sufficient to raise the stock from a low biomass state ((Figure 7f). Despite relatively low and stable levels of catch up to 2018 and no commercial catch in 2019 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 HG, CC, SoG and WCVI SARs.

The model estimates spawning biomass in 2019, SB_{2019}, at 23,223 t (posterior median), equal to 39.7% of SB_0 (Table 10). Commercial fisheries have occurred annually in PRD since the mid-1980s, with the exception of 2019, during which the effective harvest rate, U_t, was estimated to be at or below 20% (Figure 11), with the exception of 1989. Spawning biomass in 2019 is estimated to be less than the LRP of $0.3SB_0$ with a 24.1% probability (Table 10).

Central Coast

Estimated spawning biomass fuctuated 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. In 2019 there was an increase in estimated spawning biomass. The estimated biomass trend largely refects 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 were slightly negative (lower than predicted by the stock-recruit function) on average from about 1990 to 2017 and have increased to above average in 2018 and 2019 (Figure 8e). In 2019 there is evidence of strong production, similar to the 1990 to 1999 period (Figure 8f), however, the biomass state is not nearly as high as was seen during that period.

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 2019, SB_{2019}, at 33,366 t (posterior median), equal to 61.2% of SB_0 (Table 11). Spawning biomass in 2019 is estimated to be greater than the LRP of $0.3SB_0$ with a 98.2% probability (Table 11).

Strait of Georgia

The SCA model fit to the SoG stock and fishery monitoring data shows that spawning biomass has decreased in 2019 although uncertainty associated with the terminal spawning biomass estimate is large, as is the uncertainty associated with the forecast of SB_{2019} (Figure 9d). There was an increasing trend in estimated spawning biomass from about 2010 to 2016 which coincided with a decline in estimated natural mortality that began in the late 2000s (Figure 9b). Estimated natural mortality has been increasing since 2016, and has now reached a level last estimated in the late 1970s. This coincides with the recent decreasing trend in estimated spawning biomass. The large uncertainty in both spawning biomass and natural mortality estimates in 2019 may be in part a function of the decline in the spawn index from 2016 to 2019 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, insuffcient information to determine whether the decline from 2016 to 2019 represents a true decline in estimated spawning biomass. The model also has estimated above average recruitment in most years from 2010 to 2019 (Figure 9c) with the recruitment deviations showing much larger recruitment of age-2 fish in 2019 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 2017–2019 (Figure 11). The model estimates spawning biomass in 2019, SB_{2019}, at 64,662 t (posterior median), equal to 47.9% of SB_0 (Table 12). Spawning biomass in 2019 is estimated to be greater than the LRP of $0.3SB_0$ with a 87.6% probability (Table 12).

West Coast 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 suffcient to offset this below average recruitment of age-2 fish. The absence of a commercial fishery since 2005 means the realized harvest rate has been near zero for the last 14 years (Figure 11). Recent production estimates in the WCVI are at a higher spawning biomass level than those estimated during the low production, low biomass period of the last half of the 2000s and early 2010s (Figure 10f).

The model estimates spawning biomass in 2019, SB_{2019}, at 20,664 t (posterior median), equal to 44.7% of SB_0 (Table 13). Spawning biomass in 2019 is estimated to be greater than the LRP of $0.3SB_0$ with a 86.5% 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 $U_t = C_t/(C_t + SB_t)$

where C_t is catch in year t, and SB_t is estimated spawning biomass in year t. Times series of U_t relative to target harvest rate of 20% are presented in Figure 11.

Harvest recommendations for 2020

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 fxed commercial fishery cutoff of $0.25SB_0$ defined in the 1996 stock assessment (DFO 2016). 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 fxed commercial fishery cutoff of $0.25SB_0$ defined in the 1996 stock assessment (DFO 2016).

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 specifed 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 specifcation 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 frst MSE cycle (DFO 2018). A similar simulation-evaluation process occurred in 2020 to assess performance of MPs for HG, PRD, and CC (DFO 2019).

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, with productivity increasing slightly in the most recent year. The stock was below the LRP for much of that period and shows little evidence of sustained stock growth despite the absence of commercial fisheries since 2002 (2004 for the SOK fishery). In the absence of fishing, spawning biomass in 2020 is forecast at 9,891 t. The projected spawning biomass in 2020 is forecast to be below $0.3SB_0$ with 27.9 % 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 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 2020 is 0 t.

Prince Rupert District

XXXX Simulation Evaluation information 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 fuctuate at or near $0.3SB_0$ (Figure 7d). Furthermore, adjacent SARs (HG and CC) show evidence of recent prolonged periods of low biomass and low productivity: states that were entered rapidly and were preceded by high biomass levels (Kronlund et al. 2017).

In the absence of fishing, spawning biomass in 2020 is forecast to increase from 23,223 t in 2019 to an estimated 27,182 t (posterior medians). The forecast spawning biomass in 2020 is estimated to be below the LRP of $0.3SB_0$ with 20.2 % probability in the absence of fishing (Table 10).

Central Coast

XXXX Simulation Evaluation information

In the absence of fishing, spawning biomass in 2020 is forecast at 38,733 t (posterior median), increasing from 33,366 t in 2019 (Table 11). The 2020 spawning biomass is forecast to be below the LRP of $0.3SB_0$ with 4.4 % probability in the absence of fishing.

Strait of Georgia

Closed-loop feedback simulations for the SoG evaluated alternative MPs that differed only in the confguration 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.

[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.

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 (DFO 2009) 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
2. Use of separate lower and upper OCPs allows for altering the slope of the ramp portion ofthe 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 $0.3SB_0$ and $0.6SB_0$ with a 20% target harvest rate, and a maximum catch cap of 30,000 t (DFO 2018, Figure 4). In the absence of fishing, spawning biomass in 2020 is forecast at 71,215 t (posterior median) and is forecast to be below the LRP of $0.3SB_0$ with 16.2 % probability in the absence of fishing. The 2020 recommended catch calculated by applying the MP is 10,799, 152 t.

West Coast 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 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.

In the absence of fishing, spawning biomass in 2020 is forecast at 20,267 t (posterior median) and is forecast to be below the LRP of $0.3SB_0$ with 22.9 % probability in the absence of fishing.

Using a HCR with OCPs at $0.5SB_0$ and $0.6SB_0$, a 10% target harvest rate, and a maximum catch

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

cap of 2,000 t, the 2020 catch calculation is 0, 0 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 identifed 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 2019 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.

Conclusions

The 2019 Science Response includes a formal analyses of stock trend information for the Pacific Herring major SARs using the stock assessment framework reviewed in 2017 (Cleary et al. 2018).

Harvest recommendations for 2020 for PRD and CC include. . . ..

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 2019 Pacific Herring stock assessment. The spawn index has two distinct periods defined by the dominant survey method: surface surveys (1951 to 1987), and dive surveys (1988 to 2019). 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 2019
Roe seine fishery	Catch	1972 to 2019
Other fisheries	Catch	1951 to 2019
Test fishery (Seine)	Biological: number-at-age	1975 to 2019
Test fishery (Seine)	Biological: weight-at-age	1975 to 2019
Roe seine fishery	Biological: number-at-age	1972 to 2019
Roe seine fishery	Biological: weight-at-age	1972 to 2019
Roe gillnet fishery	Biological: number-at-age	1972 to 2019

Other fisheries	Biological: number-at-age	1951 to 2019
Other fisheries	Biological: weight-at-age	1951 to 2019
Surface survey	Abundance: spawn index	1951 to 1987
Dive survey	Abundance: spawn index	1988 to 2019

Table 2. Total landed catch in tonnes of Pacific Herring in the major stock assessment 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
2019	0	0	0	21,419	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	351,953	0	0
2017	0	82,597	392,747	0	0
2018	0	20,832	286,109	0	0
2019	0	15,418	356,042	0	0

Table 4. Spawn index in tonnes (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 specifed 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.

Years	Spawn index	Cumshewa	Juan Perez/Skincuttle	Louscoone	Selwyn
2019	11,624	0.025	0.919	0.016	0.040
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 to 2019	8,297	0.004	0.914	0.003	0.079
2013 to 2019	9,401	0.005	0.907	0.014	0.075
2012 to 2019	9,441	0.004	0.896	0.014	0.085
2011 to 2019	9,232	0.004	0.880	0.016	0.101
2010 to 2019	8,993	0.003	0.858	0.016	0.123

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.

Years	Spawn index	03	04	05
2019	27,190	0.010	0.452	0.538
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 to 2019	19,016	0.055	0.652	0.293
2013 to 2019	19,979	0.051	0.666	0.284
2012 to 2019	20,321	0.049	0.679	0.272
2011 to 2019	20,407	0.046	0.688	0.266
2010 to 2019	21,227	0.045	0.693	0.261

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.

Years	Spawn index	06	07	08
2019	46,255	0.323	0.641	0.036
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 to 2019	26,666	0.293	0.659	0.047
2013 to 2019	25,767	0.282	0.676	0.042
2012 to 2019	23,495	0.274	0.663	0.062
2011 to 2019	22,055	0.270	0.661	0.068

2010 to 2019	20,716	0.274	0.656	0.070

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.

Years	Spawn index	14&17	ESoG	Lazo	SDodd
2019	62,994	0.985	0.000	0.014	0.000
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 to 2019	98,408	0.827	0.006	0.146	0.021
2013 to 2019	96,306	0.841	0.005	0.133	0.020
2012 to 2019	90,847	0.843	0.006	0.127	0.024
2011 to 2019	90,197	0.859	0.005	0.113	0.023
2010 to 2019	86,223	0.861	0.004	0.102	0.032

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.

Years	Spawn index	23	24	25
2019	17,030	0.228	0.163	0.610
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 to 2019	17,776	0.412	0.166	0.421
2013 to 2019	16,988	0.402	0.151	0.447
2012 to 2019	15,540	0.360	0.178	0.461
2011 to 2019	14,887	0.350	0.192	0.458
2010 to 2019	13,645	0.359	0.181	0.460

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	18.248	23.056	30.319
$0.3SB_0$	5.475	6.917	9.096
SB_{2019}	3.547	6.944	12.692
SB_{2019}/SB_0	0.151	0.300	0.551
$SB_{2019}/0.3SB_0$	0.504	1.001	1.838
$P(SB_{2019} < 0.3SB_0)$	–	0.499	–
SB_{2020}	3.613	9.891	23.442
SB_{2020}/SB_0	0.155	0.427	1.002
$SB_{2020}/0.3SB_0$	0.515	1.423	3.339
$P(SB_{2020} < 0.3SB_0)$	–	0.278	–
$P(SB_{2020} < 0.6SB_0)$	–	0.738	–
Proportion aged 3	0.12	0.43	0.79
Proportion aged 4-10	0.10	0.28	0.56

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	45.213	58.546	87.672
$0.3SB_0$	13.564	17.564	26.302
SB_{2019}	13.141	23.223	39.807
SB_{2019}/SB_0	0.209	0.389	0.679
$SB_{2019}/0.3SB_0$	0.696	1.297	2.262
$P(SB_{2019} < 0.3SB_0)$	–	0.241	–
SB_{2020}	11.721	27.182	58.826
SB_{2020}/SB_0	0.193	0.452	1.000
$SB_{2020}/0.3SB_0$	0.642	1.508	3.332
$P(SB_{2020} < 0.3SB_0)$	–	0.202	–
$P(SB_{2020} < 0.6SB_0)$	–	0.722	–
Proportion aged 3	0.06	0.20	0.50
Proportion aged 4-10	0.42	0.71	0.89

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	43.844	54.534	71.396
$0.3SB_0$	13.153	16.360	21.419
SB_{2019}	19.331	33.366	55.574
SB_{2019}/SB_0	0.347	0.607	1.006
$SB_{2019}/0.3SB_0$	1.156	2.022	3.352
$P(SB_{2019} < 0.3SB_0)$	–	0.018	–
SB_{2020}	17.219	38.733	85.554
SB_{2020}/SB_0	0.309	0.711	1.543
$SB_{2020}/0.3SB_0$	1.031	2.369	5.143
$P(SB_{2020} < 0.3SB_0)$	–	0.044	–
$P(SB_{2020} < 0.6SB_0)$	–	0.376	–
Proportion aged 3	0.06	0.21	0.52
Proportion aged 4-10	0.39	0.69	0.88

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	107.880	135.017	192.529
$0.3SB_0$	32.364	40.505	57.759
SB_{2019}	36.009	64.662	114.166
SB_{2019}/SB_0	0.249	0.465	0.853
$SB_{2019}/0.3SB_0$	0.829	1.551	2.845
$P(SB_{2019} < 0.3SB_0)$	–	0.124	–
SB_{2020}	30.678	71.215	165.192
SB_{2020}/SB_0	0.212	0.514	1.224
$SB_{2020}/0.3SB_0$	0.706	1.715	4.081
$P(SB_{2020} < 0.3SB_0)$	–	0.162	–
$P(SB_{2020} < 0.6SB_0)$	–	0.610	–
Proportion aged 3	0.12	0.33	0.62
Proportion aged 4-10	0.25	0.48	0.71

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

Reference point	5%	50%	95%
SB_0	37.267	46.201	60.046
$0.3SB_0$	11.180	13.860	18.014
SB_{2019}	11.411	20.664	35.721
SB_{2019}/SB_0	0.240	0.442	0.785
$SB_{2019}/0.3SB_0$	0.801	1.473	2.616
$P(SB_{2019} < 0.3SB_0)$	–	0.135	–
SB_{2020}	8.810	20.267	43.080
SB_{2020}/SB_0	0.187	0.434	0.927
$SB_{2020}/0.3SB_0$	0.623	1.448	3.089
$P(SB_{2020} < 0.3SB_0)$	–	0.228	–
$P(SB_{2020} < 0.6SB_0)$	–	0.747	–
Proportion aged 3	0.12	0.32	0.64
Proportion aged 4-10	0.26	0.49	0.74

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

2020 TAC (t)	$\mathbf{P(SB_{2020} < 0.3SB_0)}$	$\mathbf{Med(SB_{2020}/0.3SB_0)}$	$\mathbf{P(SB_{2020} < 0.6SB_0)}$	$\mathbf{P(U_{2020} > 20\%)}$	$\mathbf{P(U_{2020} > 10\%)}$	$\mathbf{Med(U_{2020})}$
0	0.294	1.259	0.857	0.000	0.000	0.000

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

2020 TAC (t)	$\mathbf{P(SB_{2020} < 0.3SB_0)}$	$\mathbf{Med(SB_{2020}/0.3SB_0)}$	$\mathbf{P(SB_{2020} < 0.6SB_0)}$	$\mathbf{P(U_{2020} > 20\%)}$	$\mathbf{P(U_{2020} > 10\%)}$	$\mathbf{Med(U_{2020})}$
0	0.114	1.807	0.590	0.000	0.000	0.000

Figures

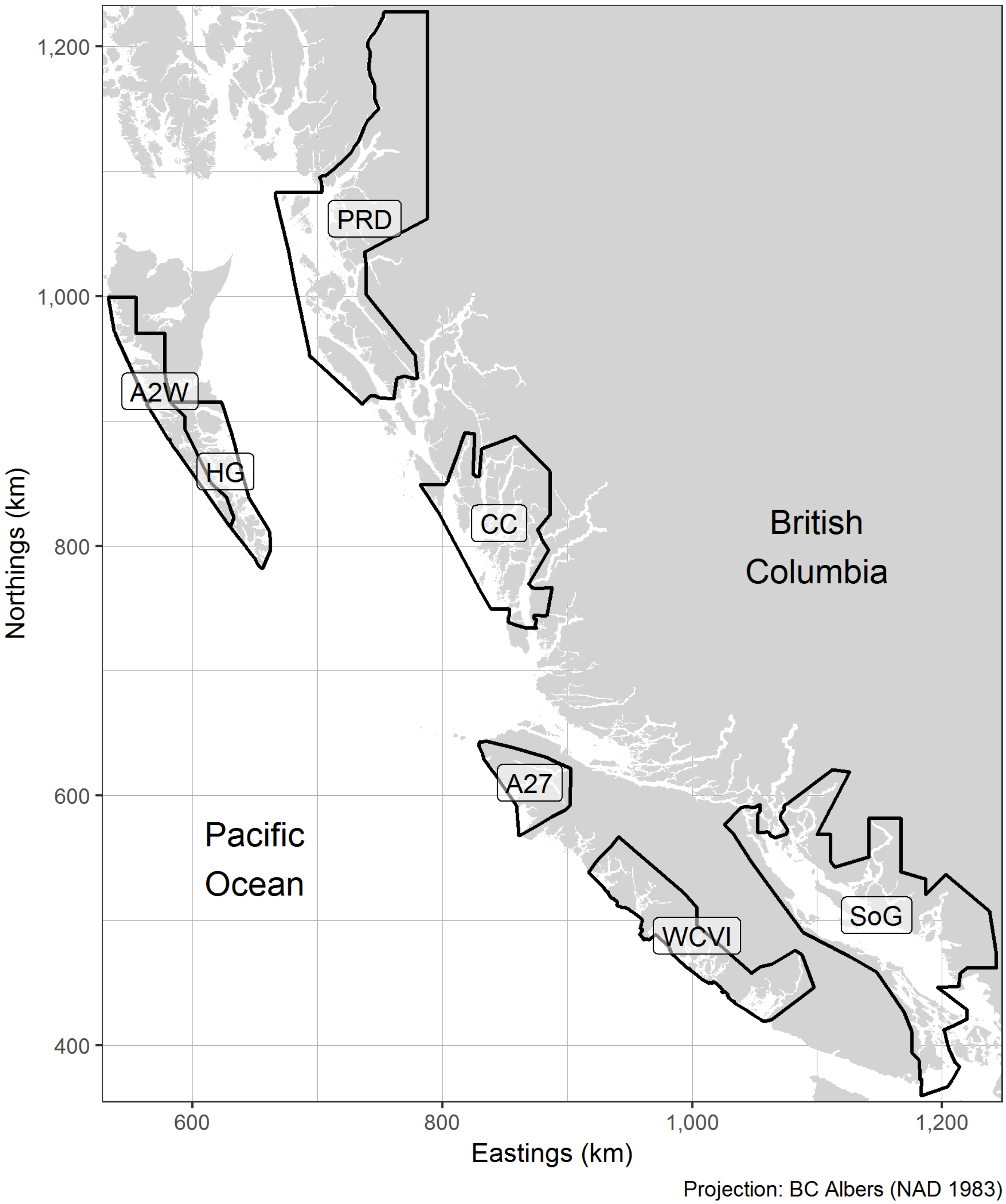

Figure 1. Boundaries for the Pacific Herring stock assessment regions (SARs) in BC. The major SARs are Haida Gwaii (HG), Prince Rupert District (PRD), Central Coast (CC), Strait of Georgia (SoG), and West Coast of Vancouver Island (WCVI). The minor SARs are Area 27 (A27) and Area 2 West (A2W). Units: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

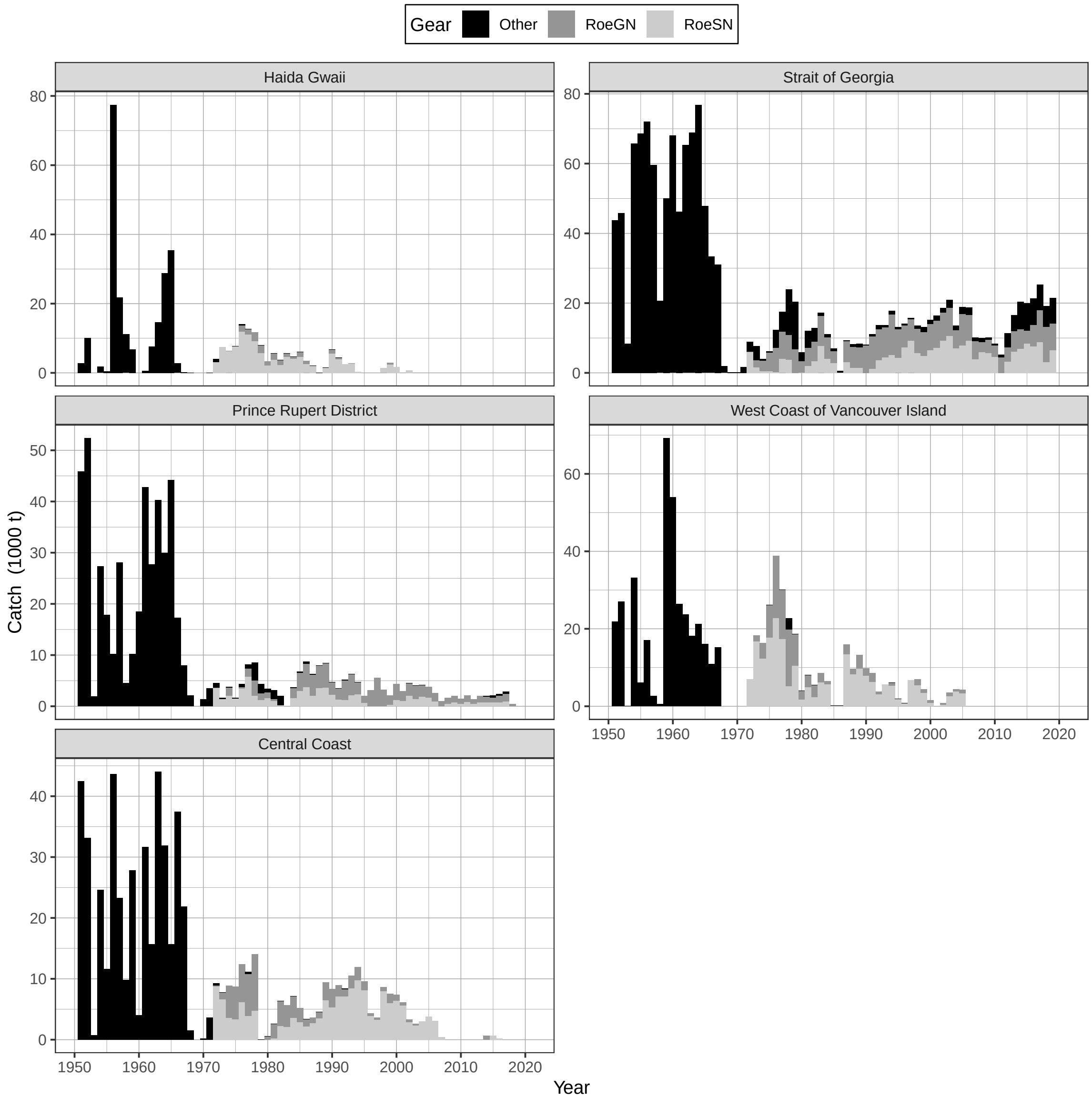

Figure 2. Time series of total landed catch in thousands of tonnes of Pacific Herring from 1951 to 2021 in the major stock assessment regions. Legend: ‘Other’ represents the reduction, the food and bait, as well as the special use fishery; ‘RoeGN’ represents the roe gillnet fishery; and ‘RoeSN’ represents the roe seine fishery.

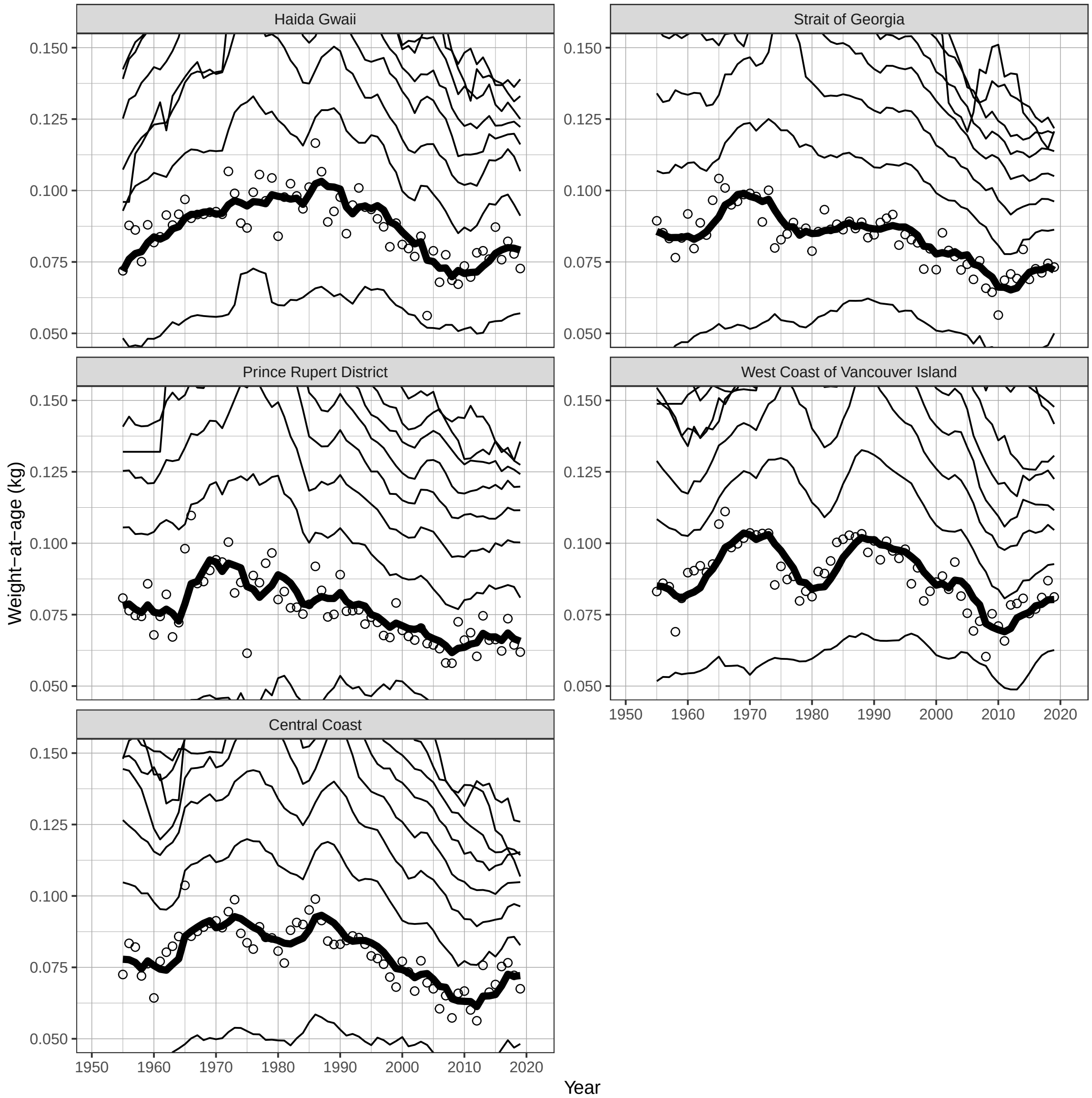

Figure 3. Time series of weight-at-age in kilograms (kg) for age-3 (circles) and 5-year running mean weight-at-age (lines) for Pacific Herring from 1951 to 2019 in the major stock assessment regions (SARs). Lines show 5-year running means for age-2 to age-10 herring (incrementing higher from the lowest 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 aged 10 and older. Note that vertical axes are cropped at 0.05 and 0.15 kg.

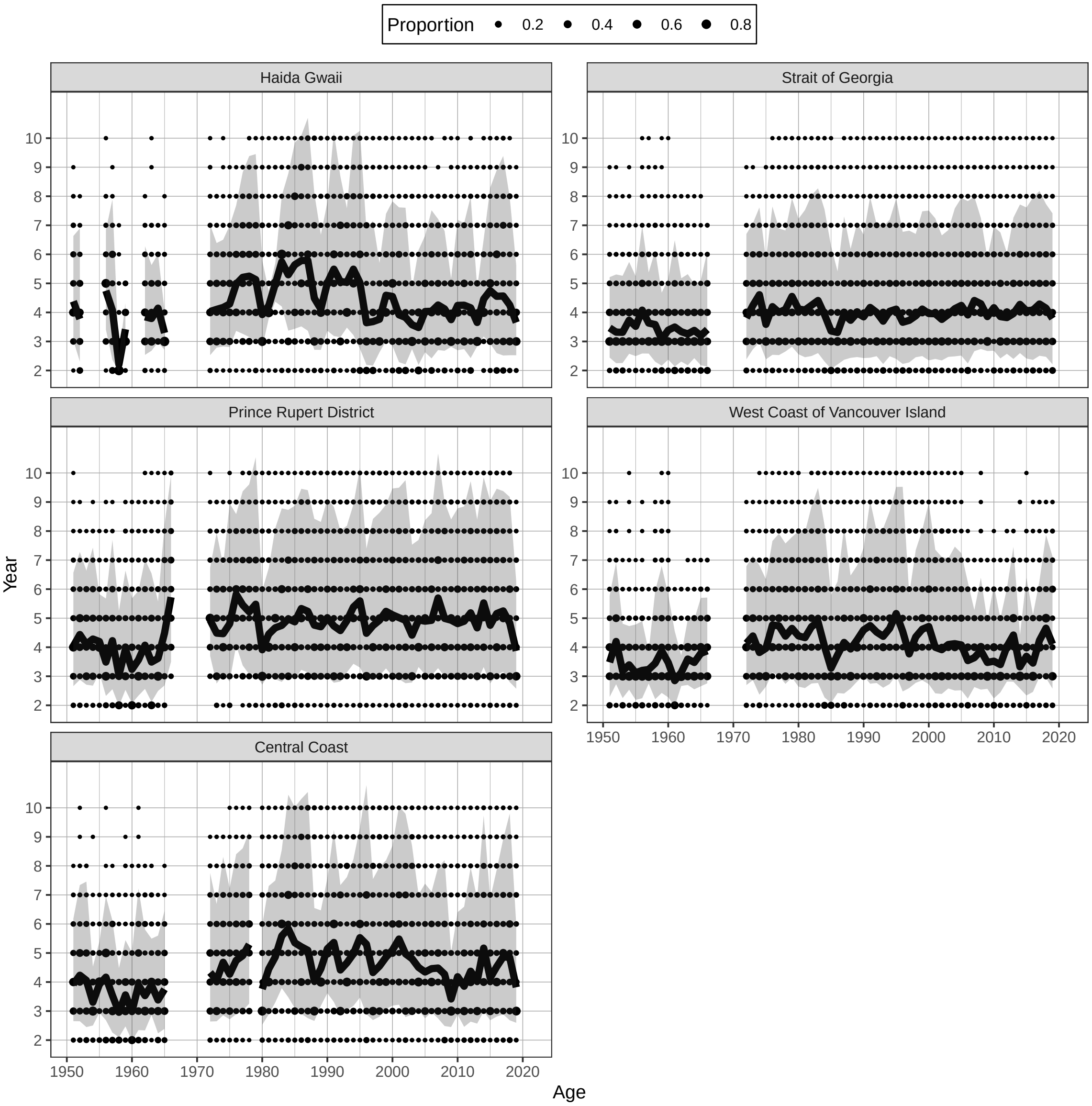

Figure 4. Time series of proportion-at-age for Pacific Herring from 1951 to 2019 in the minor stock assessment regions. The black line is the mean age, and the shaded area is the approximate 90% distribution. Biological summaries only include samples collected using seine nets (commercial and test) due to size-selectivity of other gear types such as gillnet. The age-10 class is a 'plus group' which includes fish aged 10 and older.

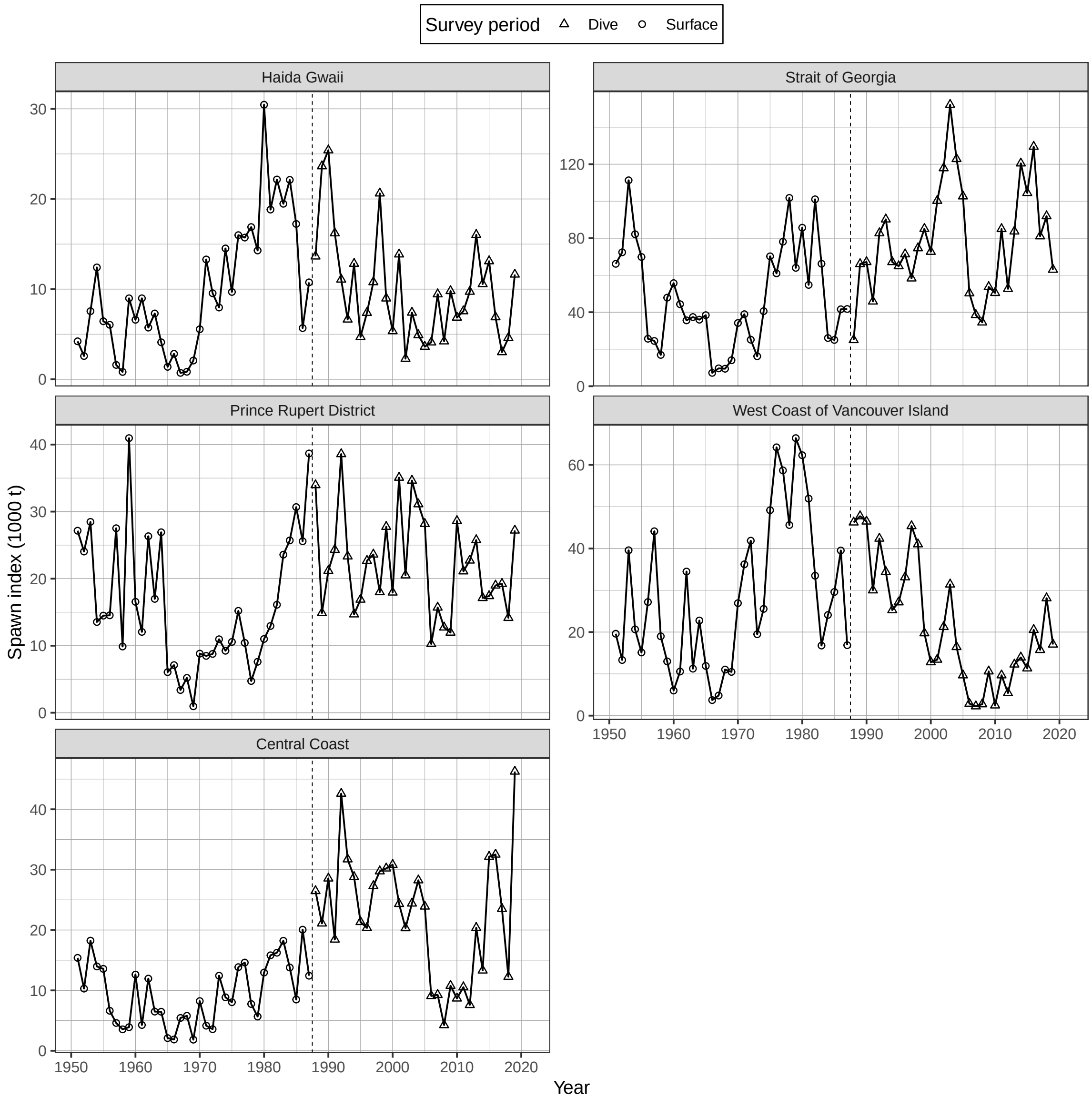

Figure 5. Time series of spawn index in thousands of tonnes for Pacific Herring from 1951 to 2019 in the major stock assessment regions. The spawn index has two distinct periods defned by the dominant survey method: surface surveys (1951 to 1987), and dive surveys (1988 to 2019). The dashed vertical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

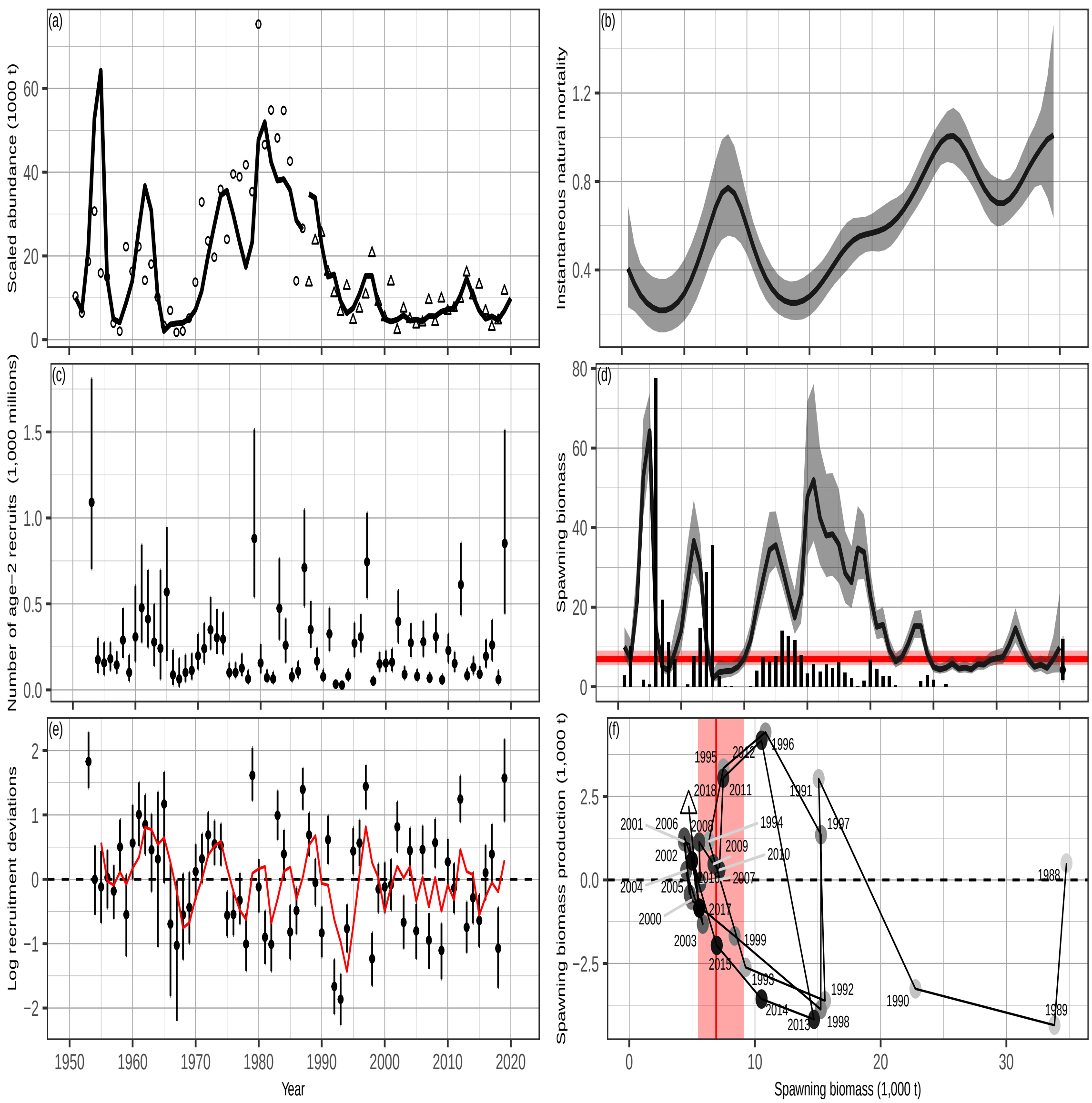

Figure 6. Model output for Pacific Herring in the Haida Gwaii major stock assessment region. Panel (a): model fit to scaled spawn survey data in thousands of tonnes. The spawn survey data (i.e., spawn index) is scaled to abundance via the spawn survey scaling parameter q. Panel (b): posterior estimates of instantaneous natural mortality rate. 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_{2020} (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 2019; maximum posterior density estimates). Grey shading becomes darker in chronological order; the triangle indicates 2018. Panels (d & f): red lines and shading indicate medians and 90% confdence intervals, respectively, for the limit reference point, $0.3SB_0$.

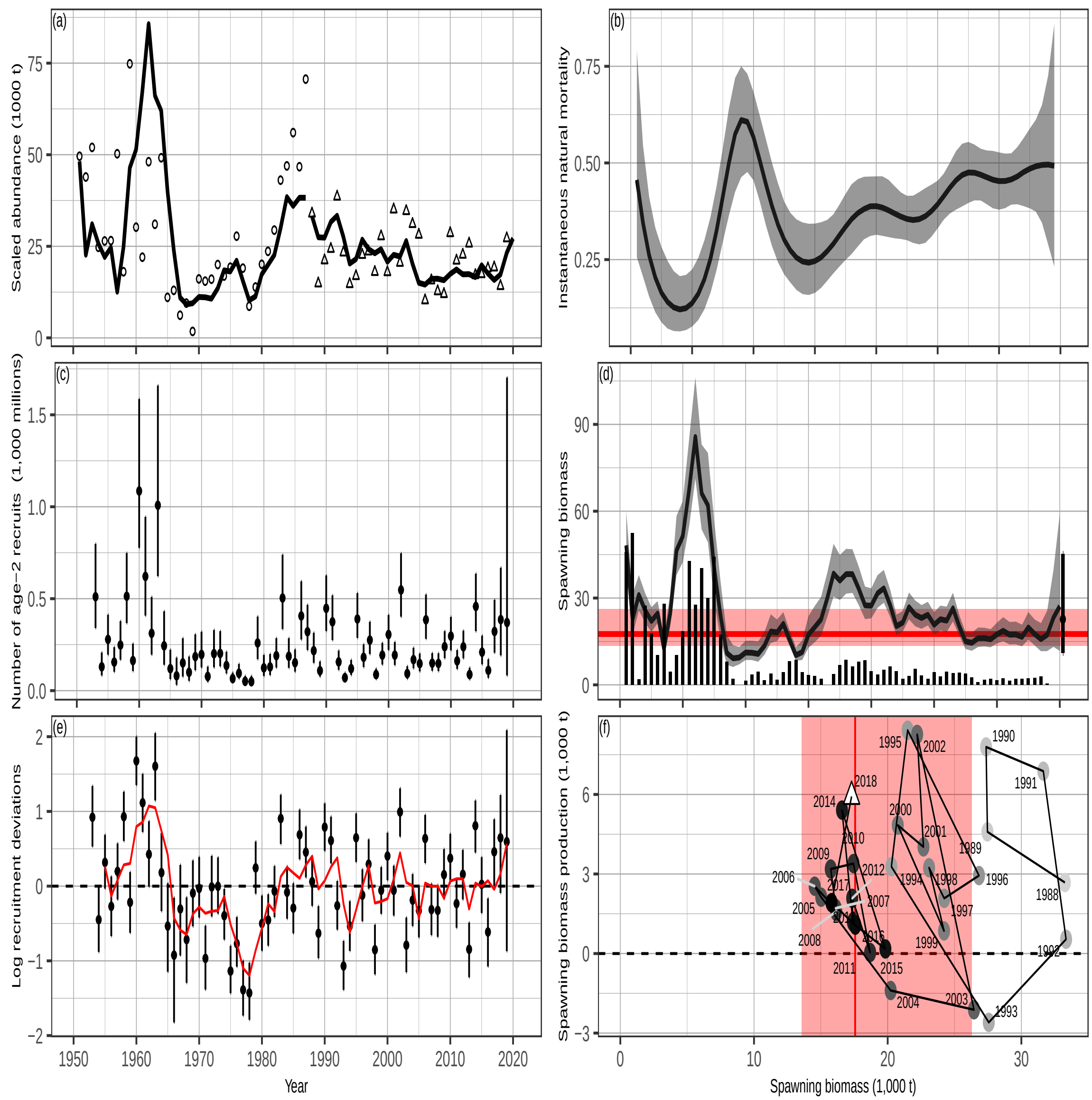

Figure 7. Model output for Pacific Herring in the Prince Rupert District major stock assessment region. See Figure 6 for description.

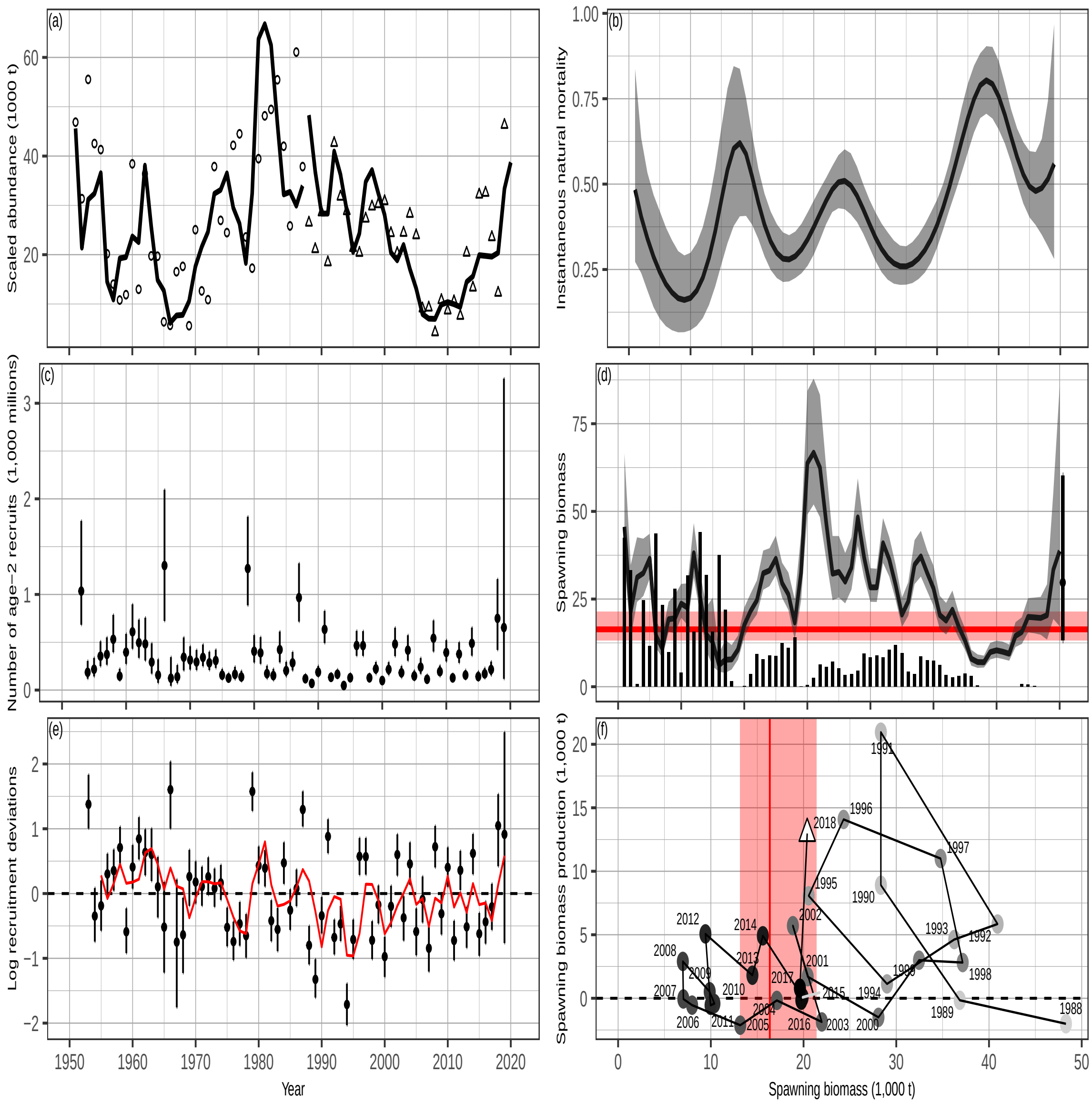

Figure 8. Model output for Pacific Herring in the Central Coast major stock assessment region. See Figure 6 for description.

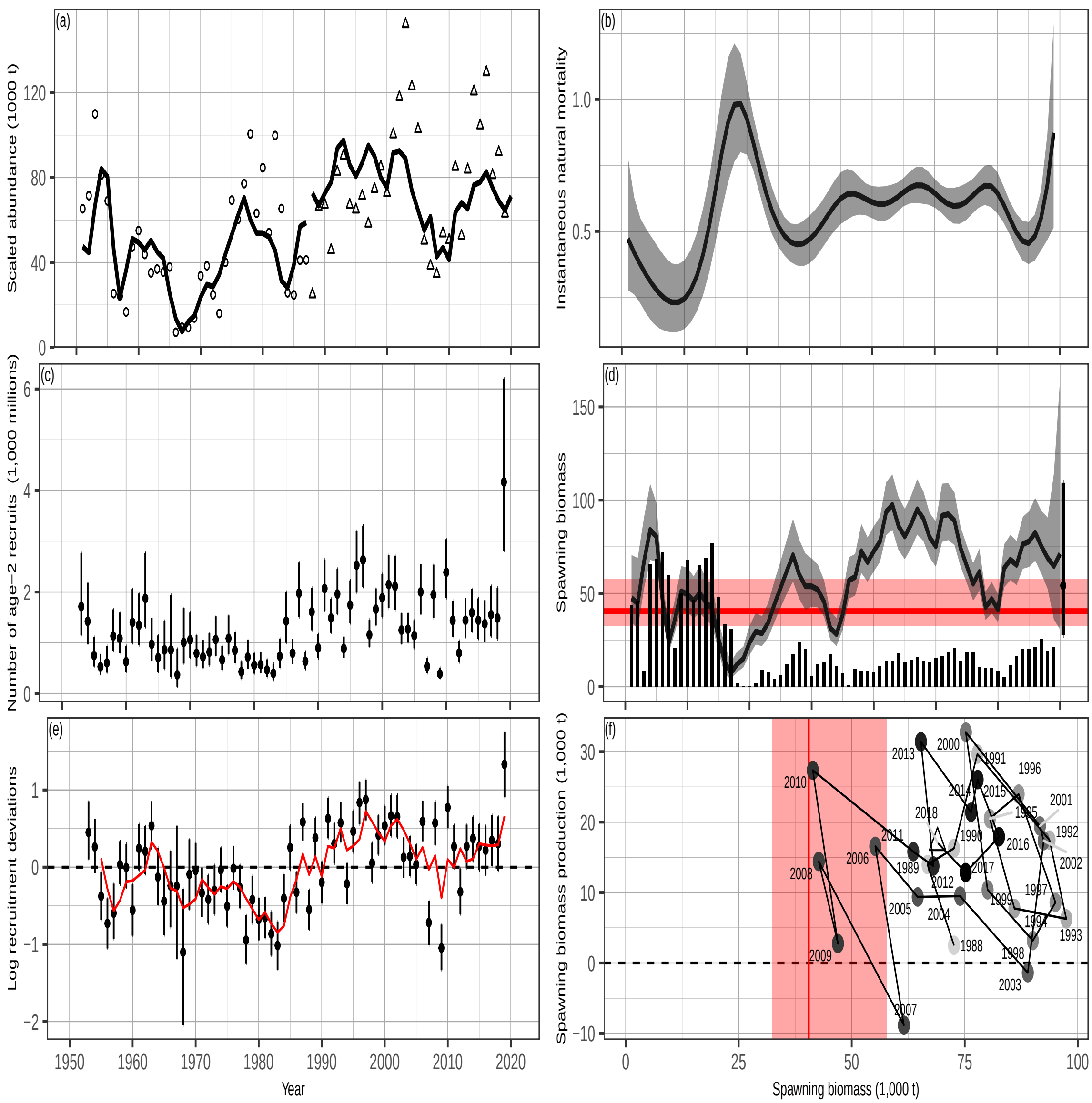

Figure 9. Model output for Pacific Herring in the Strait of Georgia major stock assessment region. See Figure 6 for description.

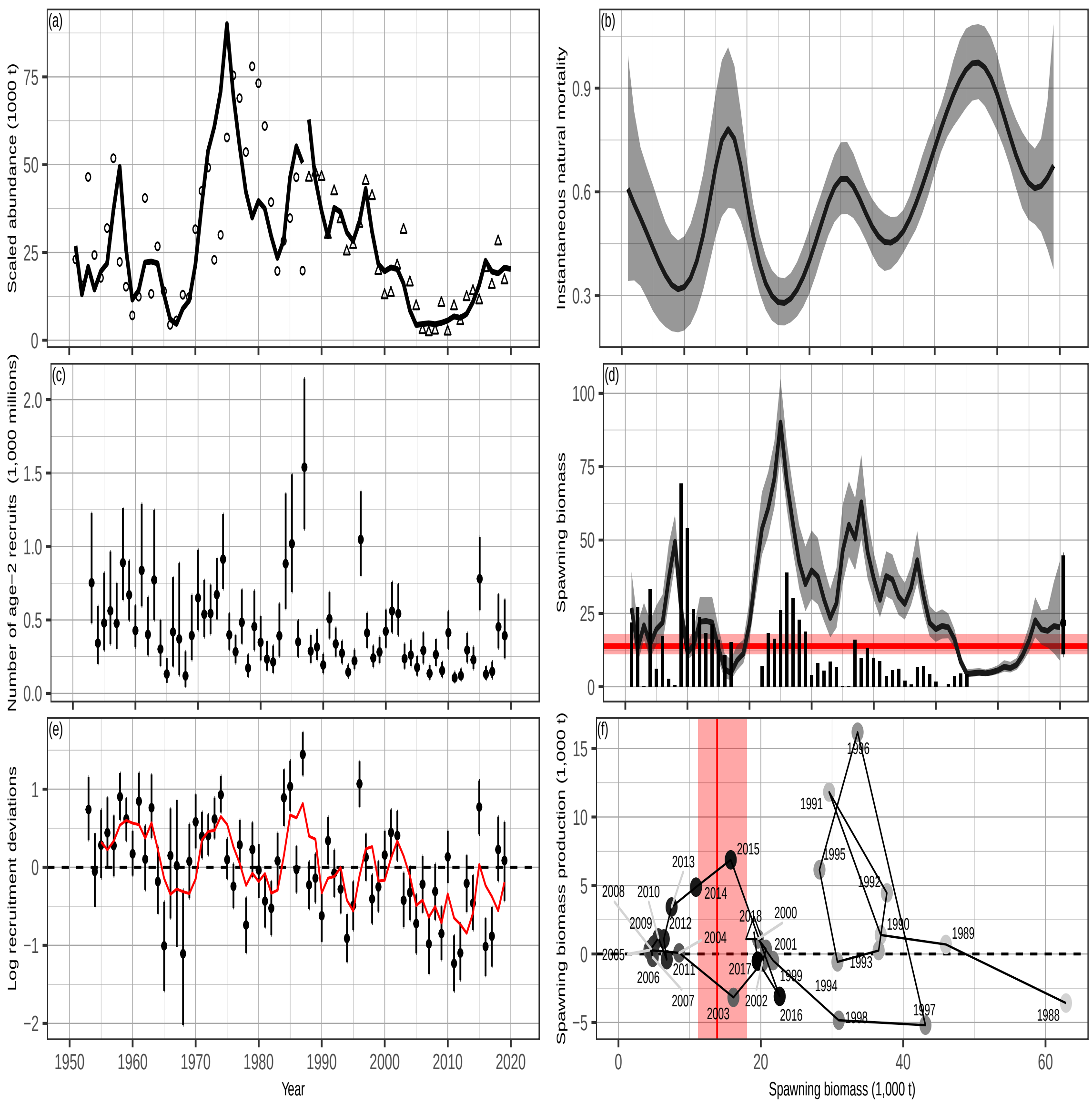

Figure 10. Model output for Pacific Herring in the West Coast Vancouver Island major stock assessment region. See Figure 6 for description.

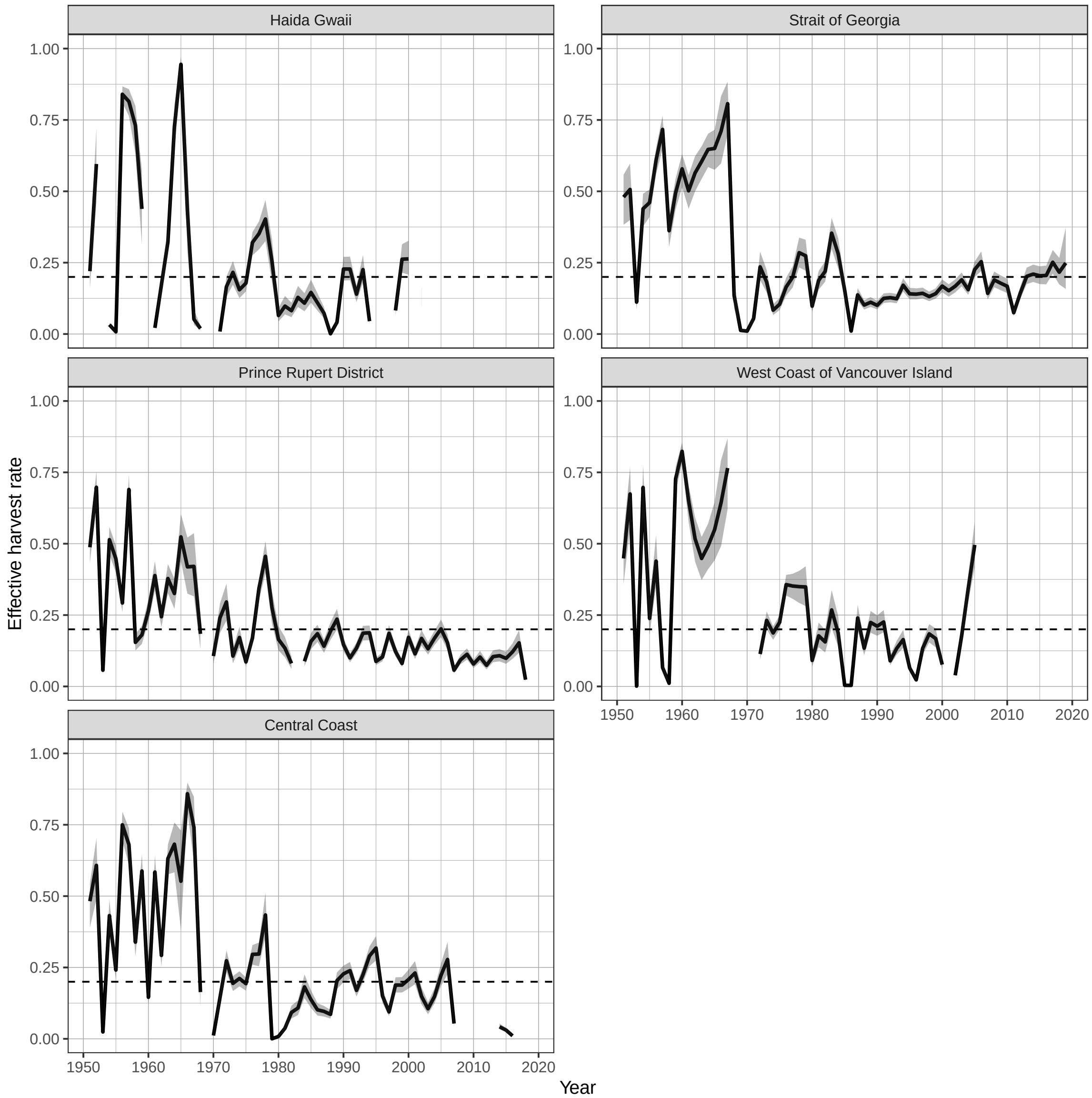

Figure 11. Time series of effective harvest rate for Pacific Herring from 1951 to 2019 in the major stock assessment regions. Effective harvest rate in year t, U_t is calculated as $U_t = C_t/(C_t + SB_t)$ where C_t is catch in year t, and SB_t is estimated spawning biomass in year t. Black lines indicate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

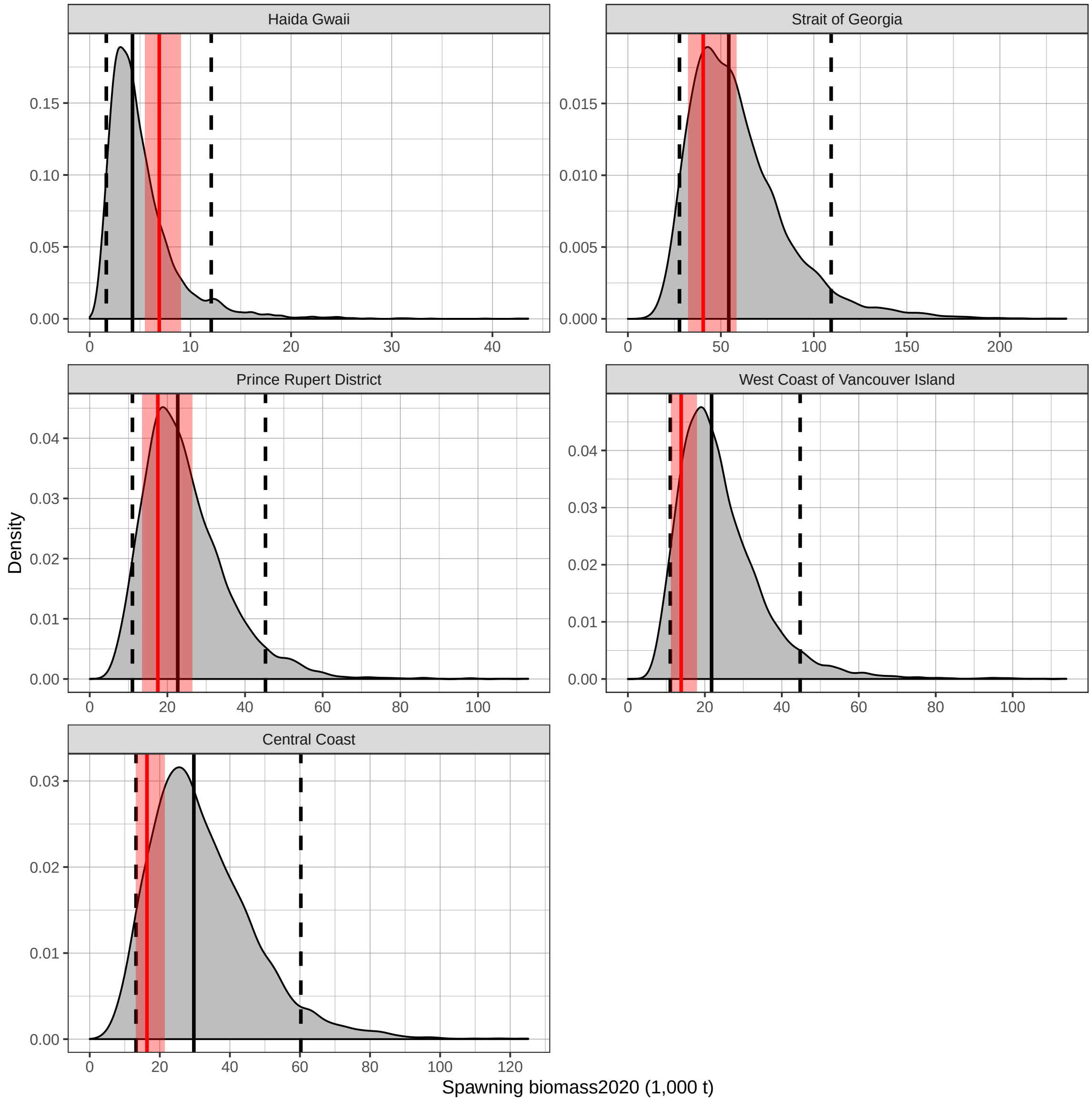

Figure 12. Projected spawning biomass assuming no fishing in 2020 SB_{2020} in thousands of tonnes for Pacific Herring in the major stock assessment regions. Vertical black lines indicate medians (solid) and 90% confdence intervals (dashed) for SB_{2020}. Vertical red lines indicate medians, and shaded red rectangles indicate 90% confdence intervals for the limit reference point, $0.3SB_0$, where SB_0 is estimated unfshed biomass.

Contributors

Name	Affiliation
Jaclyn Cleary	DFO Science, Pacific Region
Matthew Grinnell	DFO Science, Pacific Region
Sarah Hawkshaw	DFO Science, Pacific Region
Allen Kronlund	DFO Science, National Capital Region
Chris Grandin	DFO Science, Pacific Region

Name	Affiliation
Herring Technical Working Group	Various (contributions to First Nations observations)
Roger Kanno	DFO Fisheries Management, Pacific Region (reviewer)
Lesley MacDougall	DFO Centre for Science Advice, Pacific Region (editor)

Approved by

Carmel Lowe
Regional Director
Science Branch, Pacific Region
Fisheries and Oceans Canada
Science Branch, Pacific Region
Fisheries and Oceans Canada
September 30, 2019

Sources of information

Optional for regular Science Responses, and mandatory for Stock Status Updates as these must include the citation for the peer-reviewed Science Advisory Report.

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Appendix

We do not conduct formal analyses of stock trend information for the two Pacific Herring minor SARs (Area 27 (A27) and Area 2 West (A2W)).

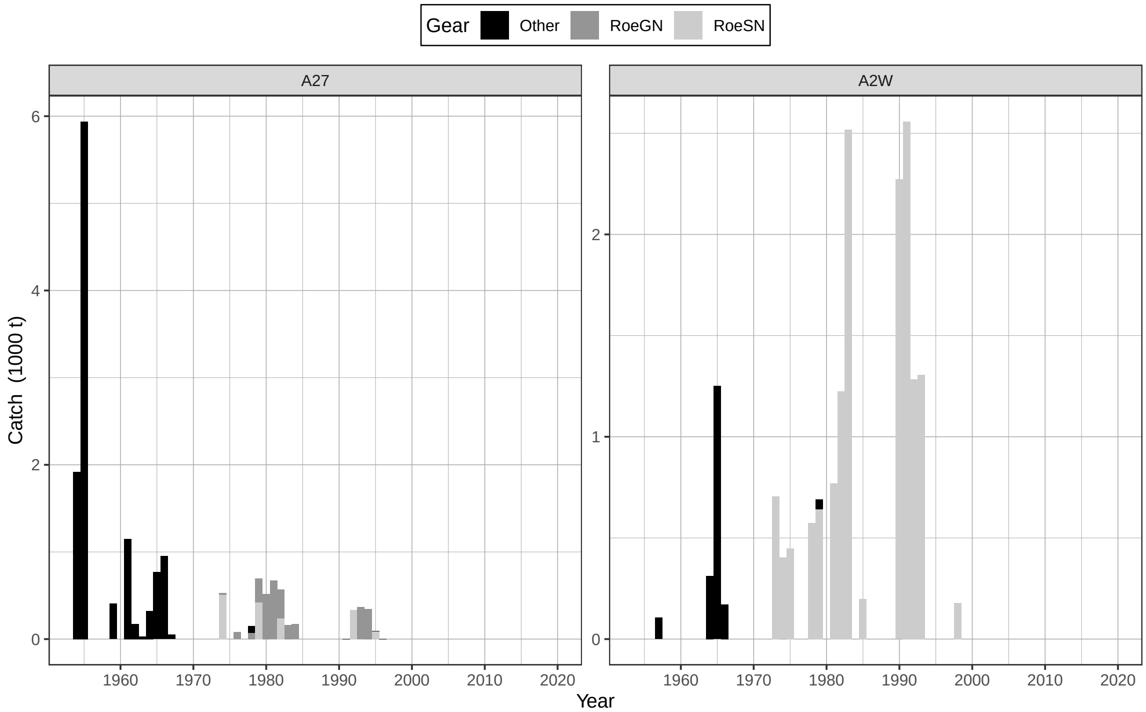

Figure 13. Time series of total landed catch in thousands of tonnes of Pacific Herring from 1977 to 2020 in the minor stock assessment regions. Legend: 'Other' represents the reduction, the food and bait, as well as the special use fishery; 'RoeGN' represents the roe gillnet fshery; and 'RoeSN' represents the roe seine fishery.

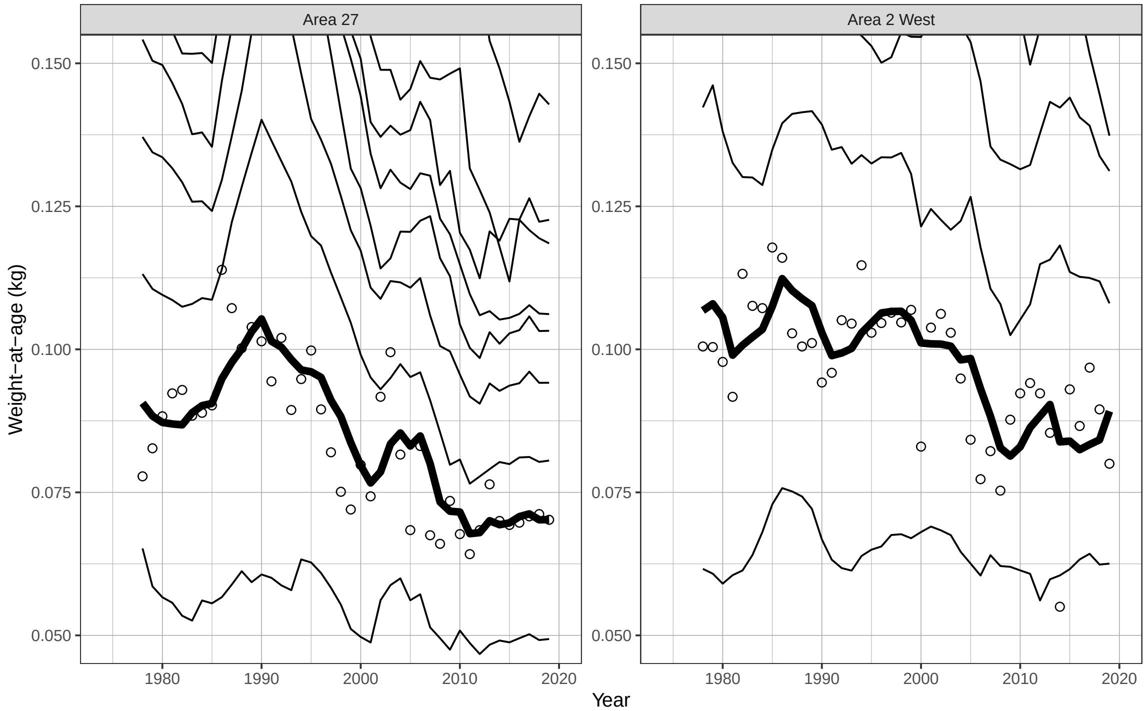

Figure 14. Time series of weight-at-age in kilograms (kg) for age-3 (circles) and 5-year running mean weight-at-age (lines) for Pacific Herring from 1978 to 2018 in the minor stock assessment regions. Lines show 5-year running means for age-2 to age-10 herring (incrementing higher from the lowest line); 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 frst non-missing value backwards; other missing values are imputed as the mean of the previous 5 years. Biological summaries only include samples collected using seine nets (commercial and test) due to size-selectivity of other gear types such as gillnet. The age-10 class is a 'plus group' which includes fsh ages 10 and older. Note that vertical axes are cropped at 0.05 and 0.15 kg.

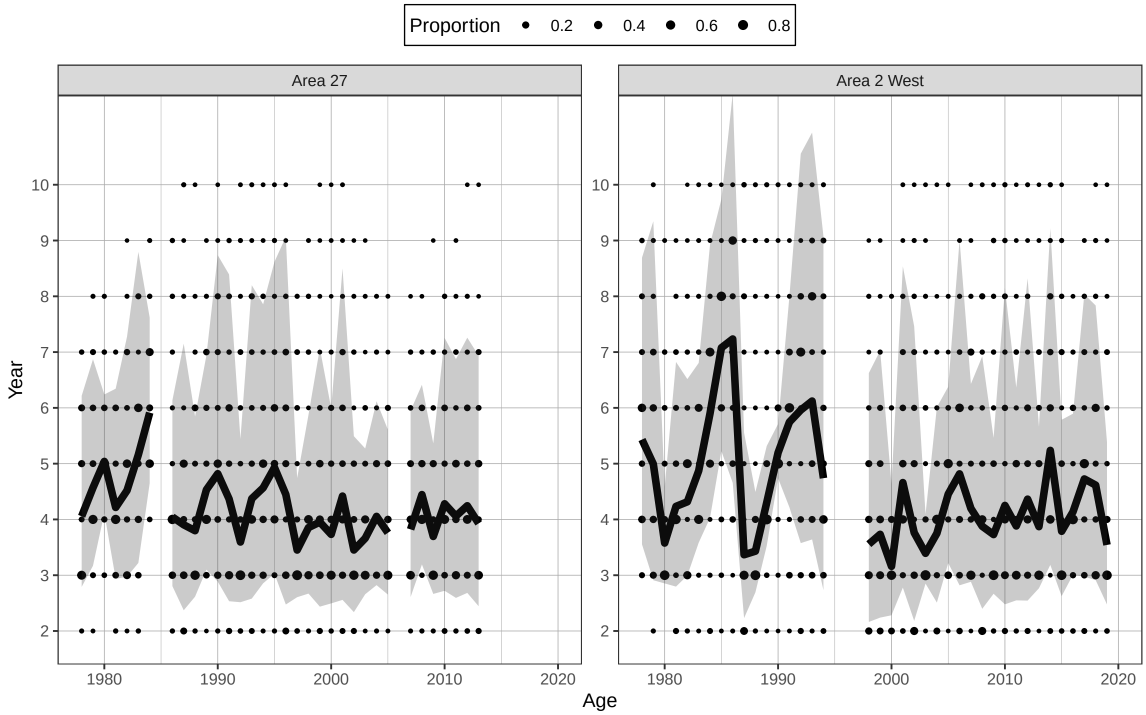

Figure 15. Time series of proportion-at-age for Pacific Herring from 1978 to 2018 in the minor stock assessment regions. The black line is the mean age, and the shaded area is the approximate 90% distribution. Biological summaries only include samples collected using seine nets (commercial and test) 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.

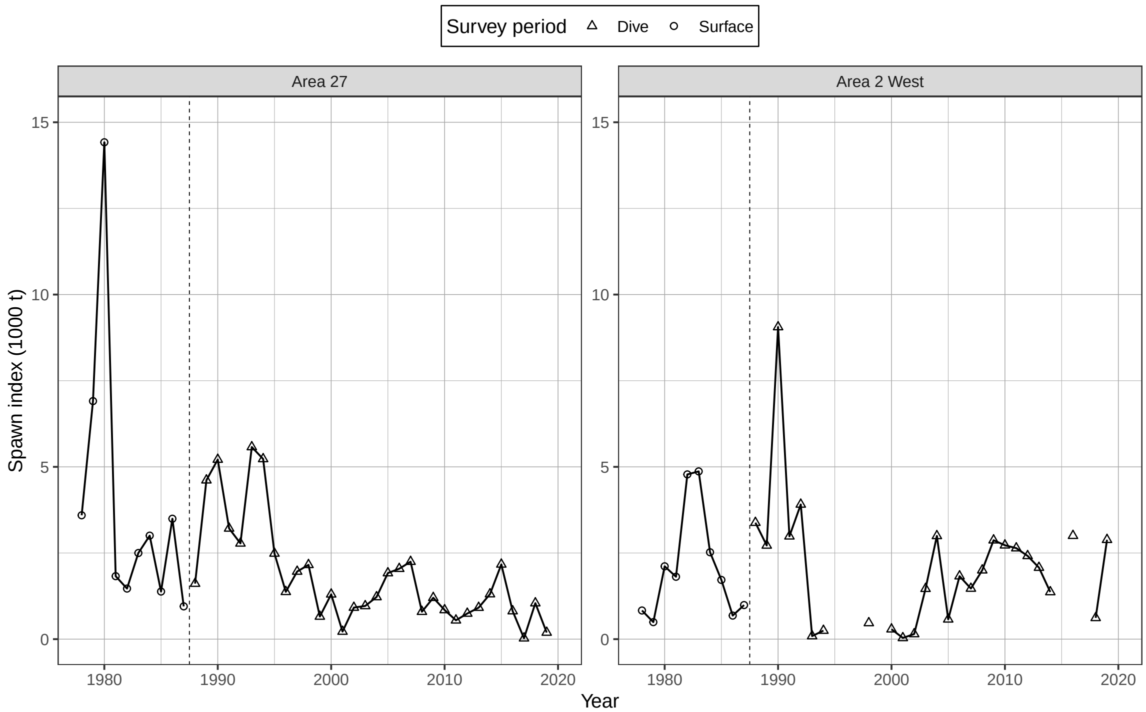

Figure 16. Time series of spawn index in thousands of tonnes for Pacific Herring from 1978 to 2018 in the minor stock assessment regions. The spawn index has two distinct periods defned by the dominant survey method: surface surveys (1951 to 1987), and dive surveys (1988 to 2018). The dashed vertical 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.

MCMC Diagnostics for the Haida Gwaii iSCAM model

These tables and figures will not be included in the final Science Response.

Table 17. Posterior (5th percentile, Median, and 95th percentile) and MPD estimates of key parameters from the Haida Gwaii AM2 model. Subscripts on q (catchability) indicate: 1 = Surface survey, 2 = Dive survey. Tau (τ) and sigma (σ) are calculated values.

Parameter	5%	50%	95%	MPD
R_0	214.213	282.255	388.892	286.689
$Steepness(h)$	0.653	0.785	0.897	0.805
M	0.232	0.407	0.691	0.378
$\overline{R}$	147.730	175.516	210.283	184.859
$\overline{R}_{init}$	9.336	30.229	152.760	33.545
ρ	0.213	0.276	0.348	0.263
ϑ	0.777	0.941	1.133	1.010
q_1	0.332	0.404	0.483	0.394
q_2	0.983	0.999	1.016	0.999
τ	0.785	0.874	0.983	0.854
σ	0.473	0.541	0.619	0.510

Table 18. Posterior (5th percentile, Median, and 95th percentile) and MPD estimates of spawning biomass (1000 t) and relative spawning biomass for the Haida Gwaii AM2 model.

	Spawning Biomass				Depletion (SB_t/SB_0)			
Year	5%	50%	95%	MPD	5%	50%	95%	MPD
2007	4.249	5.652	7.546	5.661	0.164	0.244	0.359	0.255
2008	4.293	5.565	7.206	5.573	0.165	0.241	0.344	0.251
2009	5.152	6.698	8.698	6.722	0.197	0.289	0.414	0.303
2010	5.559	7.172	9.300	7.197	0.212	0.312	0.442	0.324
2011	5.684	7.471	9.833	7.515	0.217	0.326	0.467	0.339
2012	8.004	10.517	13.888	10.641	0.305	0.456	0.655	0.480
2013	11.052	14.695	19.708	14.906	0.421	0.636	0.919	0.672
2014	7.929	10.523	14.073	10.659	0.304	0.456	0.662	0.480
2015	5.100	6.958	9.478	7.000	0.199	0.300	0.448	0.315
2016	3.591	4.997	6.947	4.962	0.141	0.216	0.328	0.224
2017	3.946	5.566	7.870	5.459	0.157	0.241	0.365	0.246
2018	3.042	4.723	7.108	4.513	0.125	0.204	0.322	0.203
2019	3.547	6.944	12.692	6.774	0.151	0.300	0.551	0.305

Table 19. Posterior (5$^{\text{th}}$ percentile, Median, and 95$^{\text{th}}$ percentile) and MPD estimates of recruitment (millions) for the Haida Gwaii AM2 model.

Year	5%	50%	95%	MPD
2007	44.793	67.713	103.643	69.766
2008	216.097	309.968	444.223	319.581
2009	37.277	58.139	87.547	59.193
2010	159.877	229.203	323.635	235.962
2011	104.409	153.330	220.953	158.247
2012	433.086	612.216	855.475	632.460
2013	56.839	83.278	124.136	86.120
2014	89.535	131.960	194.217	136.618
2015	62.916	91.946	137.827	95.481
2016	129.700	195.657	293.755	200.962
2017	171.114	260.946	406.006	272.393
2018	32.633	60.115	112.755	59.602
2019	443.032	851.959	1,511.970	905.908

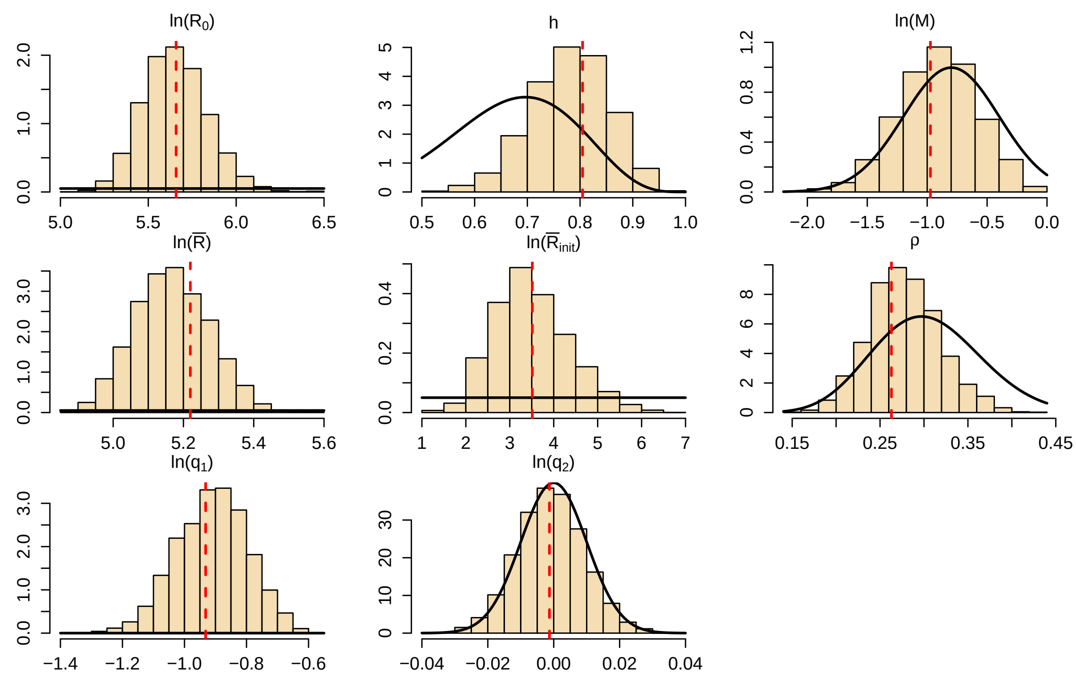

Figure 17. Prior probability distributions (lines) with comparative posterior histograms (bars) used in the Haida Gwaii AM2 model. Parameters q_k represent gears where: $k = 1$ is the surface survey and $k = 2$ is the dive survey. The dotted red lines are the MPD estimates.

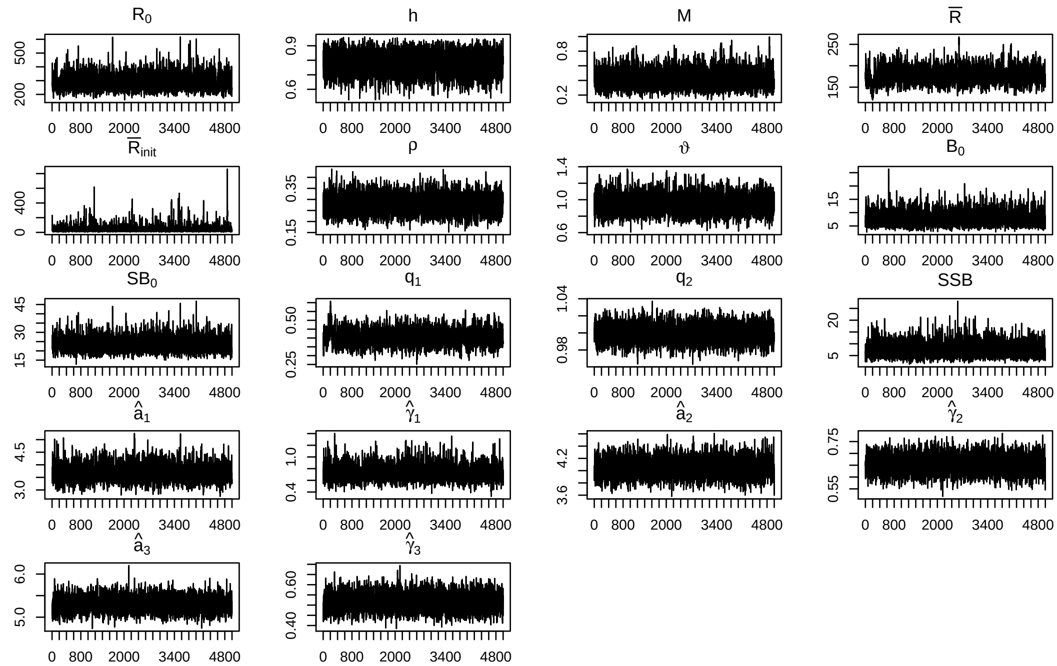

Figure 18. Trace plots for MCMC output of estimated parameters for the Haida Gwaii AM2 model. The MCMC run had chain length 5 million with a sample taken at every 1,000th iteration. The catchability parameter q_1 represents the surface survey and q_2 the dive survey. Parameters $\hat{a}_k$ (selectivity-at-age-50%), and $\hat{\gamma}_k$ (selectivity standard deviation-at-50%) represent gears as follows: $k = 1$: Other fisheries, $k = 2$: Roe seine, $k = 3$: Gillnet roe.

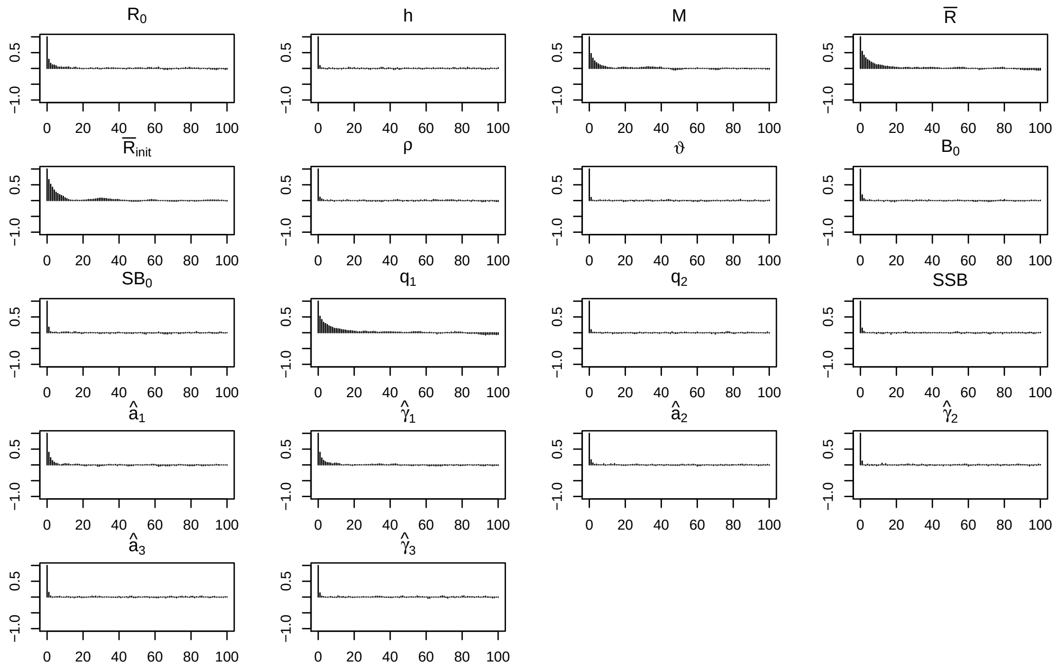

Figure 19. Autocorrelation plots for MCMC output of estimated parameters for the Haida Gwaii AM2 model. See Figure 18 for parameter descriptions.

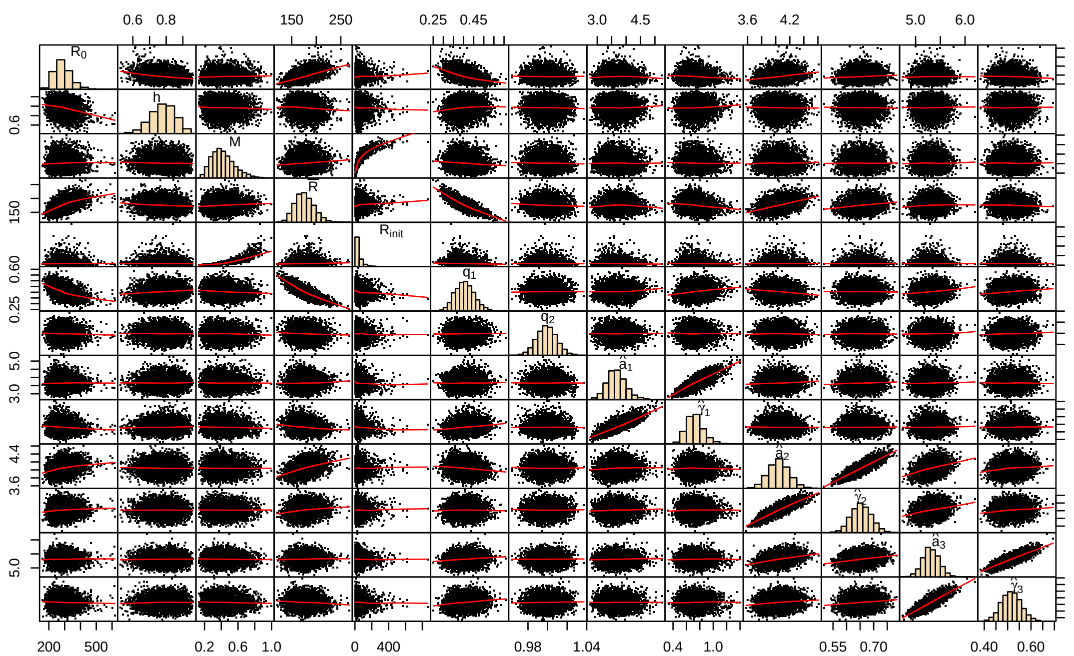

Figure 20. Pairs plots for MCMC output of estimated parameters in for the Haida Gwaii AM2 model. See Figure 18 for parameter descriptions.

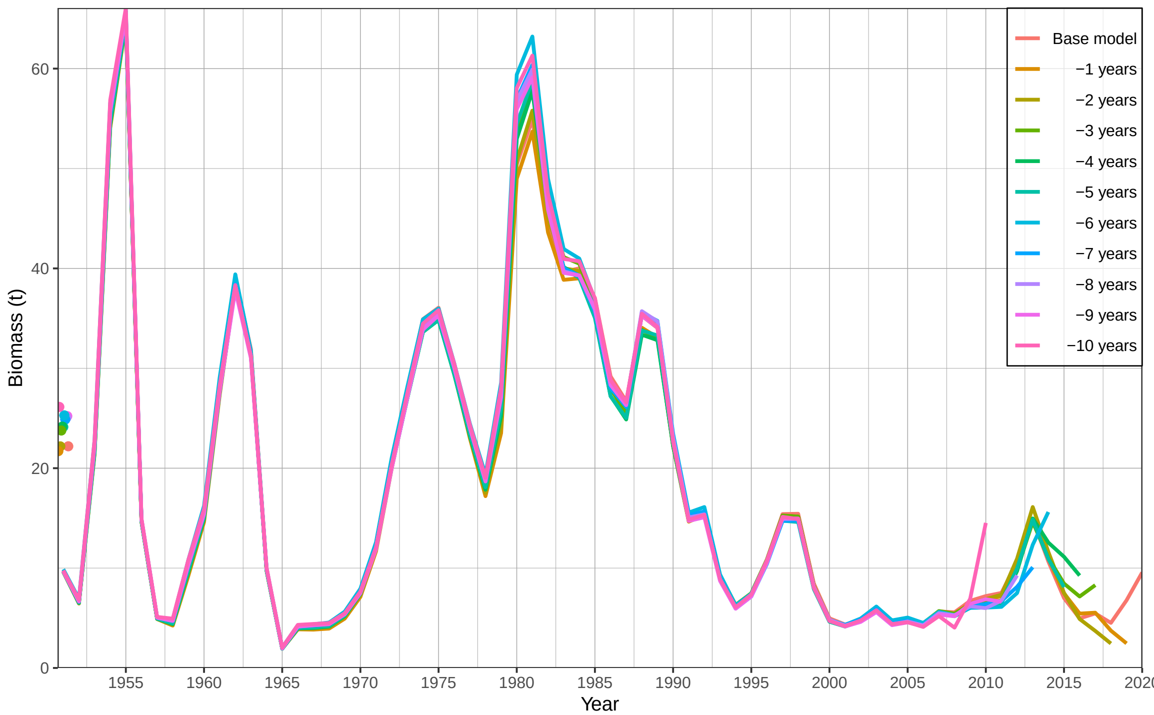

Figure 21. MPD biomass with retrospectivces for the Haida Gwaii AM2 model.

MCMC Diagnostics for the Prince Rupert District iSCAM model

These tables and figures will not be included in the final Science Response.

Table 20. Posterior (5th percentile, Median, and 95th percentile) and MPD estimates of key parameters from the Prince Rupert District AM2 model. Subscripts on q (catchability) indicate: 1 = Surface survey, 2 = Dive survey. Tau (τ) and sigma (σ) are calculated values.

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

Table 21. Posterior (5th percentile, Median, and 95th percentile) and MPD estimates of spawning biomass (1000 t) and relative spawning biomass for the Prince Rupert District AM2 model.

	Spawning Biomass				Depletion (SB_t/SB_0)			
Year	5%	50%	95%	MPD	5%	50%	95%	MPD
2007	13.083	16.105	19.820	16.163	0.174	0.273	0.383	0.293
2008	13.276	16.150	19.736	16.262	0.175	0.274	0.383	0.294
2009	12.980	15.739	19.244	15.868	0.170	0.267	0.375	0.287
2010	14.353	17.441	21.479	17.684	0.187	0.296	0.421	0.320
2011	15.087	18.687	23.405	18.984	0.196	0.318	0.458	0.344
2012	13.953	17.343	21.749	17.623	0.183	0.294	0.428	0.319
2013	14.016	17.399	21.850	17.719	0.184	0.295	0.429	0.321
2014	13.325	16.581	20.803	16.796	0.178	0.281	0.404	0.304
2015	15.676	19.827	25.137	20.034	0.212	0.335	0.485	0.363
2016	13.647	17.575	22.600	17.580	0.189	0.296	0.428	0.318
2017	11.622	15.797	21.335	15.614	0.169	0.265	0.392	0.283
2018	11.664	17.298	25.615	17.174	0.175	0.290	0.449	0.311
2019	13.141	23.223	39.807	21.916	0.209	0.389	0.679	0.397

Table 22. Posterior (5th percentile, Median, and 95th percentile) and MPD estimates of recruitment (millions) for the Prince Rupert District AM2 model.

Year	5%	50%	95%	MPD
2007	108.289	149.375	204.165	151.860
2008	106.256	147.712	203.234	150.040
2009	176.089	238.983	323.348	243.716
2010	219.200	296.659	400.947	303.286
2011	118.065	161.916	220.645	166.717
2012	175.448	238.469	326.310	246.435
2013	60.814	87.884	124.700	89.952
2014	323.159	457.885	635.803	470.728
2015	143.415	209.169	298.875	216.055
2016	70.037	110.218	170.547	112.560
2017	206.273	321.840	493.564	324.638
2018	191.466	386.385	668.298	432.165
2019	82.718	370.240	1,702.767	286.319

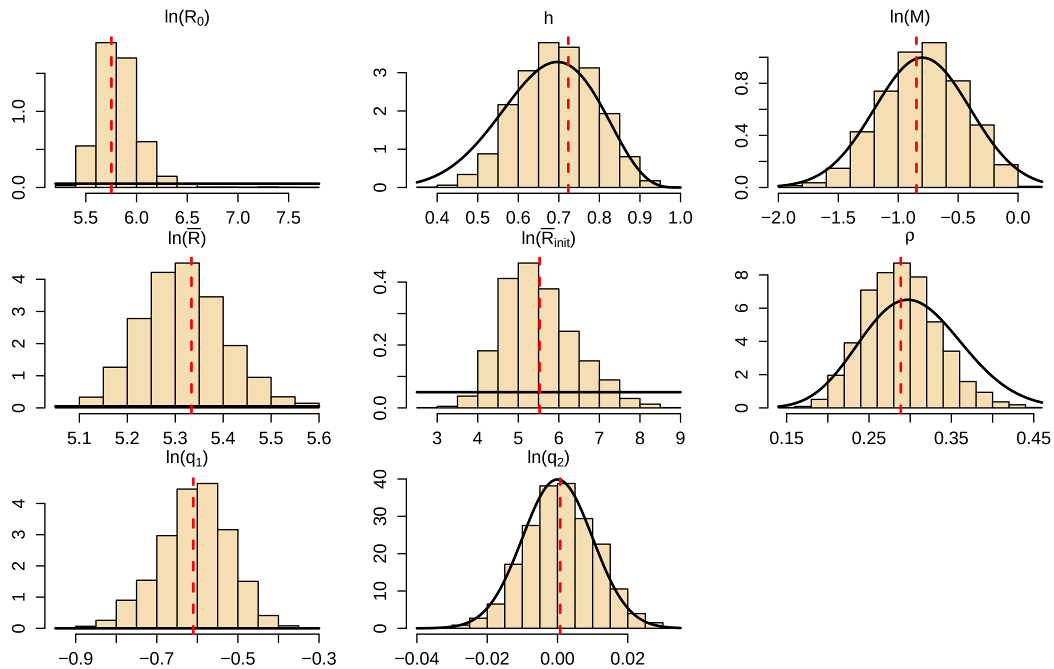

Figure 22. Prior probability distributions (lines) with comparative posterior histograms (bars) used in the Prince Rupert District AM2 model. Parameters q_k represent gears where: $k = 1$ is the surface survey and $k = 2$ is the dive survey. The dotted red lines are the MPD estimates.

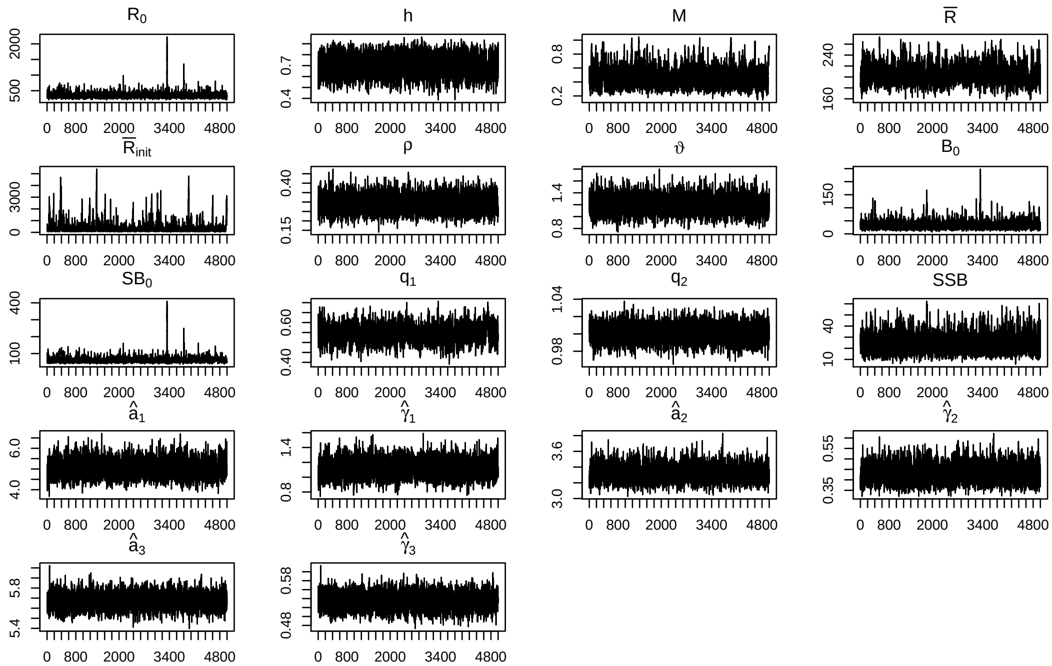

Figure 23. Trace plots for MCMC output of estimated parameters for the Prince Rupert District AM2 model. The MCMC run had chain length 5 million with a sample taken at every 1,000th iteration. The catchability parameter q_1 represents the surface survey and q_2 the dive survey. Parameters $\hat{a}_k$ (selectivity-at-age-50%), and $\hat{\gamma}_k$ (selectivity standard deviation-at-50%) represent gears as follows: $k = 1$: Other fisheries, $k = 2$: Roe seine, $k = 3$: Gillnet roe.

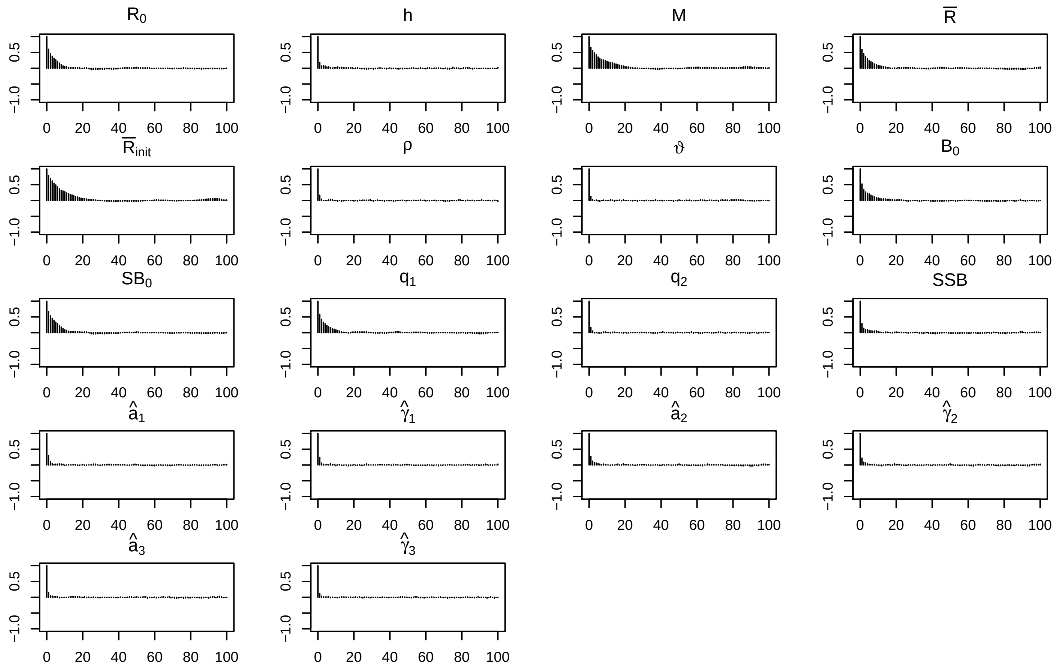

Figure 24. Autocorrelation plots for MCMC output of estimated parameters for the Prince Rupert District AM2 model. See Figure 23 for parameter descriptions.

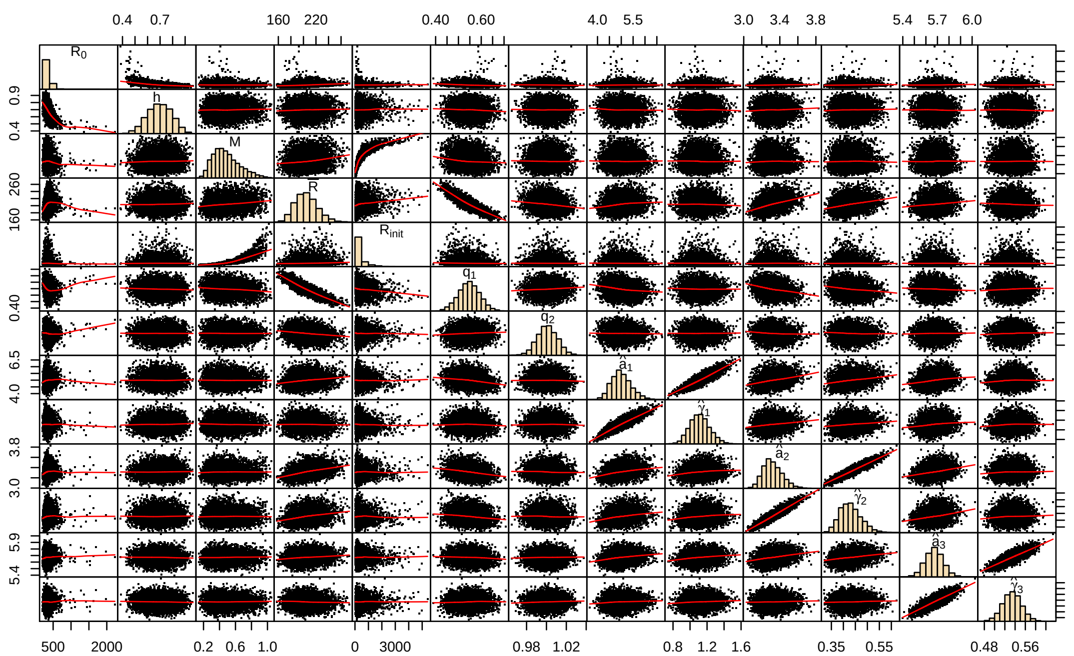

Figure 25. Pairs plots for MCMC output of estimated parameters in for the Prince Rupert District AM2 model. See Figure 23 for parameter descriptions.

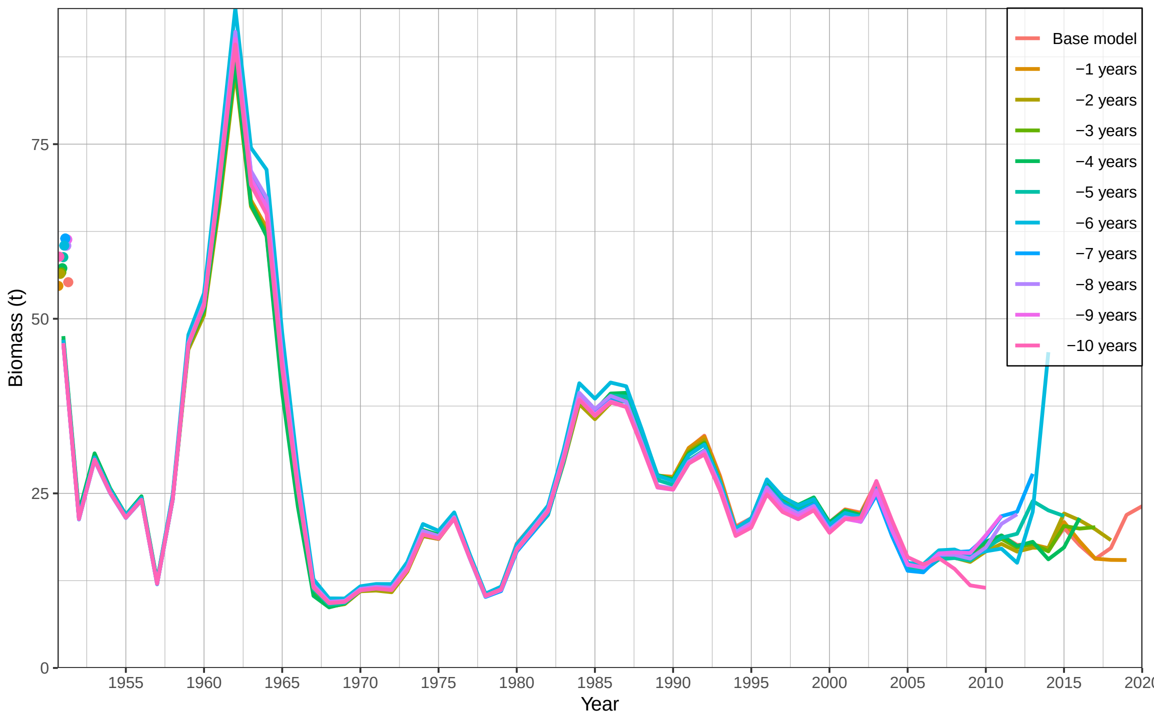

Figure 26. MPD biomass with retrospectivces for the Prince Rupert District AM2 model.

MCMC Diagnostics for the Central Coast iSCAM model

These tables and figures will not be included in the final Science Response.

Table 23. Posterior (5th percentile, Median, and 95th percentile) and MPD estimates of key parameters from the Central Coast AM2 model. Subscripts on q (catchability) indicate: 1 = Surface survey, 2 = Dive survey. Tau (τ) and sigma (σ) are calculated values.

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

Table 24. Posterior (5th percentile, Median, and 95th percentile) and MPD estimates of spawning biomass (1000 t) and relative spawning biomass for the Central Coast AM2 model.

	Spawning Biomass				Depletion (SB_t/SB_0)			
Year	5%	50%	95%	MPD	5%	50%	95%	MPD
2007	5.368	7.035	9.212	7.065	0.089	0.129	0.182	0.136
2008	5.469	6.978	8.862	6.958	0.089	0.128	0.177	0.134
2009	7.803	9.878	12.538	9.856	0.126	0.180	0.251	0.190
2010	8.279	10.386	13.133	10.384	0.134	0.190	0.265	0.200
2011	7.905	9.969	12.863	10.012	0.128	0.183	0.258	0.193
2012	7.411	9.414	12.042	9.432	0.120	0.173	0.241	0.182
2013	11.325	14.482	18.395	14.522	0.184	0.265	0.371	0.280
2014	12.202	15.608	19.805	15.711	0.199	0.284	0.395	0.303
2015	15.497	19.900	25.271	20.149	0.254	0.364	0.510	0.389
2016	15.242	19.759	25.425	20.000	0.254	0.361	0.504	0.386
2017	14.818	19.606	25.611	19.807	0.247	0.358	0.502	0.382
2018	13.439	20.394	29.228	20.899	0.234	0.370	0.558	0.403
2019	19.331	33.366	55.574	31.157	0.347	0.607	1.006	0.601

Table 25. Posterior (5th percentile, Median, and 95th percentile) and MPD estimates of recruitment (millions) for the Central Coast AM2 model.

Year	5%	50%	95%	MPD
2007	80.489	113.195	160.042	114.758
2008	403.253	541.836	728.323	550.870
2009	144.835	192.709	257.127	193.726
2010	299.725	392.849	521.617	396.601
2011	95.862	127.527	168.922	127.975
2012	284.457	376.303	499.604	377.544
2013	115.855	156.750	210.452	157.858
2014	359.592	488.530	653.905	491.897
2015	102.364	141.190	195.382	142.707
2016	123.325	169.719	231.199	171.491
2017	153.978	214.900	298.168	218.072
2018	419.942	749.811	1,160.454	821.712
2019	117.249	653.796	3,258.063	512.493

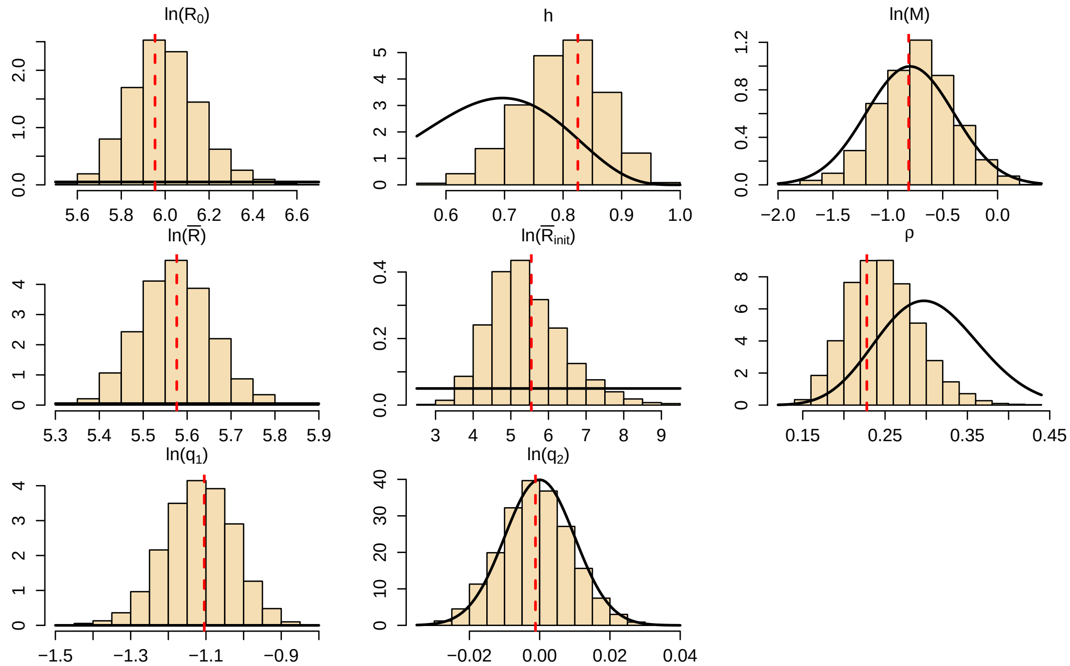

Figure 27. Prior probability distributions (lines) with comparative posterior histograms (bars) used in the Central Coast AM2 model. Parameters q_k represent gears where: $k = 1$ is the surface survey and $k = 2$ is the dive survey. The dotted red lines are the MPD estimates.

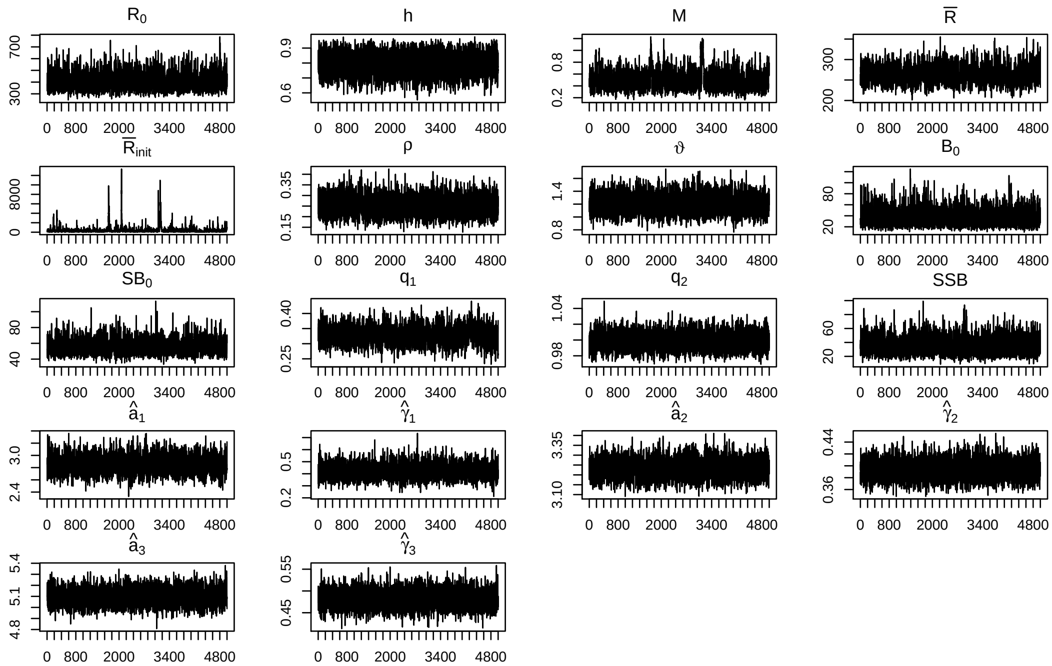

Figure 28. Trace plots for MCMC output of estimated parameters for the Central Coast AM2 model. The MCMC run had chain length 5 million with a sample taken at every 1,000th iteration. The catchability parameter q_1 represents the surface survey and q_2 the dive survey. Parameters $\hat{a}_k$ (selectivity-at-age-50%), and $\hat{\gamma}_k$ (selectivity standard deviation-at-50%) represent gears as follows: $k = 1$: Other fisheries, $k = 2$: Roe seine, $k = 3$: Gillnet roe.

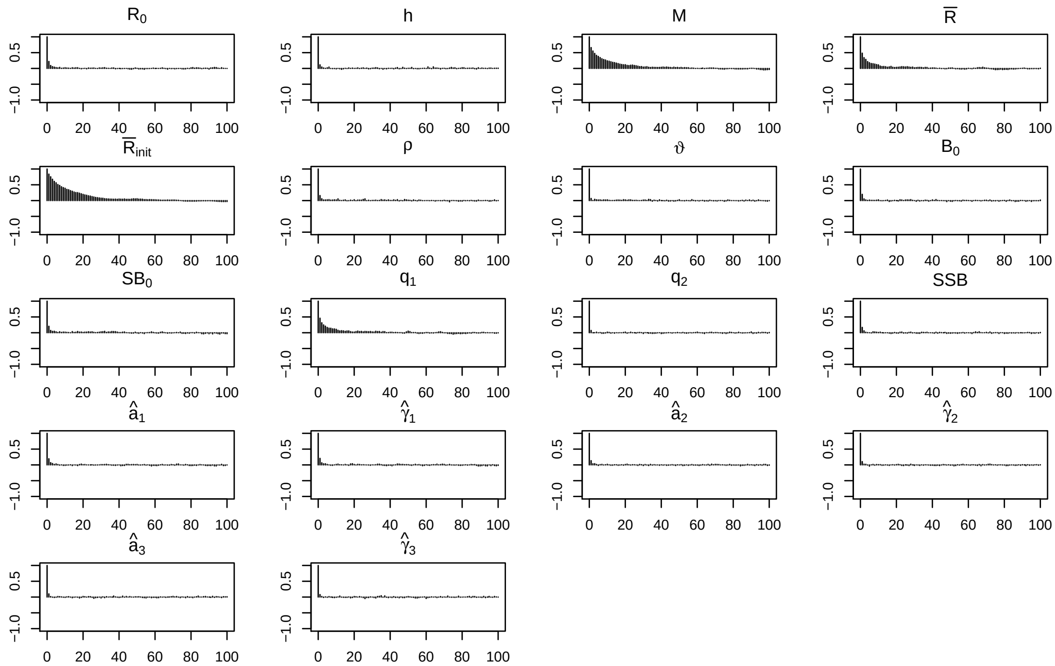

Figure 29. Autocorrelation plots for MCMC output of estimated parameters for the Central Coast AM2 model. See Figure 28 for parameter descriptions.

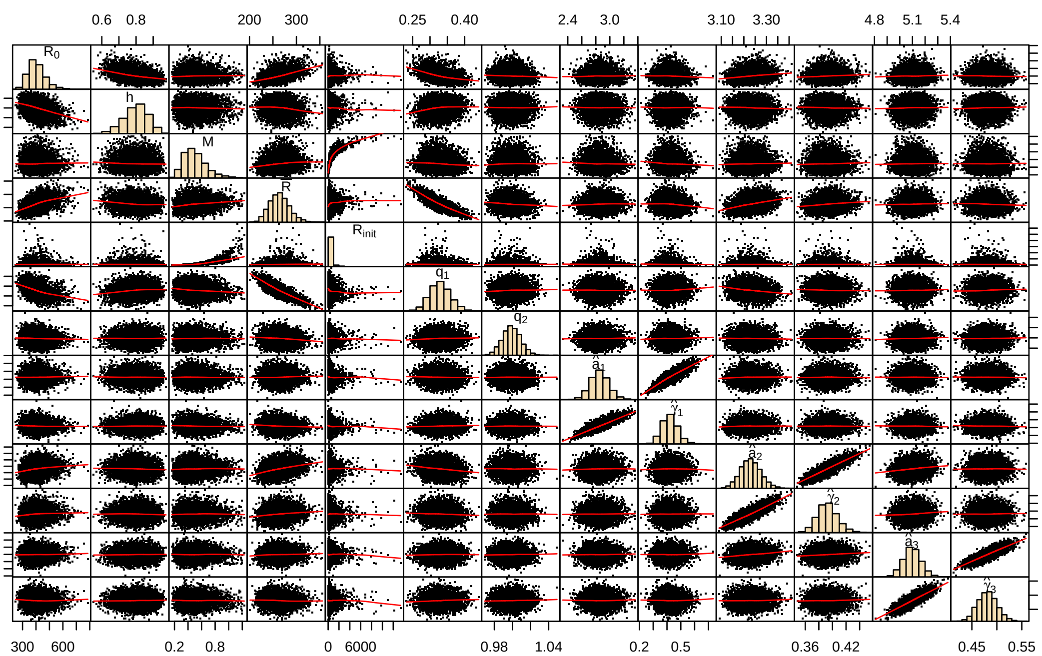

Figure 30. Pairs plots for MCMC output of estimated parameters in for the Central Coast AM2 model. See Figure 28 for parameter descriptions.

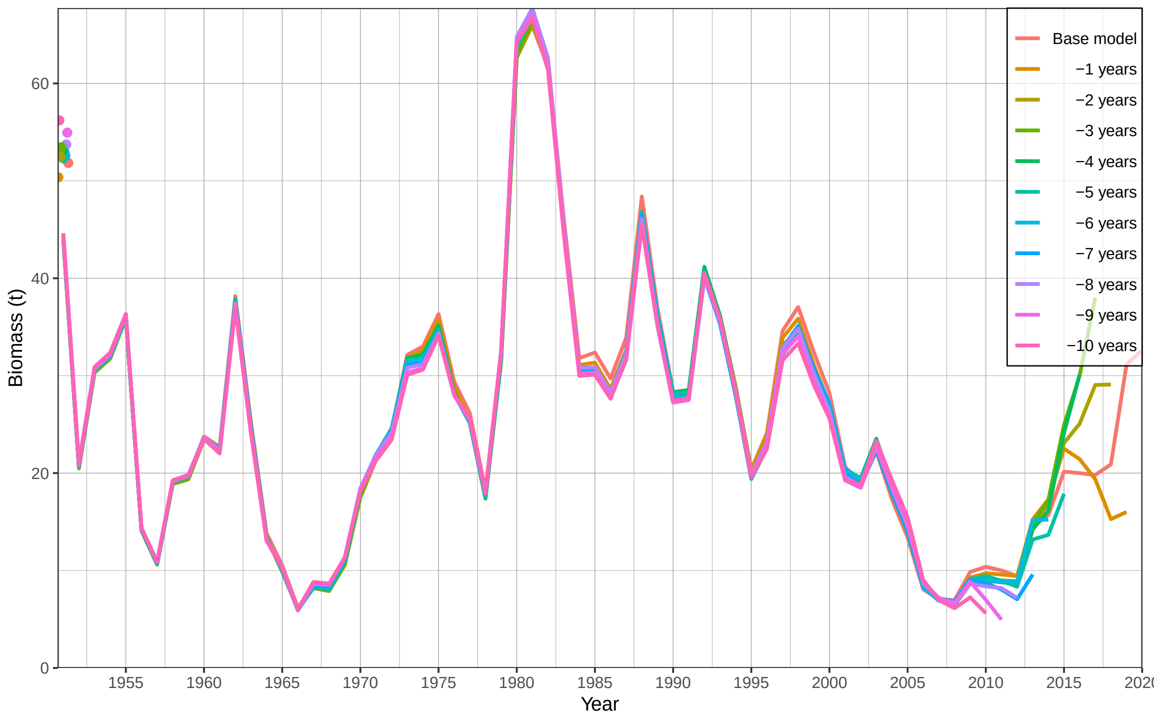

Figure 31. MPD biomass with retrospectivces for the Central Coast AM2 model.

MCMC Diagnostics for the Strait of Georgia iSCAM model

These tables and figures will not be included in the final Science Response.

Table 26. Posterior (5th percentile, Median, and 95th percentile) and MPD estimates of key parameters from the Strait of Georgia AM2 model. Subscripts on q (catchability) indicate: 1 = Surface survey, 2 = Dive survey. Tau (τ) and sigma (σ) are calculated values.

Parameter	5%	50%	95%	MPD
R_0	1,328.439	1,664.650	2,199.741	1,600.890
$Steepness(h)$	0.579	0.732	0.869	0.766
M	0.277	0.471	0.780	0.454
$\overline{R}$	959.310	1,097.640	1,264.671	1,123.560
$\overline{R}_{init}$	44.678	157.274	877.153	276.953
ρ	0.208	0.282	0.365	0.270
ϑ	1.234	1.508	1.830	1.609
q_1	0.856	1.013	1.183	1.004
q_2	0.983	1.000	1.016	0.999
τ	0.609	0.689	0.782	0.673
σ	0.370	0.431	0.502	0.410

Table 27. Posterior (5th percentile, Median, and 95th percentile) and MPD estimates of spawning biomass (1000 t) and relative spawning biomass for the Strait of Georgia AM2 model.

	Spawning Biomass				Depletion (SB_t/SB_0)			
Year	5%	50%	95%	MPD	5%	50%	95%	MPD
2007	51.378	61.550	73.976	61.644	0.302	0.454	0.615	0.480
2008	35.721	42.718	51.060	42.670	0.210	0.315	0.427	0.332
2009	39.353	46.957	56.131	46.990	0.232	0.347	0.466	0.366
2010	34.595	41.404	49.719	41.430	0.204	0.306	0.411	0.322
2011	53.280	63.626	76.347	63.855	0.314	0.470	0.630	0.497
2012	57.126	68.091	81.434	68.410	0.338	0.500	0.676	0.532
2013	54.555	65.310	78.065	65.872	0.322	0.480	0.652	0.513
2014	63.208	76.417	91.031	77.442	0.378	0.562	0.762	0.603
2015	64.167	77.852	94.071	79.370	0.385	0.572	0.779	0.618
2016	67.616	82.579	101.168	84.360	0.410	0.607	0.833	0.657
2017	60.551	75.216	94.232	76.263	0.377	0.552	0.762	0.594
2018	52.418	68.987	90.716	67.909	0.337	0.505	0.710	0.529
2019	36.009	64.662	114.166	61.135	0.249	0.465	0.853	0.476

Table 28. Posterior (5th percentile, Median, and 95th percentile) and MPD estimates of recruitment (millions) for the Strait of Georgia AM2 model.

Year	5%	50%	95%	MPD
2007	403.447	536.988	701.858	543.343
2008	1,484.594	1,948.375	2,540.092	1,976.960
2009	294.900	387.611	510.177	388.793
2010	1,881.941	2,389.135	3,039.881	2,408.400
2011	1,115.856	1,439.865	1,831.430	1,449.190
2012	616.444	799.090	1,037.957	812.841
2013	1,115.578	1,445.080	1,851.830	1,468.570
2014	1,216.730	1,594.055	2,057.289	1,627.350
2015	1,077.640	1,442.365	1,873.591	1,479.830
2016	1,007.755	1,374.365	1,838.464	1,426.570
2017	1,125.646	1,554.050	2,118.817	1,609.600
2018	1,072.075	1,487.190	2,085.024	1,528.920
2019	2,812.508	4,167.295	6,205.622	4,210.040

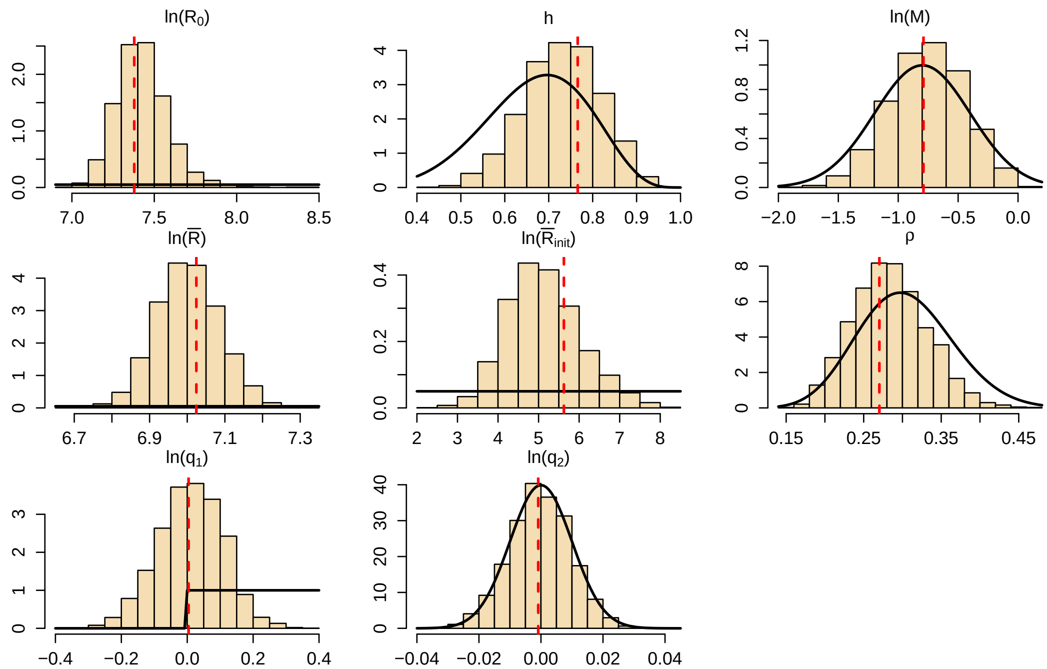

Figure 32. Prior probability distributions (lines) with comparative posterior histograms (bars) used in the Strait of Georgia AM2 model. Parameters q_k represent gears where: $k = 1$ is the surface survey and $k = 2$ is the dive survey. The dotted red lines are the MPD estimates.

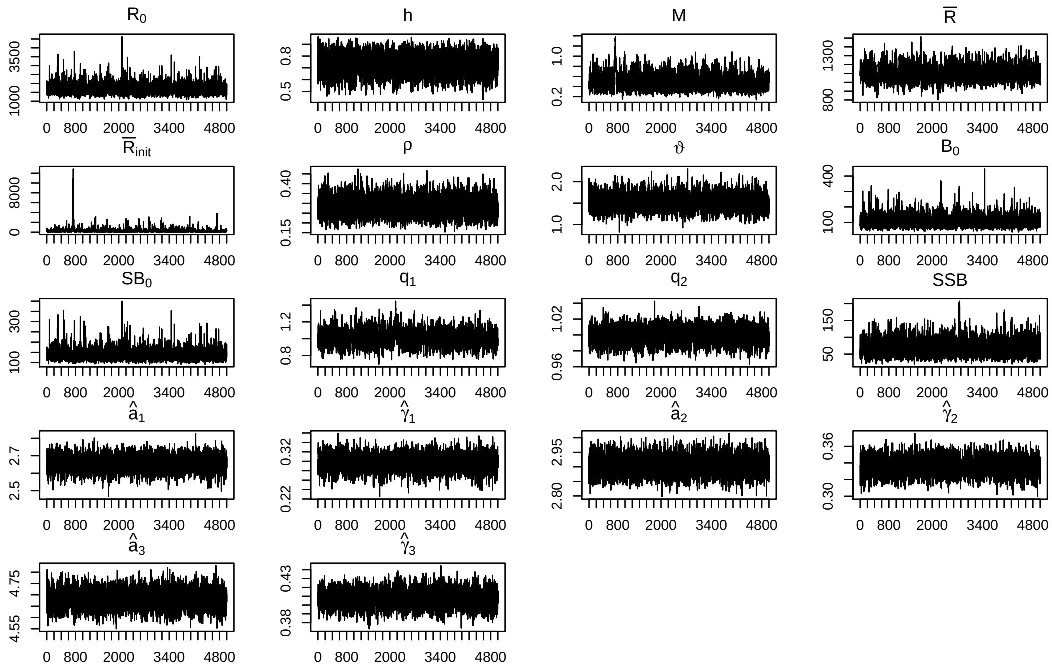

Figure 33. Trace plots for MCMC output of estimated parameters for the Strait of Georgia AM2 model. The MCMC run had chain length 5 million with a sample taken at every 1,000th iteration. The catchability parameter q_1 represents the surface survey and q_2 the dive survey. Parameters $\hat{a}_k$ (selectivity-at-age-50%), and $\hat{\gamma}_k$ (selectivity standard deviation-at-50%) represent gears as follows: $k = 1$: Other fisheries, $k = 2$: Roe seine, $k = 3$: Gillnet roe.

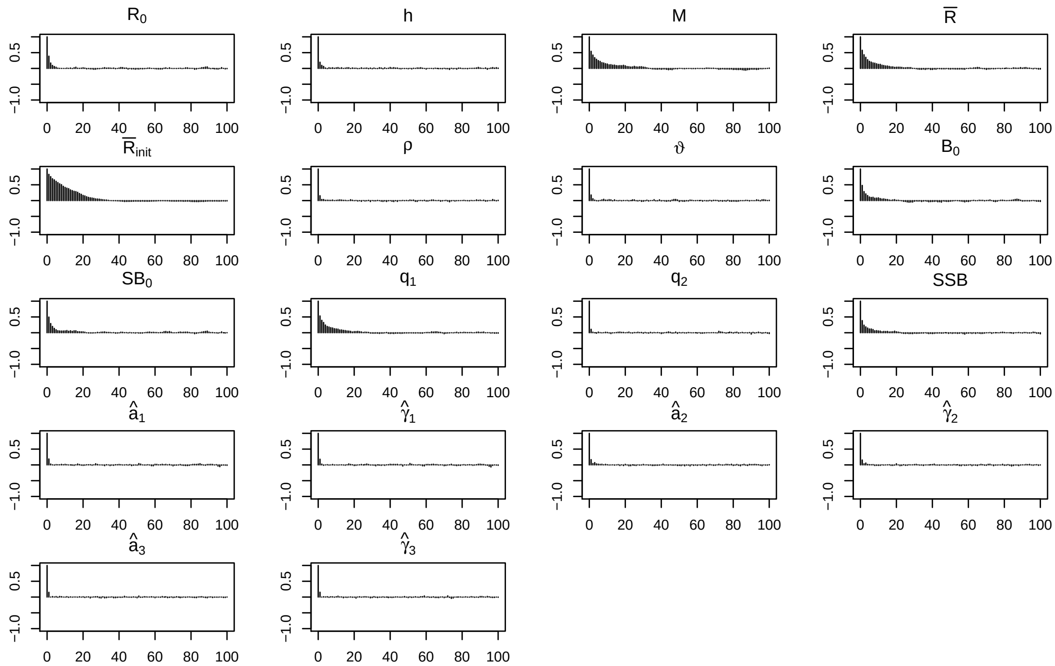

Figure 34. Autocorrelation plots for MCMC output of estimated parameters for the Strait of Georgia AM2 model. See Figure 33 for parameter descriptions.

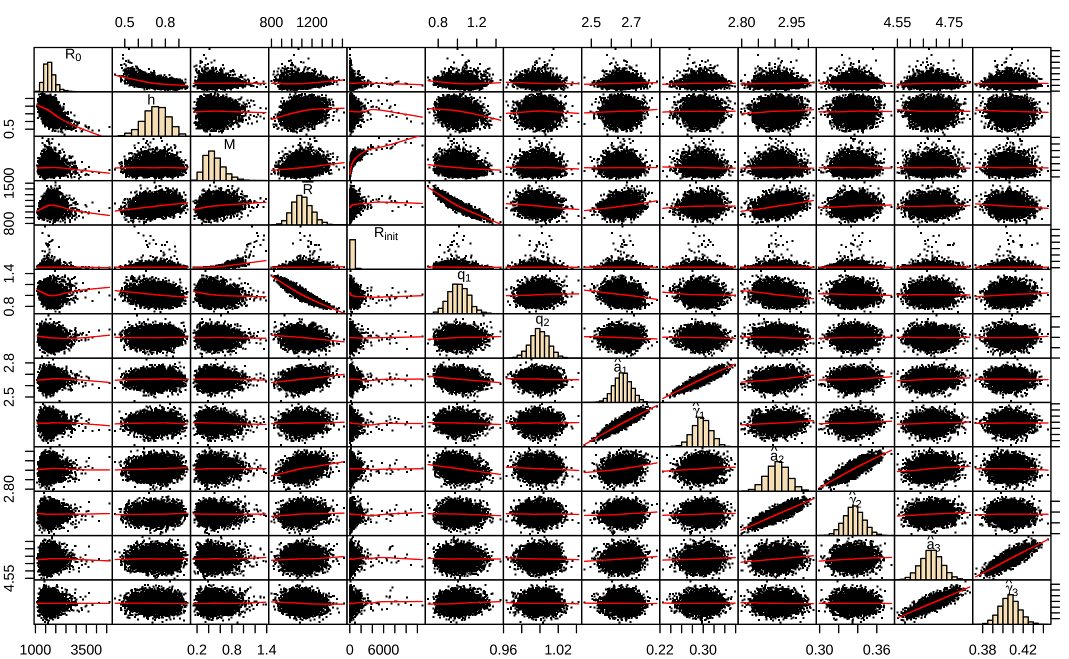

Figure 35. Pairs plots for MCMC output of estimated parameters in for the Strait of Georgia AM2 model. See Figure 33 for parameter descriptions.

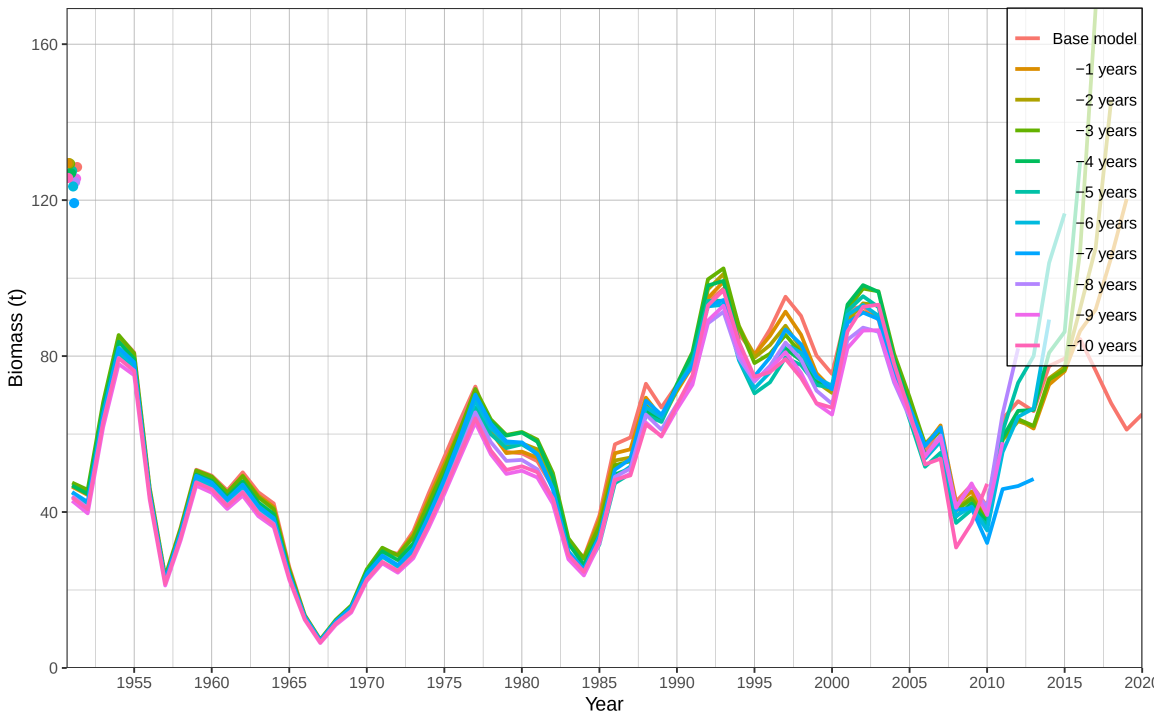

Figure 36. MPD biomass with retrospectivces for the Strait of Georgia AM2 model.

MCMC Diagnostics for the West Coast Vancouver Island iSCAM model

These tables and figures will not be included in the final Science Response.

Table 29. Posterior (5th percentile, Median, and 95th percentile) and MPD estimates of key parameters from the West Coast Vancouver Island AM2 model. Subscripts on q (catchability) indicate: 1 = Surface survey, 2 = Dive survey. Tau (τ) and sigma (σ) are calculated values.

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

Table 30. Posterior (5th percentile, Median, and 95th percentile) and MPD estimates of spawning biomass (1000 t) and relative spawning biomass for the West Coast Vancouver Island AM2 model.

	Spawning Biomass				Depletion (SB_t/SB_0)			
Year	5%	50%	95%	MPD	5%	50%	95%	MPD
2007	3.652	4.815	6.350	4.796	0.070	0.103	0.149	0.107
2008	3.533	4.566	5.909	4.542	0.068	0.098	0.140	0.101
2009	3.811	4.952	6.446	4.941	0.073	0.107	0.153	0.110
2010	4.336	5.614	7.338	5.622	0.082	0.121	0.175	0.125
2011	5.120	6.781	9.039	6.843	0.099	0.147	0.214	0.152
2012	4.847	6.366	8.492	6.427	0.093	0.137	0.199	0.143
2013	5.781	7.461	9.769	7.557	0.110	0.162	0.231	0.168
2014	8.370	10.891	14.265	11.092	0.158	0.237	0.335	0.247
2015	11.925	15.771	20.871	16.070	0.231	0.341	0.488	0.357
2016	16.836	22.646	30.510	22.974	0.330	0.491	0.701	0.511
2017	14.366	19.553	26.019	19.348	0.288	0.420	0.598	0.430
2018	13.353	19.033	26.478	18.381	0.274	0.408	0.600	0.409
2019	11.411	20.664	35.721	19.508	0.240	0.442	0.785	0.434

Table 31. Posterior (5th percentile, Median, and 95th percentile) and MPD estimates of recruitment (millions) for the West Coast Vancouver Island AM2 model.

Year	5%	50%	95%	MPD
2007	93.016	136.052	194.189	137.014
2008	187.149	264.649	369.372	267.489
2009	112.297	154.941	213.064	156.619
2010	304.796	413.067	558.377	416.556
2011	75.578	105.579	147.057	106.085
2012	87.815	120.862	169.683	122.166
2013	210.432	294.567	411.598	299.915
2014	164.714	228.627	318.033	234.233
2015	565.807	779.876	1,066.291	802.950
2016	93.061	130.252	184.238	133.440
2017	103.574	148.726	216.291	150.897
2018	306.436	453.153	674.291	456.145
2019	238.389	392.723	639.705	389.914

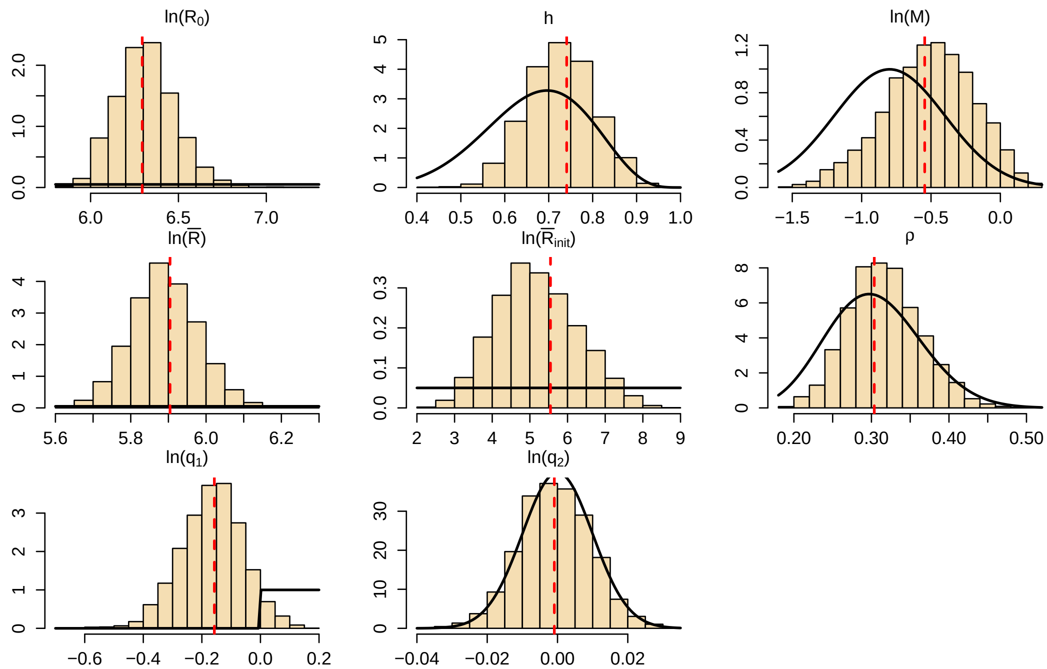

Figure 37. Prior probability distributions (lines) with comparative posterior histograms (bars) used in the West Coast Vancouver Island AM2 model. Parameters q_k represent gears where: $k = 1$ is the surface survey and $k = 2$ is the dive survey. The dotted red lines are the MPD estimates.

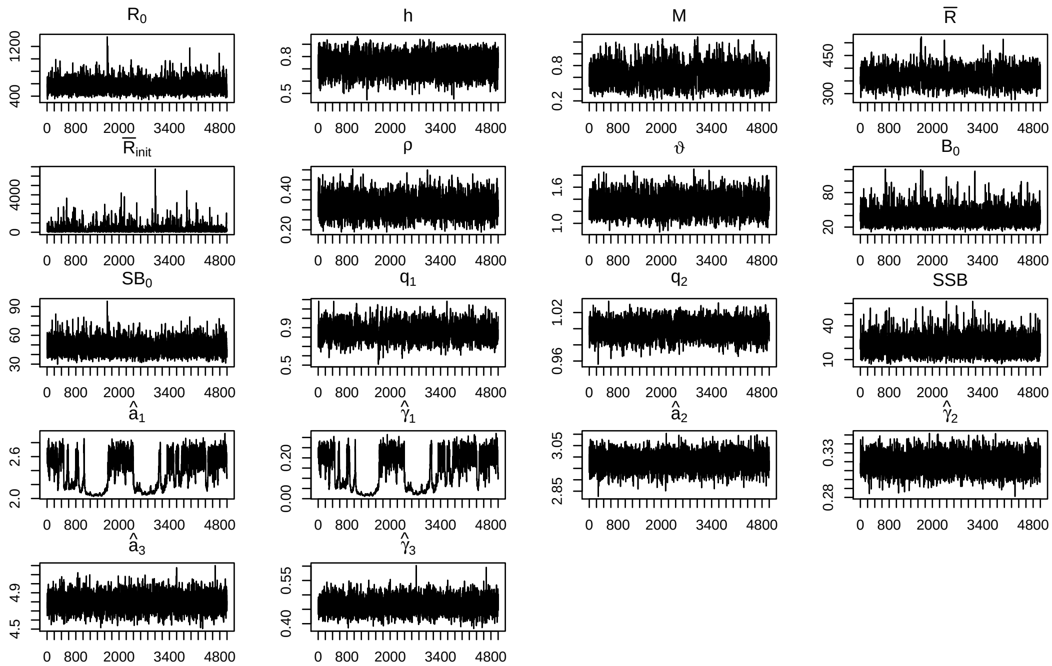

Figure 38. Trace plots for MCMC output of estimated parameters for the West Coast Vancouver Island AM2 model. The MCMC run had chain length 5 million with a sample taken at every 1,000th iteration. The catchability parameter q_1 represents the surface survey and q_2 the dive survey. Parameters $\hat{a}_k$ (selectivity-at-age-50%), and $\hat{\gamma}_k$ (selectivity standard deviation-at-50%) represent gears as follows: $k = 1$: Other fisheries, $k = 2$: Roe seine, $k = 3$: Gillnet roe.

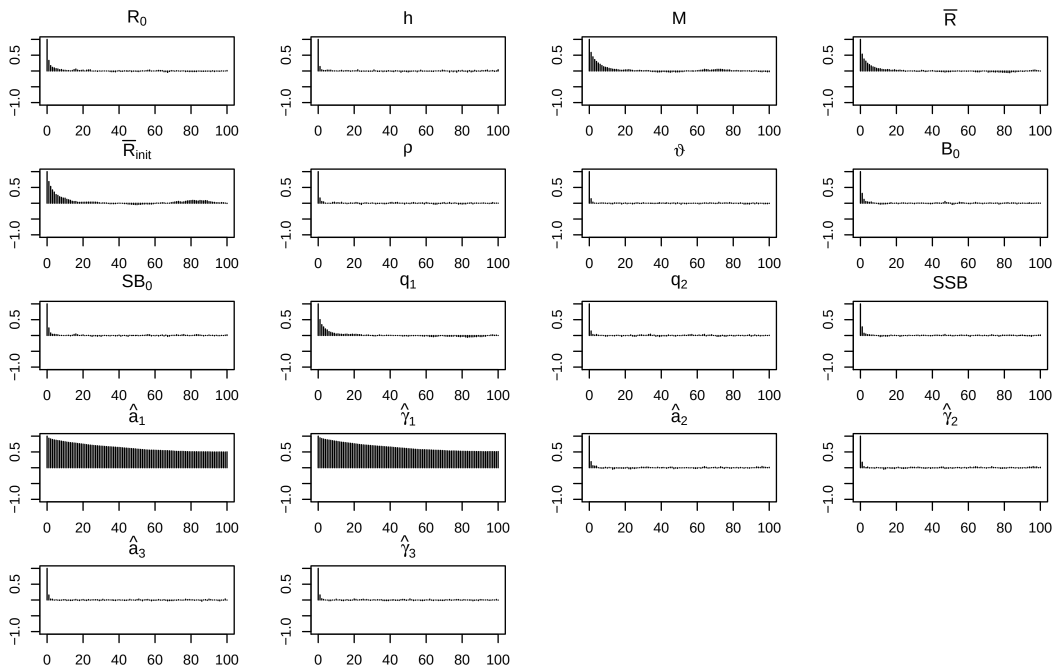

Figure 39. Autocorrelation plots for MCMC output of estimated parameters for the West Coast Vancouver Island AM2 model. See Figure 38 for parameter descriptions.

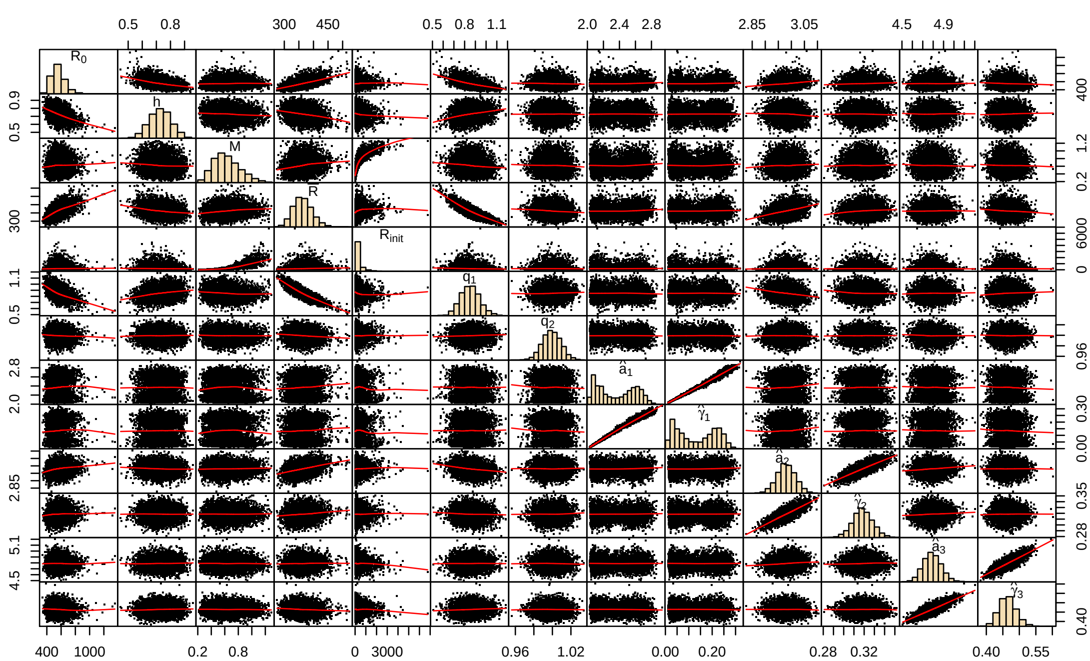

Figure 40. Pairs plots for MCMC output of estimated parameters in for the West Coast Vancouver Island AM2 model. See Figure 38 for parameter descriptions.

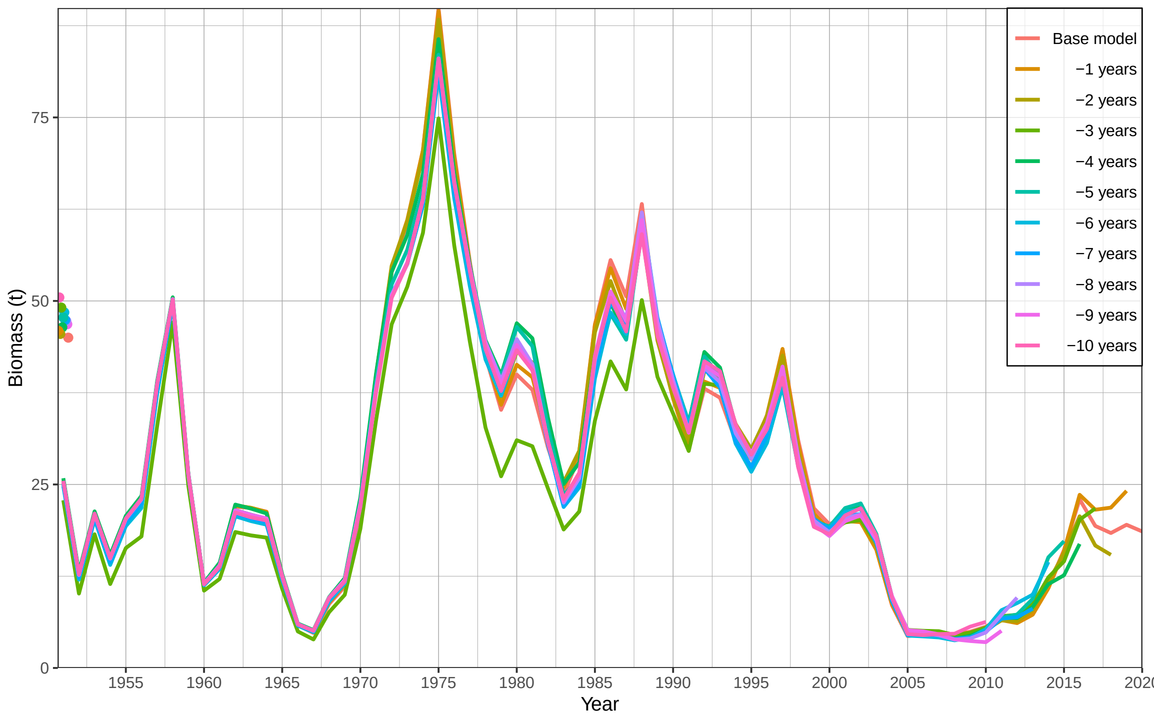

Figure 41. MPD biomass with retrospectivces for the West Coast Vancouver Island AM2 model.