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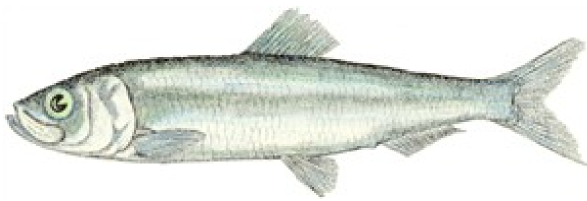
Pacific Region | Science Advisory Report 2018/002

STOCK ASSESSMENT FOR PACIFIC HERRING (*CLUPEA PALLASII*) IN BRITISH COLUMBIA IN 2017 AND FORECAST FOR 2018



Pacific Herring (Clupea pallasii). Image credit: [Fisheries and Oceans Canada](#).

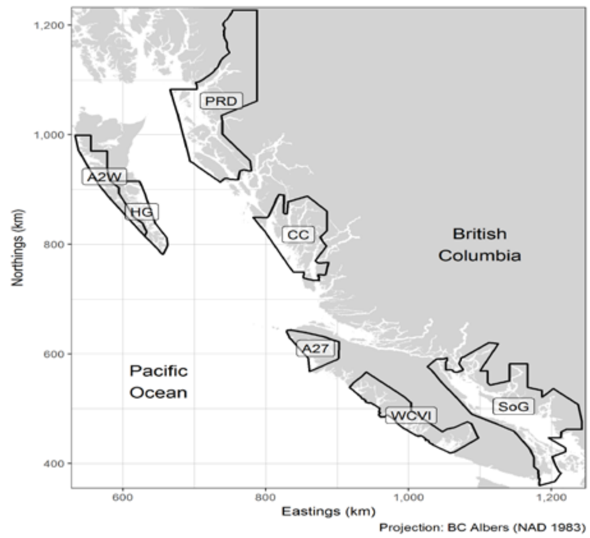


Figure 1. Boundaries for the Pacific Herring stock assessment regions (SARs) in B.C., Canada. The major SARs are Haida Gwaii (HG), Prince Rupert District (PRD), Central Coast (CC), Strait of Georgia (SoG), and West Coast of Vancouver Island (WCVI). The minor SARs are Area 27 (A27) and Area 2 West (A2W).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

Context:

*Pacific Herring (*Clupea pallasii*) is a pelagic species inhabiting inshore and offshore waters of the North Pacific. Pacific Herring east Pacific distribution ranges from California to the Beaufort Sea. Pacific Herring annually migrate between feeding and spawning areas. Fish mature and recruit to the spawning stock primarily between ages-2 and 5. In British Columbia (BC), Pacific Herring predominantly recruit at age-3. BC Pacific Herring stocks are managed based on five major (Haida Gwaii, Prince Rupert District, Central Coast, Strait of Georgia, and West Coast of Vancouver Island) and two minor (Area 2W and Area 27) stock areas (Figure 1). Catch and survey information is collected independently for each of these seven areas and science advice is provided on the same scale.*

Fisheries Management Branch annually requests science advice regarding the status of Pacific Herring stocks in BC and harvest options following the current harvest control rule and using decision tables. New to the 2017 assessment is estimation of stock productivity, and estimation of current stock status relative to the new limit reference point of $0.3SB_0$, *(DFO 2017). DFO Pacific Region is also engaged in a concurrent multi-year process to renew the management framework for Pacific Herring, which includes simulation evaluation of harvest control rules.*

This Science Advisory Report is from the October 17-18, 2017 Stock Assessment and Management

Advice for BC Pacific Herring: 2017 Status and 2018 Forecast. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada Science Advisory Schedule as they become available.

SUMMARY

- Commercial fishing for British Columbia (BC) Pacific Herring is managed in five major stock management areas: Haida Gwaii (HG), Prince Rupert District (PRD), Central Coast (CC), Strait of Georgia (SOG), and West Coast of Vancouver Island (WCVI), as well as two minor stock areas: Haida Gwaii Area 2W, and WCVI Area 27.
- For each of the five major areas, spawning biomass in 2017 (SB_{2017}) and pre-fishery forecast spawning biomass for 2018 (SB_{2018}) were assessed. Two base cases were implemented: AM1 and AM2, differing in the treatment of spawn survey scaling coefficients (q_1, q_2).
- Advice for each Pacific Herring stock in each of the five major areas is presented in decision tables showing predicted status in 2018 given a range of constant catches relative to the limit reference point (LRP) of $0.3SB_0$, the commercial fishery cut-offs (AM2 only), and target harvest rates of 10% and 20%.
- Sensitivity analyses were conducted to investigate uncertainty in the assumptions that were used to estimate the following parameters: natural mortality, observation and process errors, survey catchability (q_1, q_2), and maturity at age.
- Resolution between the performance of the AM2 and AM1 model parameterizations of q_2 will require a simulation-evaluation analysis. Further details on the analytical concerns with both AM2 and AM1 parameterizations of q_1 and q_2 can be found in Table A.1 of the 2016 Science Response (DFO 2016).
- The 2017 assessment includes estimation of stock productivity and current stock status relative to the limit reference point (LRP) of $0.3SB_0$ (DFO 2017).
- All five major stocks show declines in weight-at-age from the mid-1980s to 2010, with a levelling off and/or increase in the last five years.
- Potential impacts from the spawn on kelp fishery (SOK) (e.g., mortality, removed spawn) have not yet been formally accounted for in annual stock assessments.
- Other sources of uncertainty include structural assumptions about natural mortality, and uncertainty about the effects of fish movement and stock structure. For two stock areas (HG, WCVI), small sample sizes of age-composition samples in recent years are also a concern.

INTRODUCTION

Pacific Herring (*Clupea pallasii*) is a pelagic species migrating between inshore spawning and offshore feeding areas of the North Pacific Ocean. Herring distribution in the eastern Pacific Ocean ranges from California to the Beaufort Sea. Pacific Herring mature and recruit to the spawning stock predominantly at age-3 within British Columbia (BC).

Pacific Herring in BC are divided into five major and two minor stocks for evaluation and management (Figure 1). This stock structure is supported in part by the results of multi-year tagging and genetic studies (Hourston 1982, Beacham et al. 2008, Flostrand et al. 2009). The major stocks are: Haida Gwaii (HG), Prince Rupert District (PRD), Central Coast (CC), Strait of Georgia (SOG) and West Coast of Vancouver Island (WCVI). The two minor Pacific Herring stocks are Area 2W (on the west coast of Haida Gwaii) and Area 27 (on the west coast of Vancouver Island, centered on Quatsino Sound).

Pacific Herring in BC have been harvested for many years to provide a variety of food products. First Nations have traditionally harvested whole fish and Pacific Herring spawn-on-kelp for food, social and ceremonial purposes. Pacific Herring were commercially harvested and processed (reduced) into relatively low-value products such as fishmeal and oil from the early 1930s through the late 1960s. Commercial catches increased dramatically in the early 1960s, but were unsustainable. By 1965, most of the older fish had been removed from the spawning population by overfishing and sequential weak year-classes, attributed to a combination of unfavourable environmental conditions and low spawning biomass. The commercial fishery collapsed and was closed by the federal government in 1967. During the closure period limited fishing activity occurred at low levels from 1967-1971 (Hourston 1980). Growing interest in harvesting roe herring for export to Japan resulted in a small experimental roe harvest, beginning in 1971. The roe fishery expanded rapidly until 1983, when a fixed harvest rate was introduced to regulate catch. A series of above average year-classes in the early 1970s led to rapid rebuilding of Pacific Herring stocks and the re-opening of areas for commercial fishing.

At present, the Pacific Herring fisheries in BC consist of: commercial fishing opportunities for food and bait Pacific Herring, spawn-on-kelp (SOK) products, and roe herring. There are also opportunities for First Nations food, social, and ceremonial fisheries (FSC), and recreational fishing. Time series of commercial catch, excluding spawn-on-kelp, from 1951-2017 are presented for the five major stocks in Figures 2-11, panel d. Commercial catch is presented as vertical bars within each stock-specific spawning biomass figure.

Both fishery dependent and fishery independent time series of data are used in the assessment of Pacific Herring stocks. Fishery-dependent data include validated catch and biological samples from commercial fisheries. Fishery-independent data include biological samples from the test fishery program, and a Pacific Herring egg deposition survey (also called the spawn survey), which is used to estimate a relative index of spawner biomass.

DFO has committed to Pacific Herring Renewal to address a range of challenges facing the fishery. Science work to support this initiative includes two streams: the Operational and Strategic Streams. For the Strategic Stream, a management strategy evaluation (MSE) process is underway to conduct simulation-testing of alternative management procedures (MPs) to identify a procedure that is compliant with DFO's Fishery Decision-Making Framework Incorporating the Precautionary Approach (the PA framework) (DFO 2009) and characterize trade-offs among conservation, economic and socio-cultural objectives. A spawning biomass-based limit reference point (LRP) of 0.3*S*B0 was accepted for the major Pacific Herring stocks (DFO 2017). This recommendation was based on results of production analyses and is consistent with international best practice recommendations. Accordingly, the 2017 estimates of stock productivity, and current and projected spawning biomass relative to the LRP of $0.3SB_0$ are included.

ASSESSMENT

Stock Assessment Modeling for 2017

For the 2017 assessment, an updated version of the ISCAM (Integrated Statistical Catch-Age Model; Martell et al. 2012) was applied to assess each of the five major Pacific Herring stocks. This catch-at-age model was applied independently to each stock area and tuned to fishery-independent spawn index data, annual estimates of commercial catch since 1951, and age composition data from the commercial fishery and the test fishery charter program. The key results from stock assessments of Pacific Herring in the five major stock areas are summarized as stock reconstructions, status of spawning stock in 2017 relative to the LRP of 0.3SB_0, and projected spawning biomass in 2018.

ISCAM estimates stock-recruitment parameters, time-varying natural mortality, spawn survey scaling parameters for the surface survey (q_1) and dive survey (q_2, AM1 only) time series, and selectivity parameters for three main commercial fisheries, generating time series estimates of spawning biomass and unfished biomass. Recruitment is modelled as age-2 fish, while recruitment to the spawning biomass is assumed to occur at age-3. One-year projections for 2018 were performed for each major stock area, over a range of constant catches, to estimate the predicted stock status in 2018 relative to the limit reference point (LRP) of $0.3SB_0$, the commercial fishery cut-offs (AM2 only), and target harvest rates of 10% and 20%.

The 2017 assessment implemented the AM2 and AM1 base stock assessment models that have been used since 2011 (DFO, 2016). AM2 and AM1 differ in the treatment of spawn survey scaling parameters (q_1 and q_2) for the surface survey period (1951 to 1987) and dive survey period (1988 to 2017).

A bridging analysis was used to validate the updated ISCAM model used in the 2017 assessment. The main adjustment from model structures used in previous assessments (i.e., Martell et al., 2012; DFO 2016) was the partitioning of variance between observation and process error to improve the estimation of the variance structure. Other adjustments were made to improve computational efficiency and update input data. Parameter estimates and biomass trajectories associated with the structural adjustments were nearly identical to results from previous versions of ISCAM, supporting the adoption of the revised structure.

Sensitivity analyses were also done in association with the bridging analysis to test the interaction between leading model parameters. Results of the sensitivity analyses alone were insufficient for understanding the complex interplay between q_2 and management parameters. Therefore, both base case models were used to assess each of the five major stocks. Resolution between the AM2 and AM1 parameterization of q_2, in terms of performance, will require simulation-evaluation.

Advice to managers for the major stock areas is presented for AM2 and AM1 models in Figure 2 through Figure 11, showing time series estimates of: spawner index; instantaneous natural mortality; age-2 recruitment; spawning biomass, current stock status (SB_{2017}), projected spawning biomass in 2018 assuming no catch, and stock status relative to the LRP of $0.3SB_0$. Also shown are commercial catch totals (excluding SOK) and phase plots of spawning biomass production and spawning biomass production rate against spawning biomass. Summaries of some of these values are provided in Table 1 to Table 5. Also reported in Tables 1 to 5 are AM2 and AM1 model projected estimates, by major stock area, of the proportion of age-3 fish and proportion age-4 and older fish in the 2018 spawning population. Probabilistic decision tables provide additional information under a range of potential Total Allowable Catch (TAC) values (Table 6 to Table 15). Probability distributions for projected spawning biomass assuming no fishing in 2018, SB_{2018}, is presented in Figure 12.

Sources of Uncertainty

Recruitment and natural mortality are considered to be the most important processes determining the productivity of BC Pacific Herring stocks. Factors driving age-3 recruitment to the spawning biomass, forecast by the assessment model, are not fully understood. Instantaneous natural mortality (*M*) is estimated to be increasing for HG, decreasing for PRD and CC, and possibly increasing for SOG and WCVI stocks. The reasons for these changes are not clear at present, but are under investigation. Natural mortality is an important parameter in the stock assessment model because it affects estimates of current stock biomass and also the estimate of the unfished biomass. Long term declines in body size (weight at age) have been observed for all BC Pacific Herring stocks from the early 1980s-2010, with a levelling off and/or increase at the low end of the range in most recent years. Factors causing these changes are not understood.

The current assessment framework presents BC Pacific Herring as five discrete homogeneous stocks and does not consider between-stock movement or uncertainty in stock structure. Mechanisms to characterize reference points for Pacific Herring stock that allow for spatial distribution, stock structure, and genetic diversity are not well understood. Future development of population dynamics models that include spatial dynamics and/or stock structure may lead to candidate LRPs and performance indicators that characterize broader definitions of serious harm. Spatial operating models could also inform management options at finer spatial scales than the current major management areas.

Fishery removals are presented and included for roe herring and whole herring fisheries only. Removals associated with spawn-on-kelp fisheries are not currently included in the annual stock assessment process.

Modelling results reflect only the structural assumptions specified in the model, and weights assigned to the various data components. This represents a minimum estimate of uncertainty. While uncertainty in estimated parameters and derived quantities is explicitly addressed using a Bayesian approach, alternative model and stock structure assumptions - including alternative forecasting methods - would reveal greater levels of uncertainty.

Finally there are some information gaps and uncertainties associated with low sampling coverage. For some major stock areas in recent years (HG, WCVI), small sample sizes of age-composition samples are a concern as they may not accurately present the age composition of the population in those areas, or may have insufficient precision. For the minor stocks areas (2W and 27), incomplete or the complete lack of spawn surveys and biological sampling has occurred in recent years, which reduces the ability to provide reliable stock assessment advice.

ANALYSIS

HAIDA GWAII (HG)

Data

Haida Gwaii was closed to commercial roe fisheries from 2002–2013 and 2015–2017, and to commercial SOK fisheries from 2004–2013 and 2015–2017 (Figure 2, panel d). Commercial roe and SOK fishing opportunities were available in 2014; however they were not pursued following an agreement between the commercial sector and local First Nations.

The spawn index decreased from 6,888 t in 2016 to 3,016 t in 2017. Biological samples (seine-caught) in 2017 contained 14% age-2 fish, 32% age-3 fish, and 54% age-4 and older.

Stock productivity and recruitment

The AM2 and AM1 models estimate a declining trend in spawning stock biomass since 2013. Estimates of spawning biomass have remained low in most years since 2000, including 2017. Also in most years since 2000, including the most recent year between 2016 and 2017 spawning periods, the HG stock has been in a low productivity, low biomass state, indicating negative stock growth.

Both AM1 and AM2 estimate a low number of age-2 recruits in 2017.

Although model estimates of natural mortality remain highly uncertain, there is an increasing trend in the median estimates of natural mortality since 2012.

Estimated stock status and status relative to biological reference points

AM2 estimates the median spawning biomass in 2017, SB_{2017}, at 3,963 t (equal to 17% of SB_0). AM1 estimates the median SB_{2017} at 7,336 t (25% of SB_0). Based on a comparison of median estimates, both AM2 and AM1 models estimate SB_{2017} to be below the LRP of $0.3SB_0$ with greater than a 50% probability.

Projected spawning biomass in 2018 and spawning biomass related to HCR metrics

Age-3 recruitment in 2018 is predicted to be low because of the low numbers of age-2 recruits estimated in 2017.

Assuming no fishing in 2018, the projected median estimates of pre-fishery spawning biomass in 2018, SB_{2018}, are 4,346 t (AM2) and 7,302 t (AM1), which are similar to SB_{2017} levels.

Given these projections, it is estimated there is an 81% (AM2) and 65% (AM1) probability the stock will be below the LRP of $0.3SB_0$ in the absence of fishing. Under AM2, the projected pre-fishery spawning biomass in 2018, SB_{2018}, has a 94% chance of being below the 1996 fixed cutoff (10,700 t).

PRINCE RUPERT DISTRICT (PRD)

Data

The combined total validated catch for the seine roe, the gillnet roe, and the food and bait fisheries was 2,849 t for the 2016/17 Pacific Herring season (Figure 4, panel d). Commercial spawn-on-kelp operations also occurred in 2017.

The spawn index increased from 18,985 t in 2016 to 19,235 t in 2017. Biological samples (seine-caught) in 2017 contained approximately 1% age-2 fish, 16% age-3 fish, and 83% age-4 and older.

Stock productivity and recruitment

Since the mid-1990s, the PRD stock has been characterized by two periods of consistent and stable spawning biomass: 1996-2003 and 2006-2017. From 2005 onward, including the most recent year between 2016 and 2017 spawning seasons, spawning biomass production for the PRD stock has been positive, indicating stock growth.

Both AM1 and AM2 estimate an average number of age-2 recruits in 2017.

Although model estimates of natural mortality remain highly uncertain, there is a decreasing trend in the median estimates of natural mortality since 2006.

Estimated stock status and status relative to biological reference points

AM2 estimates the median spawning biomass in 2017, SB_{2017}, at 21,738 t (equal to 34% of SB_0). AM1 estimates the median SB_{2017} at 22,821 t (36% of SB_0). Based on a comparison of median estimates, both AM2 and AM1 models estimate SB_{2017} to be above the LRP of $0.3SB_0$ with greater than a 50% probability and less than a 95% probability.

Projected spawning biomass in 2018 and spawning biomass related to HCR

Assuming no fishing in 2018, both AM2 and AM1 predict a continued stable trend in spawning biomass, with the median estimates of the projected pre-fishery spawning biomass in 2018, SB_{2018}, of 23,924 t (AM2) and 24,903 t (AM1).

Given these projections, it is estimated that there is a 27% (AM2) and 26% (AM1) probability the stock will be below the LRP of $0.3SB_0$ in the absence of fishing. Under AM2, the projected pre-fishery spawning biomass in 2018, SB_{2018}, has a 3% chance of being below the 1996 fixed cutoff (12,100 t).

CENTRAL COAST (CC)

Data

There were no commercial roe fisheries in 2017 (Figure 6, panel d). Spawn-on-kelp operations occurred in all statistical areas in 2017.

The spawn index decreased from 32,508 t in 2016 to 23,517 t in 2017. Biological samples (seine-caught) in 2017 contained 3% age-2 fish, 17% age-3 fish, and 80% age-4 and older.

Stock productivity and recruitment

The AM2 and AM1 models estimate an increasing trend in spawning stock biomass since 2012, including 2017. From 2012 onward, including the most recent year between 2016 and 2017 spawning seasons, spawning biomass production for the CC stock has been positive, indicating stock growth.

Both AM2 and AM1 estimate an average-to-below-average number of age-2 recruits in 2017. Age-5 fish were estimated to comprise the highest proportion of fish in 2017, arising from the 2012 cohort.

Although model estimates of natural mortality remain highly uncertain, there is a decreasing trend in the median estimates of natural mortality since 2008.

Estimated stock status and status relative to biological reference points

AM2 estimates the median spawning biomass in 2017, SB_{2017}, at 30,474 t (equal to 55% of SB_0). AM1 estimates the median SB_{2017} at 49,624 t (80% of SB_0). Based on a comparison of median estimates, both AM2 and AM1 models estimate SB_{2017} to be above the LRP of $0.3SB_0$ with greater than a 95% probability.

Projected spawning biomass in 2018 and spawning biomass related to HCR

Assuming no fishing in 2018, the projected median estimates of pre-fishery spawning biomass in 2018, SB_{2018}, are 32,458 t (AM2) and 50,259 t (AM1), which are similar to SB_{2017} levels.

Given these projections, it is estimated there is a 3% (AM2) and 1% (AM1) probability the stock will be below the LRP of $0.3SB_0$ in the absence of fishing. Under AM2, the projected pre-fishery spawning biomass in 2018, SB_{2018}, has a 5% chance of being below the 1996 fixed cutoff (17,600 t).

STRAIT OF GEORGIA (SOG)

Data

The combined total validated catch for the seine roe, the gillnet roe, and the food and bait and special use fisheries was 25,279 t for the 2016/17 Pacific Herring season (Figure 8, panel d), the largest combined catch since 1972. Biological samples (seine-caught) in 2017 contained 8% age-2 fish, 28% age-3 fish, and 63% age-4 and older.

The spawn index decreased from 129,502 t in 2016 to 81,064 t in 2017. Biological samples (seine-caught) in 2017 contained relatively equal proportions of age-3 (28%), age-4 (29%), and age-5 (23%) fish.

Stock productivity and recruitment

The AM2 and AM1 models estimate an increasing trend in spawning stock biomass since 2010. From 2008 onward, including the most recent year between 2016 and 2017 spawning seasons, spawning biomass production for the SOG stock has been positive, indicating stock growth.

Both AM1 and AM2 estimate an above-average number of age-2 recruits in 2017. Age-3 and -4 fish comprise the highest estimated proportion of fish in the population in 2017, which is consistent with the previous 5 years.

Model estimates of natural mortality remain highly uncertain in the most recent years. AM2 estimates a decreasing trend in the median estimates of natural mortality since 2008, and AM1 estimates an increasing trend in the median estimates of natural mortality since 2015.

Estimated stock status and status relative to biological reference points

AM2 estimates the median spawning biomass in 2017 (SB_{2017}) at 114,626 t (equal to 81% of SB_0). AM1 estimates the median SB_{2017} at 175,962 t (108% of SB_0). Based on a comparison of median estimates, both AM2 and AM1 models estimate SB_{2017} to be above the LRP of $0.3SB_0$ by greater than 95% probability.

Projected spawning biomass in 2018 and spawning biomass related to HCR

Assuming no fishing in 2018, the projected median estimates of pre-fishery spawning biomass in 2018, SB_{2018}, are 125,285 t (AM2) and 169,910 t (AM1), declining from 2017.

Given these projections, it is estimated there is a 0% probability the stock will be below the LRP of $0.3SB_0$ in the absence of fishing (AM2 and AM1). Under AM2, the projected pre-fishery spawning biomass in 2018, SB_{2018} has a 0% chance of being below the 1996 fixed cutoff (21,200 t).

WEST COAST OF VANCOUVER ISLAND (WCVI)

Data

This area was closed to commercial fisheries since 2006, with SOK permitted in 2011 (Figure 10, panel d).

The spawn index decreased from 20,528 t in 2016 to 15,734 t in 2017. Biological samples (seine-caught) contained a high proportion of age-4 fish (66%), with 3% age-2 and 8% age-3 fish.

Stock productivity and recruitment

The AM2 and AM1 models estimate a decline in spawning stock biomass from 2016 to 2017. In most years since 2005, including the most recent year between 2016 and 2017 spawning seasons, the WCVI stock has been in a prolonged low productivity, low biomass state, indicating negative stock growth. At these low biomass levels, the WCVI stock is characterized by abrupt differences in year-to-year survey biomass.

Both AM1 and AM2 estimate a below-average number of age-2 recruits in 2017 and there was a higher proportion of age-4 fish relative to age-2 and age-3 fish.

Although model estimates of natural mortality remain highly uncertain, there is an increasing trend in the median estimates of natural mortality since 2014.

Estimated stock status and status relative to biological reference points

AM2 estimates the median spawning biomass in 2017, SB_{2017}, at 17,742 t (equal to 37% of SB_0). AM1 estimates the median SB_{2017} at 32,805 t (56% of SB_0). Based on a comparison of median estimates, both AM2 and AM1 models estimate SB_{2017} to be above the LRP of $0.3SB_0$, by greater than 50% probability but less than 95% probability.

Projected spawning biomass in 2018 and spawning biomass related to HCR

Age-3 recruitment in 2018 is predicted to be low because of the low numbers of age-2 recruits estimated in 2017.

Assuming no fishing in 2018, the projected median estimates of pre-fishery spawning biomass in 2018, SB_{2018}, are 20,003 t (AM2) and 34,886 t (AM1), similar to SB_{2017} levels.

Given these projections, there is a 20% (AM2) and 5% (AM1) probability the stock will be below the LRP of $0.3SB_0$ in the absence of fishing. Under AM2, the projected pre-fishery spawning biomass in 2018, SB_{2018} has a 45% chance of being below the 1996 fixed cutoff (18,800 t).

MINOR STOCKS

- Stock assessments were not completed for the two Pacific Herring minor stock areas.
- A commercial spawn-on-kelp fishery last occurred in Area 2W in 2014 and the last commercial roe Pacific Herring fishery occurred in 1998. Herring spawn was not surveyed in Area 2W in 2015 or 2017. The spawn index was 3,001 t in 2016.
- A commercial spawn-on-kelp fishery last occurred Area 27 in 2014 and the last commercial roe Pacific Herring fishery was in 1994. Herring spawn was incompletely surveyed in Area 27 during 2017, with a survey index of 26 t. The spawn index was 814 t in 2016.

REFERENCE POINTS

The 2017 assessment includes: an updated production analysis (Figure 2 to 11, panels e and f); estimation of current stock status relative to the LRP of $0.3SB_0$; and the probability of the projected stock status (SB_{2018}) being below the LRP, which is presented in the decision tables (Table 6 to Table 15). To mitigate short-term consequences to resource users, Kronlund et al. (2017) recommend the phasing-in of any new management procedure designed to avoid LRPs and achieve targets (i.e., changes to data collection, stock assessment models and/or harvest control rules). A process for applying the LRP for annual decision-making is still under development. Candidate Upper Stock Reference points (USR) are also presented:

Proposed candidate USRs for exploration through the Strategic Stream of Pacific Herring management renewal were introduced:

- USR = long-term average spawning biomass SB_{avg},
- USR = long-term average biomass during a productive period $SB_{avg\text{-}prod}$,
- USR = 2× LRP (e.g., $0.6SB_0$), and
- USR = SB_0.

A single USR has not yet been approved, as it is acknowledged that a fully specified set of objectives that includes LRPs, USRs and target reference points (TRPs) is part of an ongoing process to meet goals for renewal of the Pacific Herring management system and consistency with the DFO PA Framework (DFO 2009).

Ecosystem and Forage Fish Considerations

Pacific Herring play a key role in marine ecosystems and are a food source for a variety of piscivorous species including Pacific Salmon (Coho – *Oncorhynchus kisutch*, and Chinook, *O.*

tshawytscha), Pacific Hake (*Merluccius productus*), Pacific Halibut (*Hippoglossus stenolepis*), Arrowtooth Flounder (*Atheresthes stomias*), and Dogfish Shark (*Squalus acanthias*) (Schweigert et al. 2010). Pacific Herring are also believed to be important in the diet of many marine mammal predators. During the time-period captured in the Pacific Herring assessment (1951-2017), population sizes of seals, sea lions and baleen whales, which forage on Pacific Herring, have increased (DFO 2003; DFO 2010; Carretta et al. 2011; Crawford and Irvine 2011).

Researchers continue to develop a greater understanding of ecosystem processes and the role that Pacific Herring play in the ecosystem. The need for a multi-species definition for serious harm for forage fish is considered in both international and domestic policies. Ecosystem-wide analyses of alternative harvest policies for the management of forage fish have been presented in recent literature (e.g., Pikitch et al. 2012). However, these harvest policies and implied reference points have not been applied in practice and it is therefore not possible to establish best practices based on precedent. Future research to support adjustment of biological reference points for BC Pacific Herring based on ecosystem considerations will require review of empirical data, meta-analyses and simulation model studies.

CONCLUSIONS AND ADVICE

Decision tables for 2018 are presented for AM2 and AM1 base case model runs for the five major stock areas: HG, PRD, CC, SOG, and WCVI (Table 6 to Table 15). Below is an example of how to read the tables for PRD:

> Under the assumptions of AM2 for PRD (Table 8, row 9), given a 2018 catch of 5,000 t, the estimated probability that the harvest rate (*U'*) exceeds the 20% target rate is 0.503 (50%), and the probability that SB_{2018} < fixed cut-off (12,100 t) is estimated to be 0.144 (14%). At this harvest level, the estimated probability that SB_{2018} < LRP is 0.451 (45%).

Note that fixed cutoffs and the 20% harvest rate are taken from the existing Pacific Herring harvest control rule (HCR) (DFO 2016). The LRP for Pacific Herring stocks was introduced in 2017 (DFO 2017). The LRP recommendation of $0.3SB_0$ was based on apparent states of low productivity and low biomass (LP-LB) observed for three of the five major stocks (HG, WCVI, CC). While LP-LB states were not observed in the historical time-series for SOG and PRG, the same LRP recommendation of $0.3SB_0$ was recommended for these stocks by proxy (DFO 2017). For these two stocks, The AM2 fishery cutoffs established in 1996 (Schweigert et al. 1997, DFO 2016) are below the LRP. Simulation-testing of the validity and performance of $0.3SB_0$ as an LRP for all stocks, but especially SOG and PRD, is recommended.

Recommendations for future work include:

- Simulation-test management procedures, including data-collection, model assumptions, reference points and harvest control rules (for all fisheries, including SOK).
- Quantify mortality and removals (eggs) associated with the spawn-on-kelp fishery.
- Quantify uncertainty in the spawn index (annual estimates of variance and biases).
- Investigate potential for stock-specific prior probability distribution on q2, and ways to incorporate year-to-year variability in q2.
- Update stock-specific maturity ogives.
- Investigate alternative patterns of time varying natural mortality.

OTHER CONSIDERATIONS

Simulation analyses of performance of alternative HCRs will occur within a Management Strategy Evaluation (MSE) process, focusing on establishing Management Procedures compliant with the DFO's Fishery Decision-Making Framework Incorporating the Precautionary Approach (DFO 2009), including avoiding Limit Reference Points (LRP) with high probability and establishing Upper Stock Reference (USR) points or target biomass levels.

SOURCES OF INFORMATION

This Science Advisory Report is from the October 17 & 18, 2017 'Stock assessment and management advice for BC Pacific Herring: 2017 status and 2018 forecast'. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

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APPENDIX

Tables

Table 1. Posterior (5th percentile, median, and 95th percentile) of proposed reference points for the Haida Gwaii models. Biomass numbers are in thousands of tonnes. Legend: SB_0 is unfished spawning biomass, SB_{2017} is estimated spawning biomass in 2017, SB_{2018} is predicted spawning biomass assuming no fishing in 2018, proportion aged 3 is the predicted proportion of age-3 fish assuming no fishing in 2018, and proportion aged 4-10 is the predicted proportion of age-4 fish and older assuming no fishing in 2018.

-	AM2			AM1		
Reference point	5%	50%	95%	5%	50%	95%
SB_0	18.319	23.098	30.163	22.781	29.818	40.026
$0.3SB_0$	5.496	6.929	9.049	6.834	8.945	12.008
SB_{2017}	1.980	3.963	8.005	3.434	7.336	15.433
SB_{2017}/SB_0	0.083	0.171	0.347	0.118	0.246	0.495
SB_{2018}	1.900	4.346	11.326	3.044	7.302	18.483
Proportion aged 3	0.09	0.34	0.70	0.09	0.31	0.67
Proportion aged 4-10	0.15	0.38	0.68	0.17	0.42	0.71

Table 2. Posterior (5th percentile, median, and 95th percentile) of proposed reference points for the Prince Rupert District models. See Table 1 for description.

-	AM2			AM1		
Reference point	5%	50%	95%	5%	50%	95%
SB_0	46.919	61.097	92.122	47.786	62.595	91.271
$0.3SB_0$	14.076	18.329	27.637	14.336	18.779	27.381
SB_{2017}	12.656	21.738	36.537	12.213	22.821	41.708
SB_{2017}/SB_0	0.193	0.344	0.595	0.182	0.358	0.669
SB_{2018}	12.893	23.924	44.818	12.606	24.903	50.081
Proportion aged 3	0.07	0.23	0.55	0.07	0.24	0.54
Proportion aged 4-10	0.39	0.68	0.87	0.39	0.68	0.87

Table 3. Posterior (5th percentile, median, and 95th percentile) of proposed reference points for the Central Coast models. See Table 1 for description.

-	AM2			AM1		
Reference point	5%	50%	95%	5%	50%	95%
SB_0	44.424	55.347	71.220	49.235	62.063	81.175
$0.3SB_0$	13.327	16.604	21.366	14.770	18.619	24.352
SB_{2017}	18.518	30.474	47.125	27.553	49.624	85.709
SB_{2017}/SB_0	0.328	0.545	0.898	0.449	0.801	1.324
SB_{2018}	17.728	32.458	60.684	25.958	50.259	96.481
Proportion aged 3	0.07	0.25	0.56	0.07	0.22	0.52
Proportion aged 4-10	0.38	0.66	0.85	0.42	0.69	0.87

Table 4. Posterior (5th percentile, median, and 95th percentile) of proposed reference points for the Strait of Georgia models. See Table 1 for description.

-	AM2			AM1		
Reference point	5%	50%	95%	5%	50%	95%
SB_0	110.088	138.795	199.081	126.823	162.050	229.336
$0.3SB_0$	33.026	41.638	59.724	38.047	48.615	68.801
SB_{2017}	70.478	114.626	176.690	102.598	175.962	304.613
SB_{2017}/SB_0	0.464	0.813	1.313	0.610	1.078	1.796
SB_{2018}	71.847	125.285	216.387	92.908	169.910	323.468
Proportion aged 3	0.09	0.25	0.51	0.10	0.26	0.52
Proportion aged 4-10	0.42	0.67	0.85	0.40	0.64	0.82

Table 5. Posterior (5th percentile, median, and 95th percentile) of proposed reference points for the West Coast of Vancouver Island models. See Table 1 for description.

-	AM2			AM1		
Reference point	5%	50%	95%	5%	50%	95%
SB_0	37.870	46.890	61.469	45.961	58.491	76.910
$0.3SB_0$	11.361	14.067	18.441	13.788	17.547	23.073
SB_{2017}	9.719	17.742	30.650	16.877	32.805	62.881
SB_{2017}/SB_0	0.201	0.373	0.654	0.297	0.559	1.021
SB_{2018}	10.183	20.003	41.001	16.914	34.886	73.564
Proportion aged 3	0.11	0.32	0.63	0.11	0.31	0.60
Proportion aged 4-10	0.24	0.48	0.72	0.27	0.51	0.74

Table 6. Probabilistic decision table for Haida Gwaii, AM2 model. Legend: TAC is total allowable catch, P indicates the probability, SB_0 is unfished spawning biomass, SB_{2018} is predicted spawning biomass assuming the specified TAC in 2018, Med indicates the median, and U_{2018} is the predicted harvest rate given the specified TAC in 2018.

2018 TAC (metric tonnes)	P(SB_{2018} < 0.3SB_0)	Med(SB_{2018}/ 0.3SB_0)	P(SB_{2018} < 10,700)	Med(SB_{2018} < 10,700)	P(U_{2018} > 20%)	P(U_{2018} > 10%)	Med(U_{2018})
0	0.808	0.630	0.938	0.406	0.000	0.000	0.000
400	0.821	0.598	0.943	0.387	0.041	0.399	0.088
457	0.824	0.593	0.944	0.384	0.068	0.501	0.100
500	0.825	0.589	0.944	0.382	0.096	0.570	0.109
600	0.829	0.581	0.945	0.377	0.177	0.697	0.129
770	0.835	0.569	0.946	0.369	0.332	0.829	0.163
800	0.836	0.566	0.946	0.368	0.359	0.847	0.169
965	0.842	0.553	0.948	0.360	0.501	0.905	0.200
1,000	0.843	0.550	0.948	0.358	0.529	0.915	0.207
1,500	0.857	0.515	0.952	0.335	0.791	0.978	0.295
1,620	0.860	0.508	0.953	0.329	0.830	0.982	0.315
1,700	0.862	0.502	0.954	0.325	0.851	0.986	0.328

Table 7. Probabilistic decision table for Haida Gwaii, AM1 model. See Table 6 for description.

2018 TAC (metric tonnes)	P(SB_{2018} < 0.3SB_0)	Med(SB_{2018}/ 0.3SB_0)	P(U_{2018} > 20%)	P(U_{2018} > 10%)	Med(U_{2018})
0	0.654	0.808	0.000	0.000	0.000
400	0.669	0.785	0.002	0.116	0.053
457	0.671	0.781	0.006	0.170	0.061
500	0.673	0.778	0.013	0.212	0.066
600	0.676	0.772	0.032	0.324	0.079
770	0.682	0.762	0.086	0.504	0.101
800	0.684	0.760	0.096	0.537	0.104
965	0.689	0.749	0.170	0.660	0.125
1,000	0.690	0.748	0.184	0.683	0.129
1,500	0.710	0.718	0.446	0.878	0.188
1,620	0.715	0.711	0.504	0.908	0.201
1,700	0.718	0.706	0.542	0.920	0.210

Table 8. Probabilistic decision table for Prince Rupert District, AM2 model. See Table 6 for description.

2018 TAC (metric tonnes)	$P(SB_{2018} < 0.3SB_0)$	$Med(SB_{2018}/0.3SB_0)$	$P(SB_{2018} < 12{,}100)$	$Med(SB_{2018} < 12{,}100)$	$P(U_{2018} > 20\%)$	$P(U_{2018} > 10\%)$	$Med(U_{2018})$
0	0.265	1.271	0.034	1.977	0.000	0.000	0.000
2,400	0.361	1.169	0.077	1.817	0.025	0.483	0.098
2,440	0.362	1.167	0.077	1.814	0.027	0.500	0.100
2,545	0.367	1.163	0.079	1.808	0.034	0.548	0.104
3,000	0.382	1.144	0.090	1.778	0.087	0.705	0.122
3,500	0.400	1.122	0.103	1.745	0.171	0.822	0.142
4,000	0.419	1.099	0.116	1.711	0.277	0.902	0.162
4,500	0.436	1.078	0.130	1.678	0.385	0.946	0.181
5,000	0.451	1.057	0.144	1.646	0.503	0.970	0.201
5,200	0.460	1.049	0.147	1.633	0.546	0.977	0.208
5,500	0.469	1.037	0.156	1.613	0.605	0.983	0.220
6,000	0.485	1.016	0.168	1.580	0.687	0.989	0.239
7,000	0.522	0.976	0.198	1.517	0.807	0.995	0.276

Table 9. Probabilistic decision table for Prince Rupert District, AM1 model. See Table 6 for description.

2018 TAC (metric tonnes)	$P(SB_{2018} < 0.3SB_0)$	$Med(SB_{2018}/0.3SB_0)$	$P(U_{2018} > 20\%)$	$P(U_{2018} > 10\%)$	$Med(U_{2018})$
0	0.264	1.311	0.000	0.000	0.000
2,400	0.339	1.208	0.029	0.443	0.095
2,440	0.340	1.206	0.033	0.459	0.096
2,545	0.343	1.202	0.041	0.502	0.100
3,000	0.356	1.184	0.094	0.651	0.118
3,500	0.374	1.163	0.168	0.778	0.137
4,000	0.392	1.143	0.258	0.858	0.155
4,500	0.408	1.121	0.358	0.913	0.174
5,000	0.425	1.101	0.462	0.945	0.193
5,200	0.432	1.092	0.501	0.956	0.200
5,500	0.441	1.079	0.553	0.967	0.211
6,000	0.456	1.059	0.633	0.979	0.229
7,000	0.486	1.017	0.763	0.992	0.265

Table 10. Probabilistic decision table for Central Coast, AM2 model. See Table 6 for description.

2018 TAC (metric tonnes)	P(SB_{2018} < 0.3SB_0)	Med(SB_{2018}/ 0.3SB_0)	P(SB_{2018} < 17,600)	Med(SB_{2018} < 17,600)	P(U_{2018} > 20%)	P(U_{2018} > 10%)	Med(U_{2018})
0	0.034	1.933	0.047	1.844	0.000	0.000	0.000
3,000	0.069	1.791	0.087	1.712	0.011	0.386	0.091
3,320	0.074	1.776	0.092	1.697	0.021	0.500	0.100
4,000	0.083	1.744	0.102	1.667	0.069	0.709	0.120
4,500	0.090	1.721	0.111	1.645	0.121	0.810	0.135
5,150	0.100	1.690	0.124	1.616	0.215	0.893	0.153
6,000	0.115	1.649	0.142	1.578	0.360	0.942	0.178
6,800	0.133	1.612	0.159	1.543	0.502	0.968	0.200
6,900	0.135	1.608	0.162	1.538	0.522	0.970	0.203
7,000	0.137	1.603	0.165	1.534	0.540	0.973	0.206
9,000	0.184	1.511	0.212	1.445	0.791	0.992	0.261
10,550	0.221	1.440	0.250	1.378	0.894	0.997	0.303
12,000	0.259	1.372	0.286	1.315	0.936	0.999	0.341

Table 11. Probabilistic decision table for Central Coast, AM1 model. See Table 6 for description.

2018 TAC (metric tonnes)	P(SB_{2018} < 0.3SB_0)	Med(SB_{2018}/ 0.3SB_0)	P(U_{2018} > 20%)	P(U_{2018} > 10%)	Med(U_{2018})
0	0.007	2.675	0.000	0.000	0.000
3,000	0.014	2.545	0.001	0.088	0.059
3,320	0.015	2.530	0.002	0.133	0.065
4,000	0.016	2.501	0.009	0.260	0.078
4,500	0.018	2.481	0.018	0.372	0.088
5,150	0.021	2.455	0.037	0.502	0.100
6,000	0.024	2.421	0.079	0.657	0.116
6,800	0.027	2.387	0.132	0.766	0.132
6,900	0.028	2.383	0.139	0.777	0.133
7,000	0.028	2.379	0.147	0.788	0.135
9,000	0.037	2.299	0.347	0.922	0.172
10,550	0.045	2.234	0.502	0.964	0.201
12,000	0.056	2.173	0.635	0.982	0.227

Table 12. Probabilistic decision table for Strait of Georgia, AM2 model. See Table 6 for description.

2018 TAC (metric tonnes)	P(SB_{2018} < 0.3SB_0)	Med(SB_{2018}/ 0.3SB_0)	P(SB_{2018} < 21,200)	Med(SB_{2018} < 21,200)	P(U_{2018} > 20%)	P(U_{2018} > 10%)	Med(U_{2018})
0	0.003	2.951	0.000	5.910	0.000	0.000	0.000
12,000	0.008	2.729	0.000	5.466	0.010	0.422	0.094
12,800	0.009	2.714	0.000	5.436	0.016	0.500	0.100
14,000	0.010	2.692	0.000	5.391	0.030	0.616	0.109
15,000	0.011	2.671	0.000	5.353	0.047	0.695	0.117
17,500	0.013	2.623	0.000	5.259	0.116	0.842	0.136
20,000	0.015	2.573	0.000	5.166	0.210	0.918	0.154
26,200	0.025	2.453	0.000	4.937	0.501	0.983	0.200
30,000	0.031	2.382	0.001	4.798	0.671	0.992	0.228
35,000	0.041	2.291	0.002	4.617	0.824	0.997	0.263
36,000	0.044	2.273	0.003	4.582	0.848	0.997	0.270
38,000	0.049	2.236	0.003	4.508	0.883	0.998	0.285

Table 13. Probabilistic decision table for Strait of Georgia, AM1 model. See Table 6 for description.

2018 TAC (metric tonnes)	P(SB_{2018} < 0.3SB_0)	Med(SB_{2018}/ 0.3SB_0)	P(U_{2018} > 20%)	P(U_{2018} > 10%)	Med(U_{2018})
0	0.001	3.452	0.000	0.000	0.000
12,000	0.002	3.275	0.002	0.151	0.069
12,800	0.003	3.264	0.003	0.197	0.074
14,000	0.003	3.247	0.005	0.277	0.081
15,000	0.003	3.232	0.009	0.342	0.086
17,500	0.004	3.193	0.025	0.501	0.100
20,000	0.004	3.156	0.054	0.641	0.114
26,200	0.006	3.066	0.189	0.851	0.148
30,000	0.009	3.008	0.316	0.922	0.168
35,000	0.011	2.935	0.472	0.961	0.195
36,000	0.012	2.919	0.501	0.968	0.200
38,000	0.015	2.890	0.559	0.977	0.211

Table 14. Probabilistic decision table for West Coast of Vancouver Island, AM2 model. See Table 6 for description.

2018 TAC (metric tonnes)	P(SB_{2018} < 0.3SB_0)	Med(SB_{2018}/ 0.3SB_0)	P(SB_{2018} < 18,800)	Med(SB_{2018} < 18,800)	P(U_{2018} > 20%)	P(U_{2018} > 10%)	Med(U_{2018})
0	0.203	1.413	0.447	1.064	0.000	0.000	0.000
2,000	0.272	1.315	0.505	0.993	0.033	0.476	0.097
2,075	0.276	1.311	0.508	0.990	0.040	0.503	0.100
3,000	0.310	1.267	0.537	0.957	0.193	0.812	0.143
3,610	0.330	1.239	0.553	0.936	0.342	0.905	0.170
4,300	0.354	1.208	0.576	0.912	0.502	0.955	0.200
5,000	0.380	1.175	0.596	0.888	0.644	0.978	0.231
6,000	0.410	1.130	0.623	0.854	0.790	0.990	0.272
7,500	0.459	1.063	0.662	0.801	0.906	0.997	0.332
8,000	0.476	1.041	0.675	0.784	0.928	0.999	0.352
9,000	0.503	0.996	0.698	0.751	0.957	1.000	0.389
10,000	0.533	0.952	0.717	0.718	0.974	1.000	0.426

Table 15. Probabilistic decision table for West Coast of Vancouver Island, AM1 model. See Table 6 for description.

2018 TAC (metric tonnes)	P(SB_{2018} < 0.3SB_0)	Med(SB_{2018}/ 0.3SB_0)	P(U_{2018} > 20%)	P(U_{2018} > 10%)	Med(U_{2018})
0	0.050	1.980	0.000	0.000	0.000
2,000	0.070	1.904	0.002	0.091	0.056
2,075	0.071	1.901	0.003	0.103	0.058
3,000	0.085	1.866	0.018	0.343	0.084
3,610	0.092	1.843	0.046	0.500	0.100
4,300	0.102	1.817	0.101	0.656	0.118
5,000	0.110	1.791	0.180	0.771	0.137
6,000	0.124	1.753	0.309	0.873	0.163
7,500	0.146	1.698	0.501	0.947	0.200
8,000	0.154	1.680	0.563	0.957	0.213
9,000	0.169	1.644	0.665	0.975	0.237
10,000	0.185	1.608	0.746	0.986	0.261

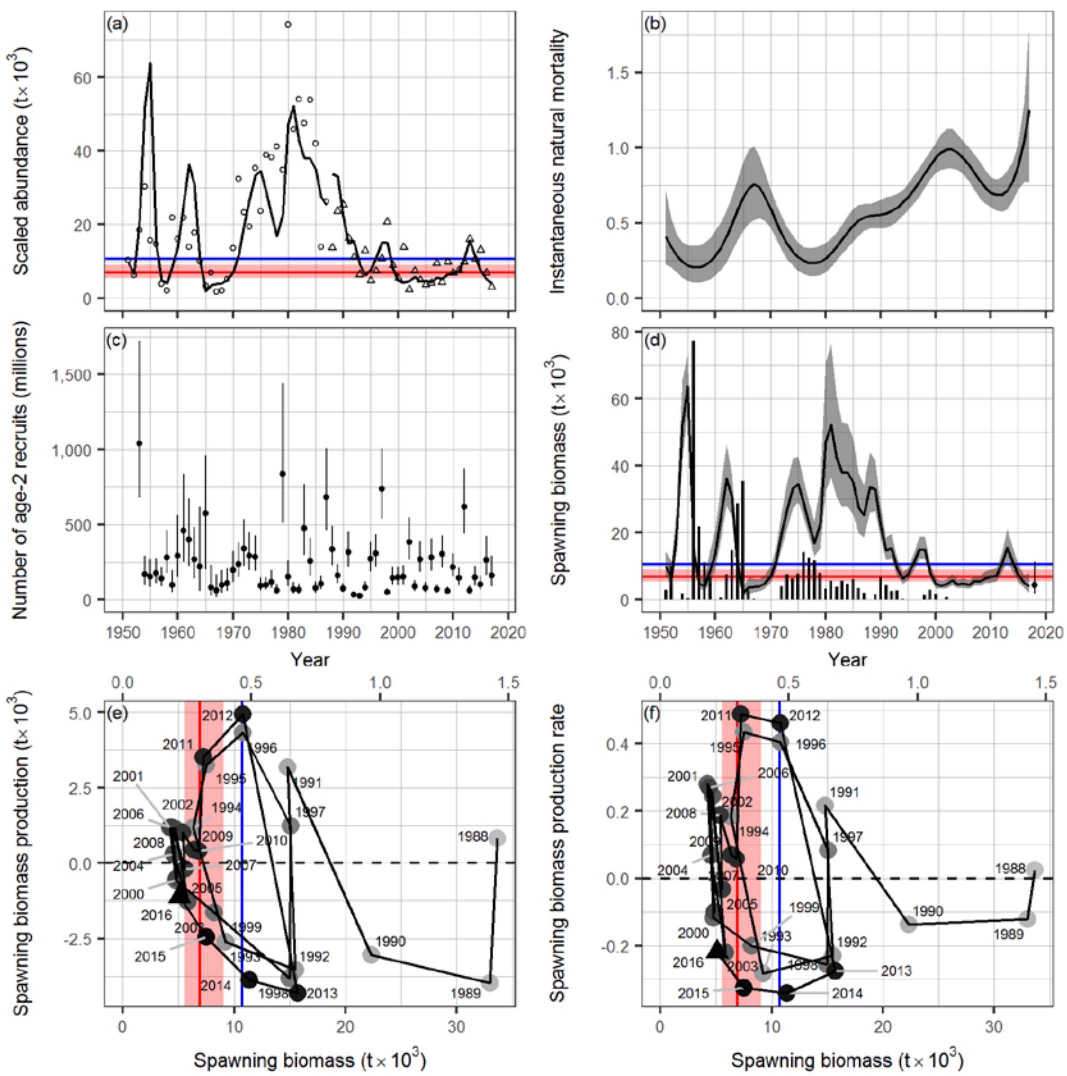

Figure 2. Model output for Pacific Herring in the HG major stock assessment region for AM2. Panel (a): model fit to time series of scaled spawn survey data in thousands of metric tonnes (t x 10^3). Spawn index has two distinct periods defined by the dominant survey method: surface (1951 to 1987), and dive surveys (1988 to 2017). 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. Line and shaded area indicate the median and 90% credible interval, respectively. Panel (c): reconstructed number of age-2 recruits in millions. Circles with vertical lines indicate medians and 90% credible intervals, respectively. Panel (d): posterior estimate of spawning biomass (SB_t) for each year t in thousands of metric tonnes (t x 10^3). Line and shaded area indicate median and 90% credible interval, respectively. Also shown is projected spawning biomass assuming no fishing (SB_{2018}) at the far right: the circle and vertical line indicates the median and 90% credible interval, respectively. Time series of vertical lines indicates commercial catch, excluding spawn on kelp (SOK). Panels (e & f): phase plots of spawning biomass production and spawning biomass production rate against spawning biomass, respectively, for the dive survey period (MPD estimates). The black triangle indicates 2016. Grey shading becomes darker in chronological order. The axis scale at the top of panels (e & f) is spawning biomass depletion, SB/SB_0. Panels (a, d, e, & f): red lines indicate median and red shading indicates 90% credible interval for the limit reference point (LRP), $0.3SB_0$, where SB_0 is the estimated unfished biomass; if present, horizontal and vertical blue lines indicate 1996 fixed cutoffs, AM2 plots only (HG: 10,700 t, PRD: 12,100 t, CC: 17,600 t, SOG: 21,200 t, WCVI: 18,800 t). Scales are different between AM2 and AM1 (shown in separate figures).

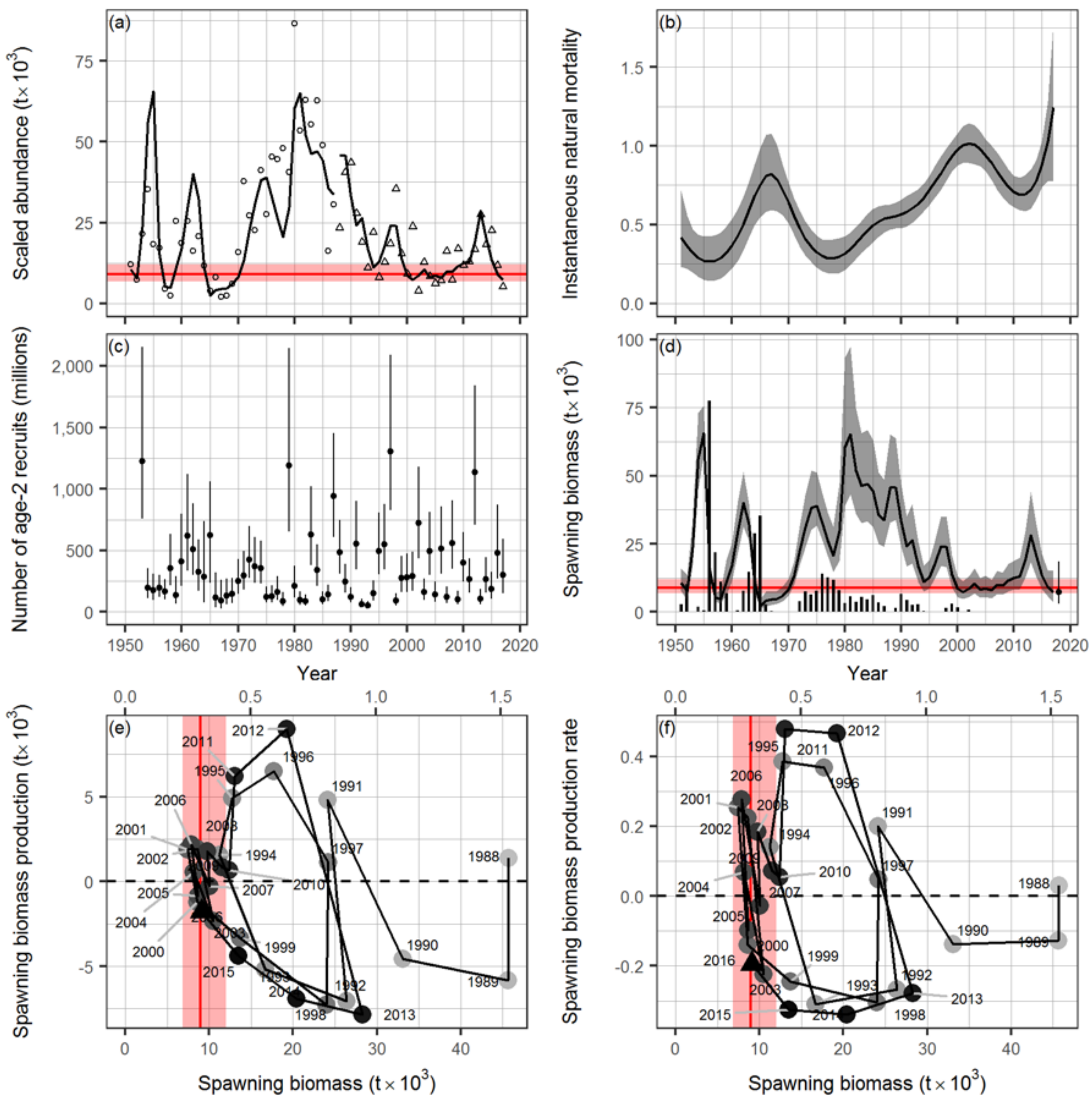

Figure 3. Model output for Pacific Herring in the HG major stock assessment region for AM1. See Figure 2 for description.

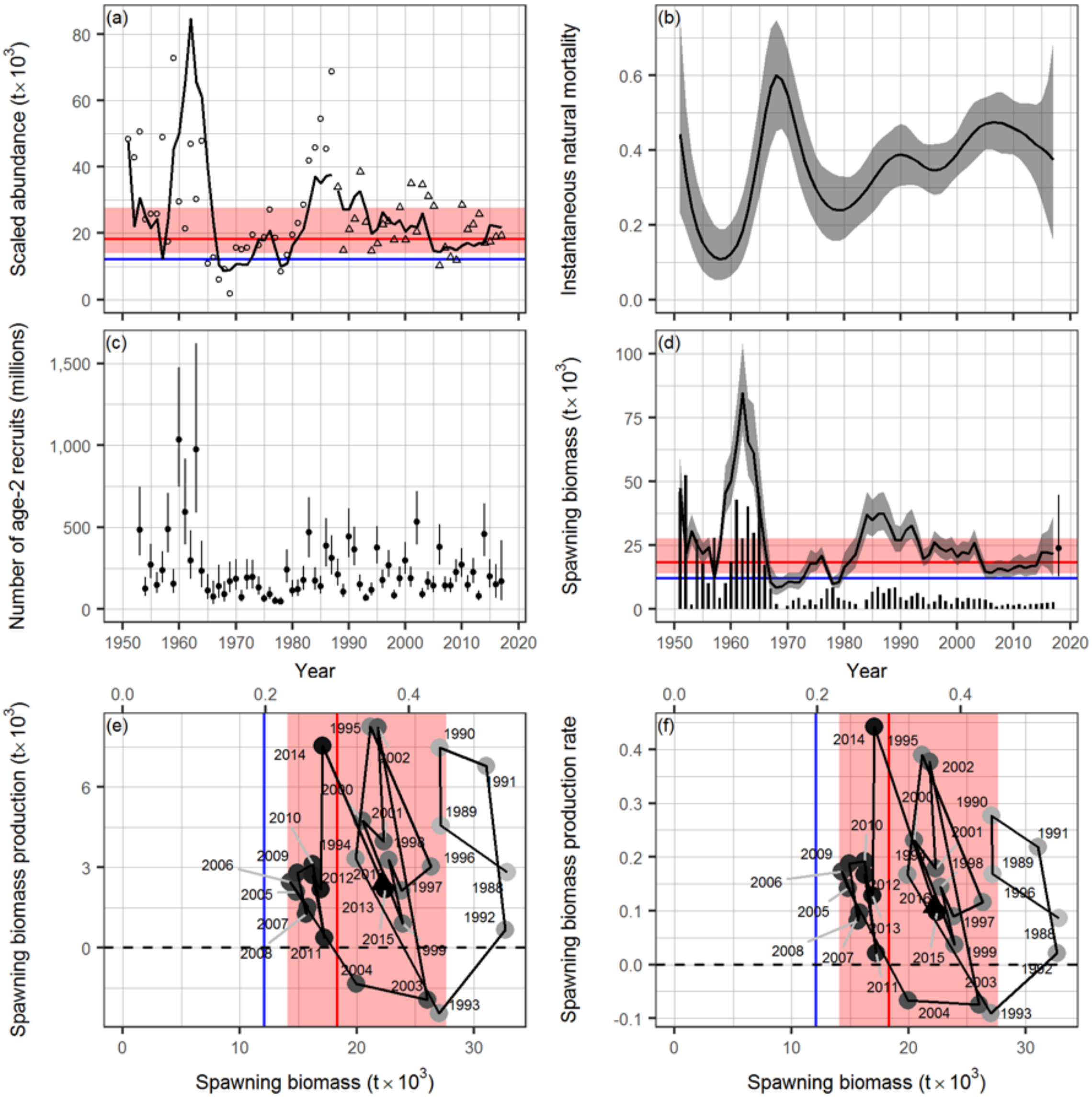

Figure 4. Model output for Pacific Herring in the PRD major stock assessment region (SAR) for AM2. See Figure 2 for description.

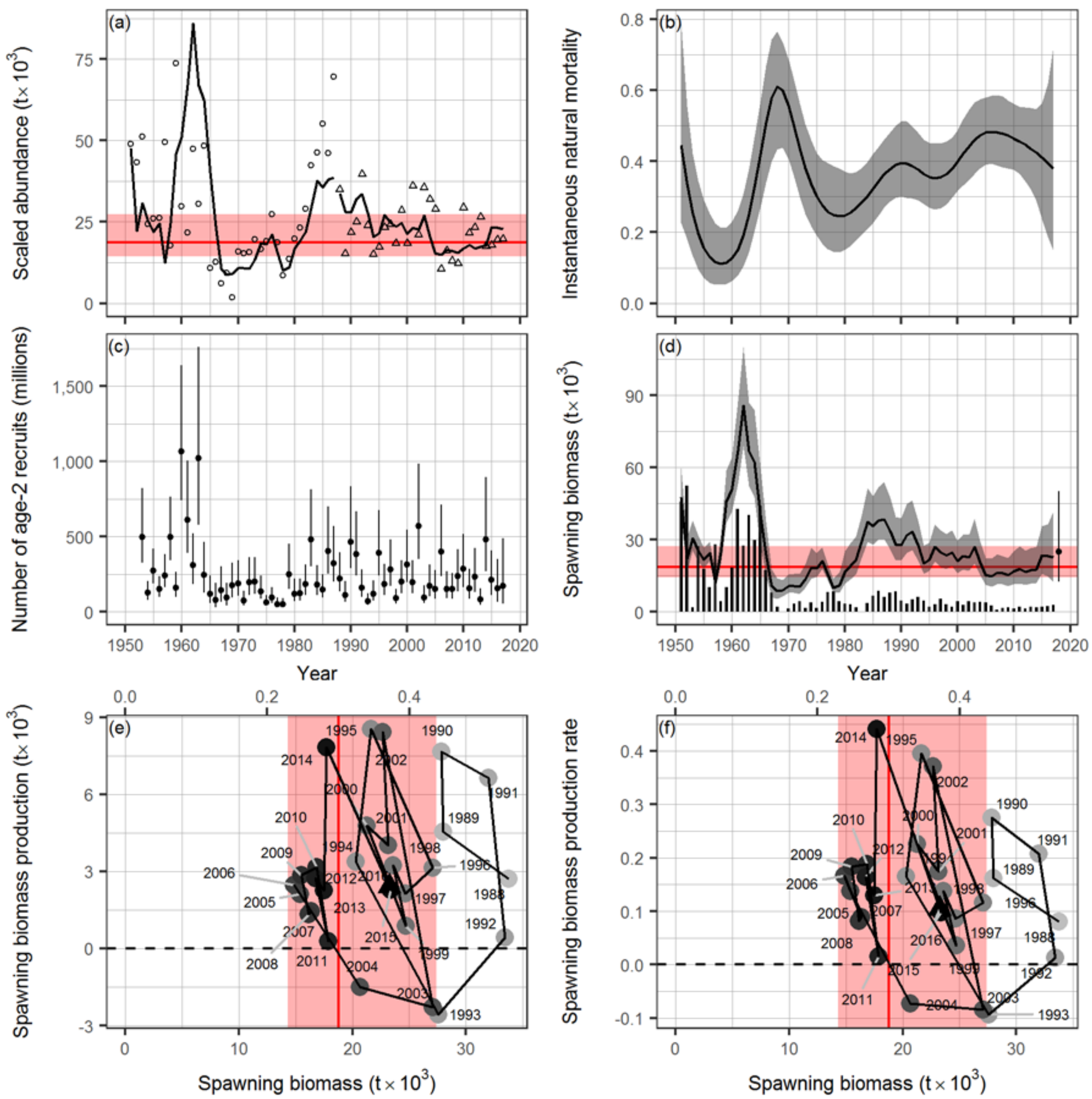

Figure 5. Model output for Pacific Herring in the PRD major stock assessment region for AM1. See Figure 2 for description.

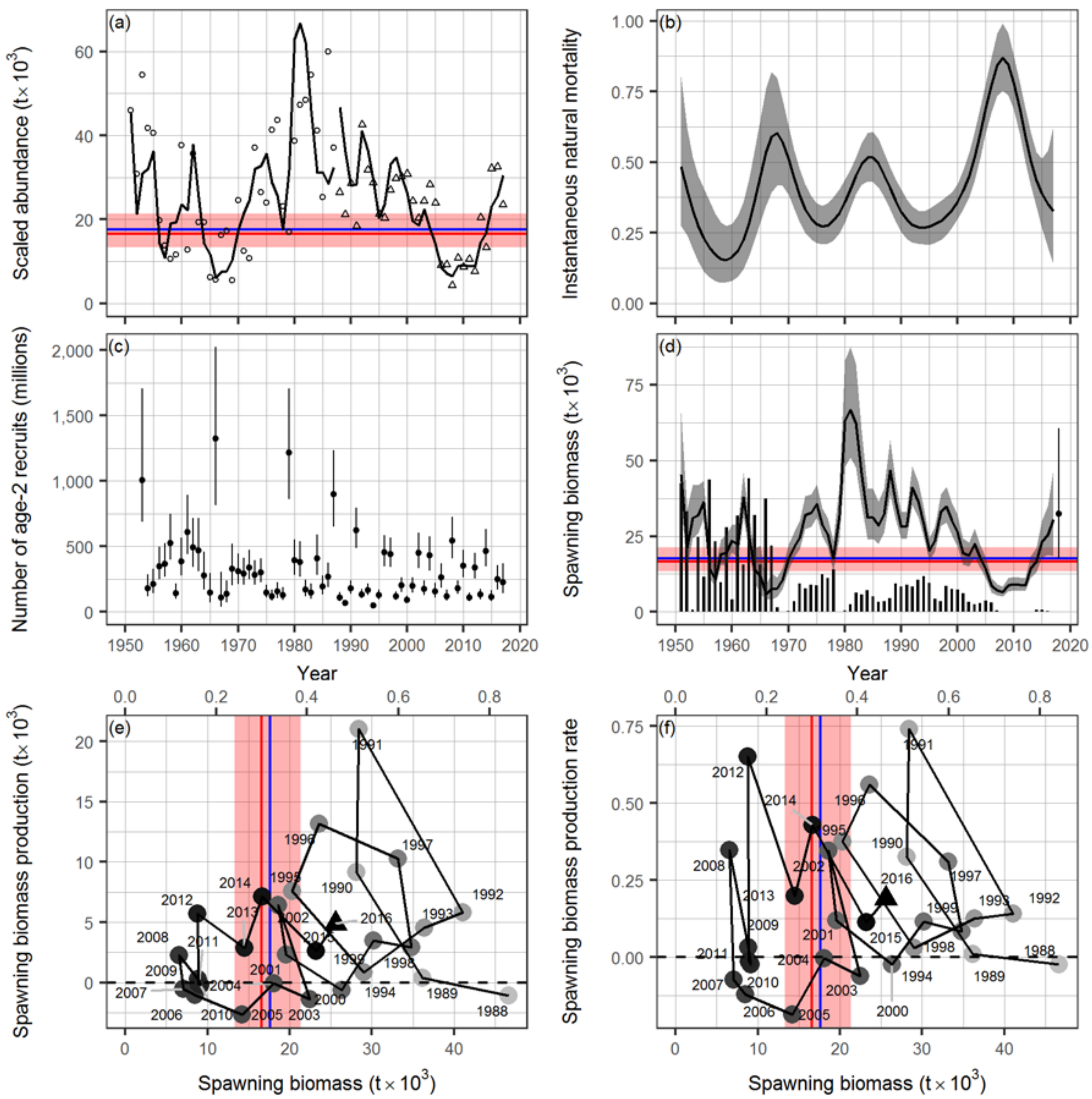

Figure 6. Model output for Pacific Herring in the CC major stock assessment region for AM2. See Figure 2 for description.

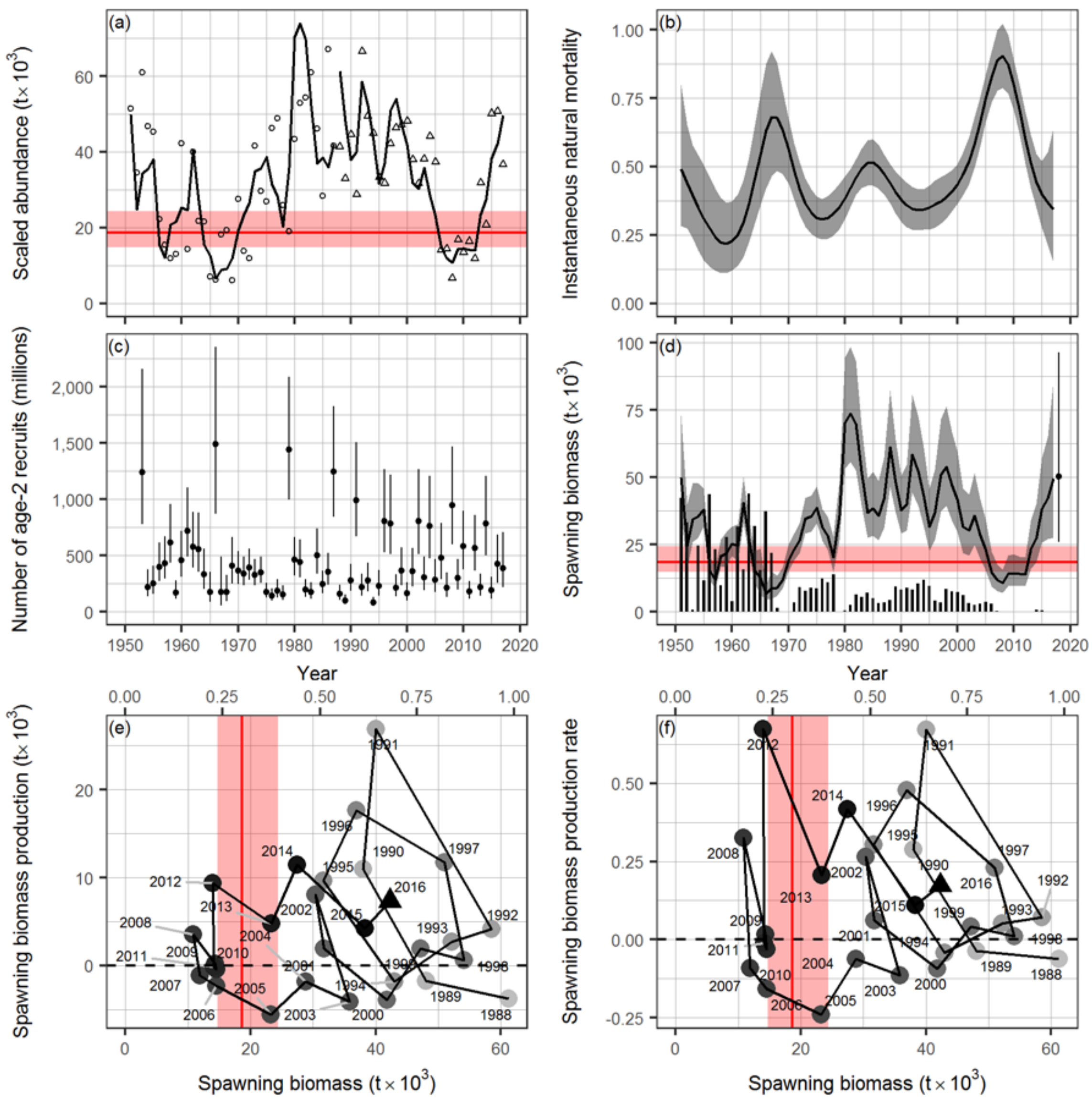

Figure 7. Model output for Pacific Herring in the CC major stock assessment region for AM1. See Figure 2 for description.

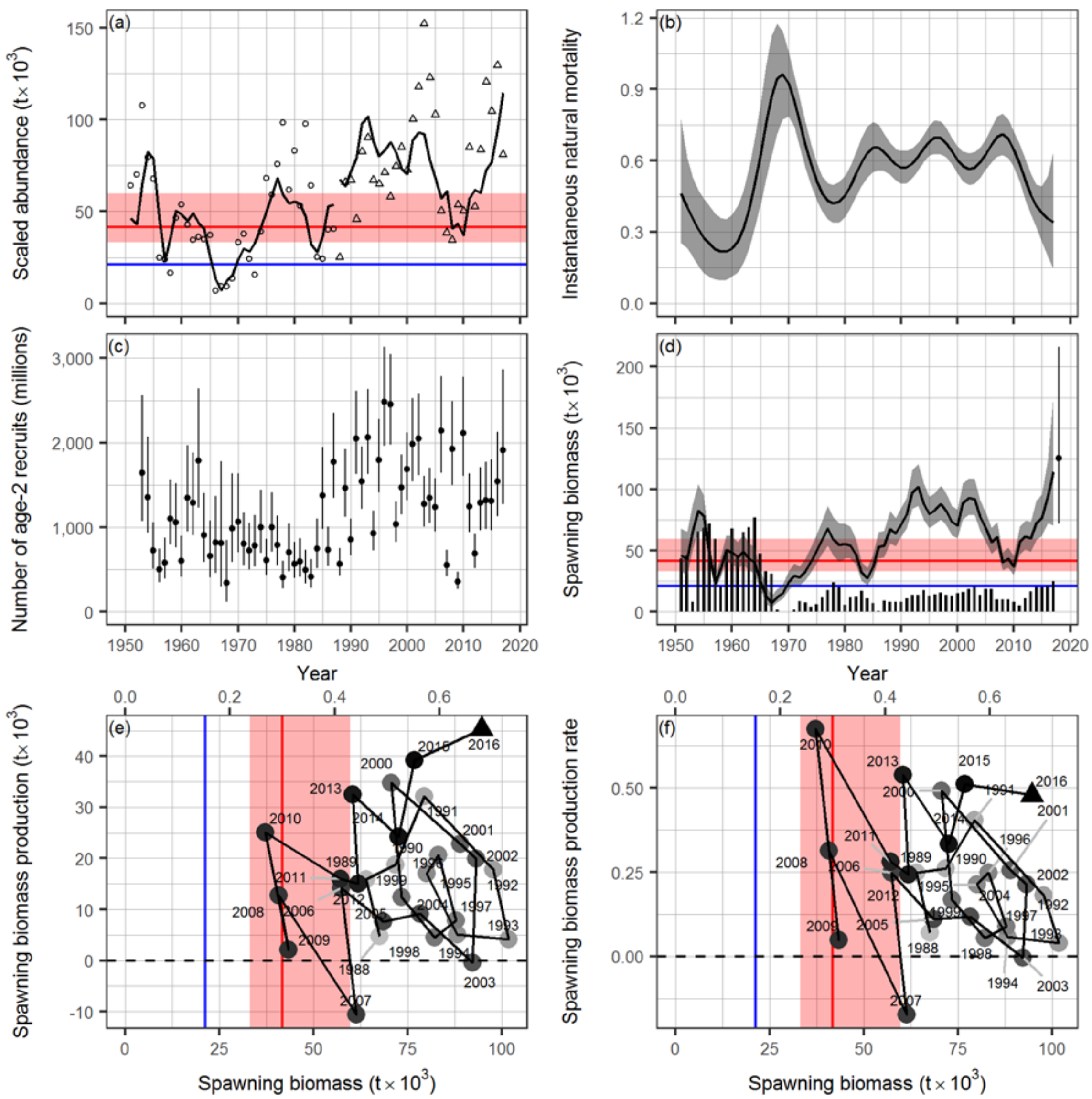

Figure 8. Model output for Pacific Herring in the SOG major stock assessment region for AM2. See Figure 2 for description.

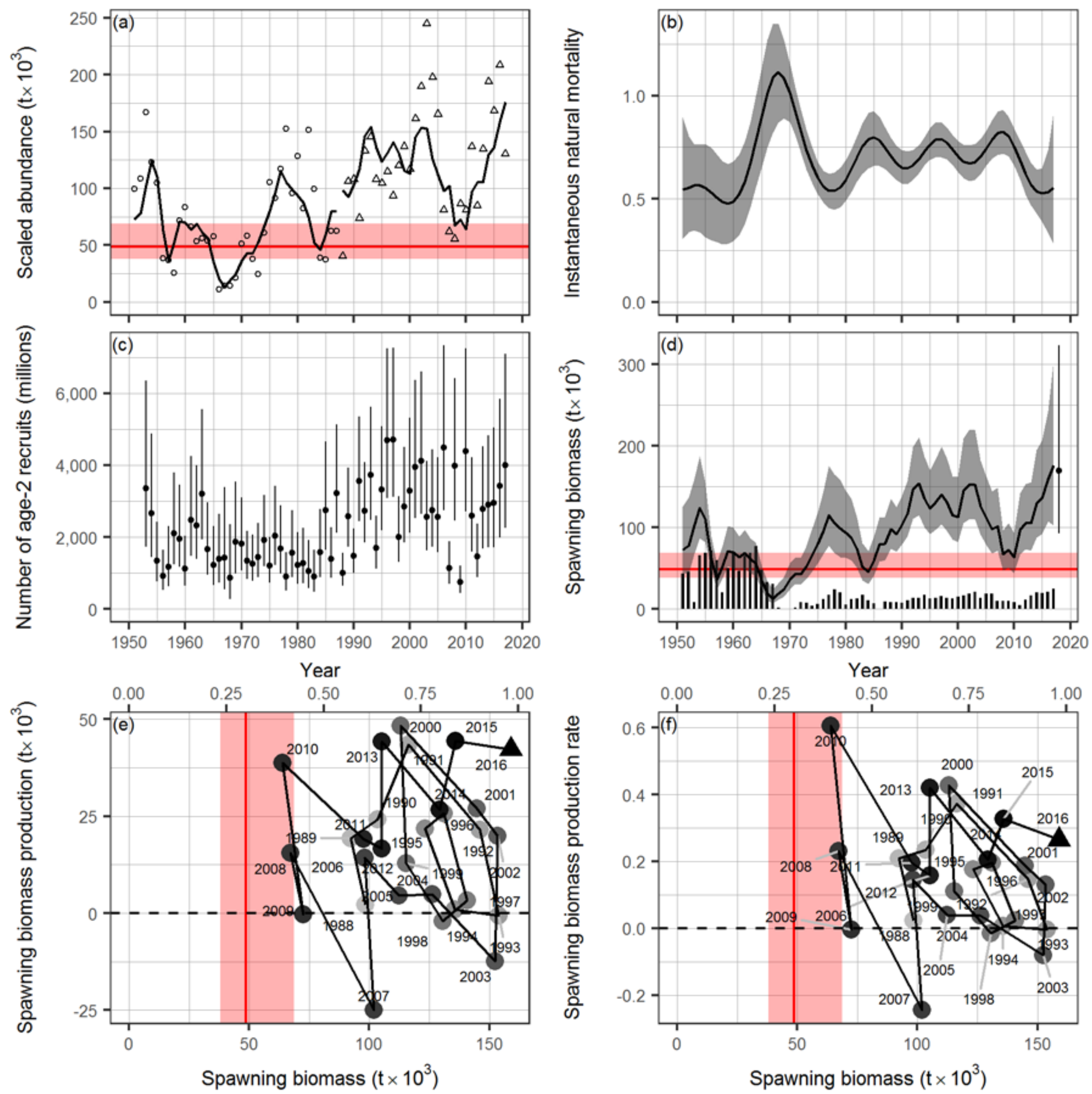

Figure 9. Model output for Pacific Herring in the SOG major stock assessment region for AM1. See Figure 2 for description.

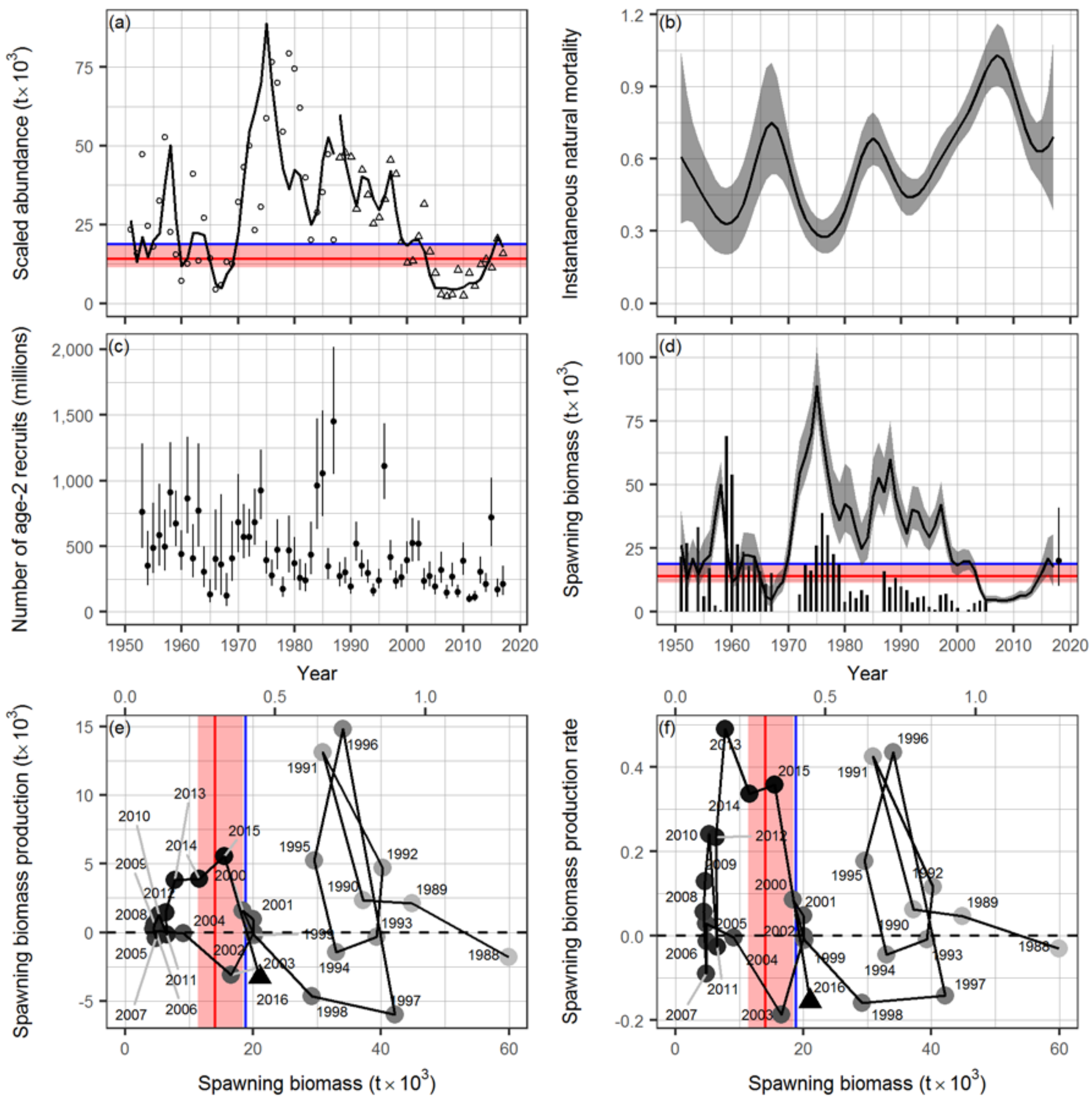

Figure 10. Model output for Pacific Herring in the WCVI major stock assessment region for AM2. See Figure 2 for description.

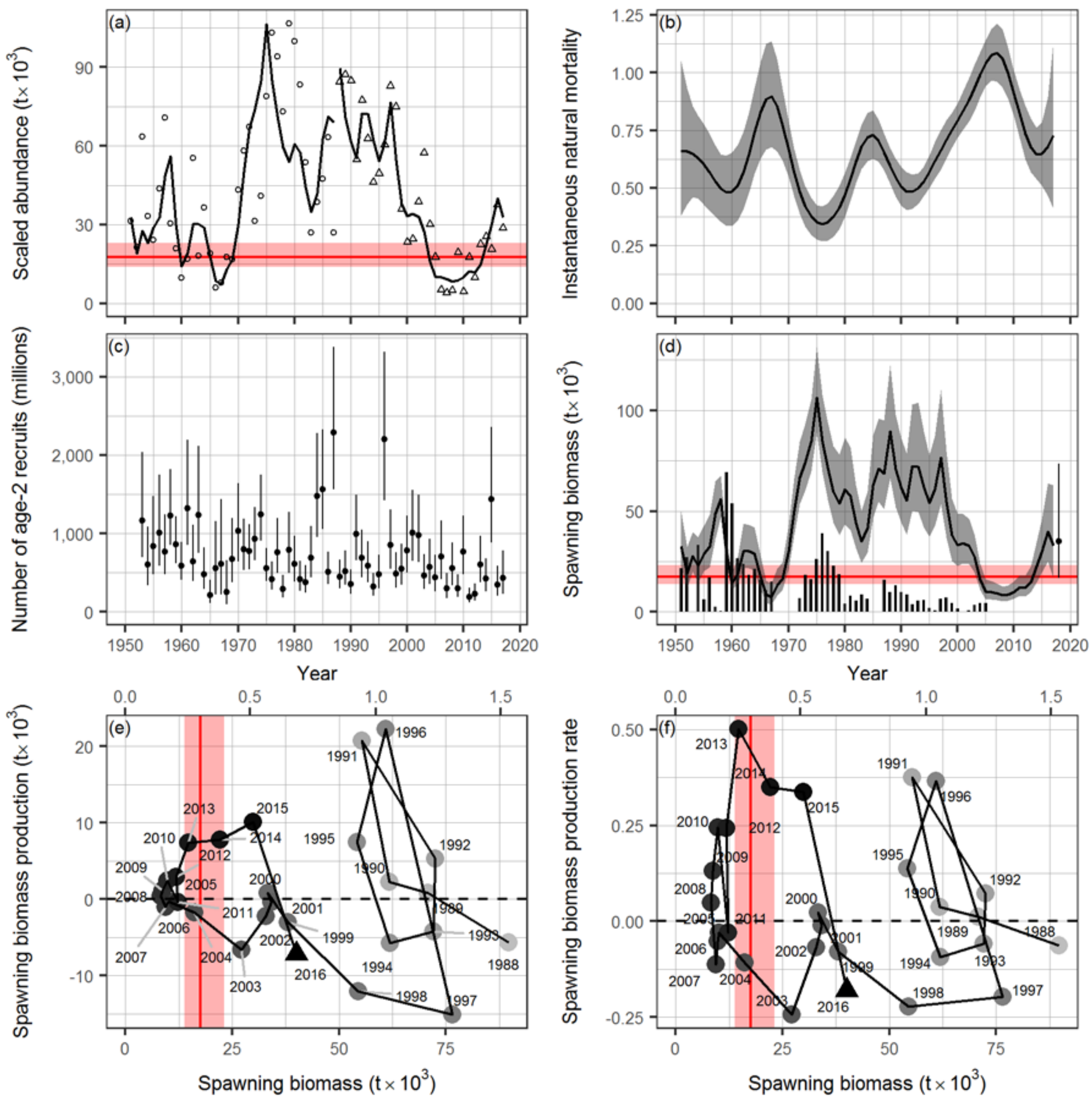

Figure 11. Model output for Pacific Herring in the WCVI major stock assessment region for AM1. See Figure 2 for description.

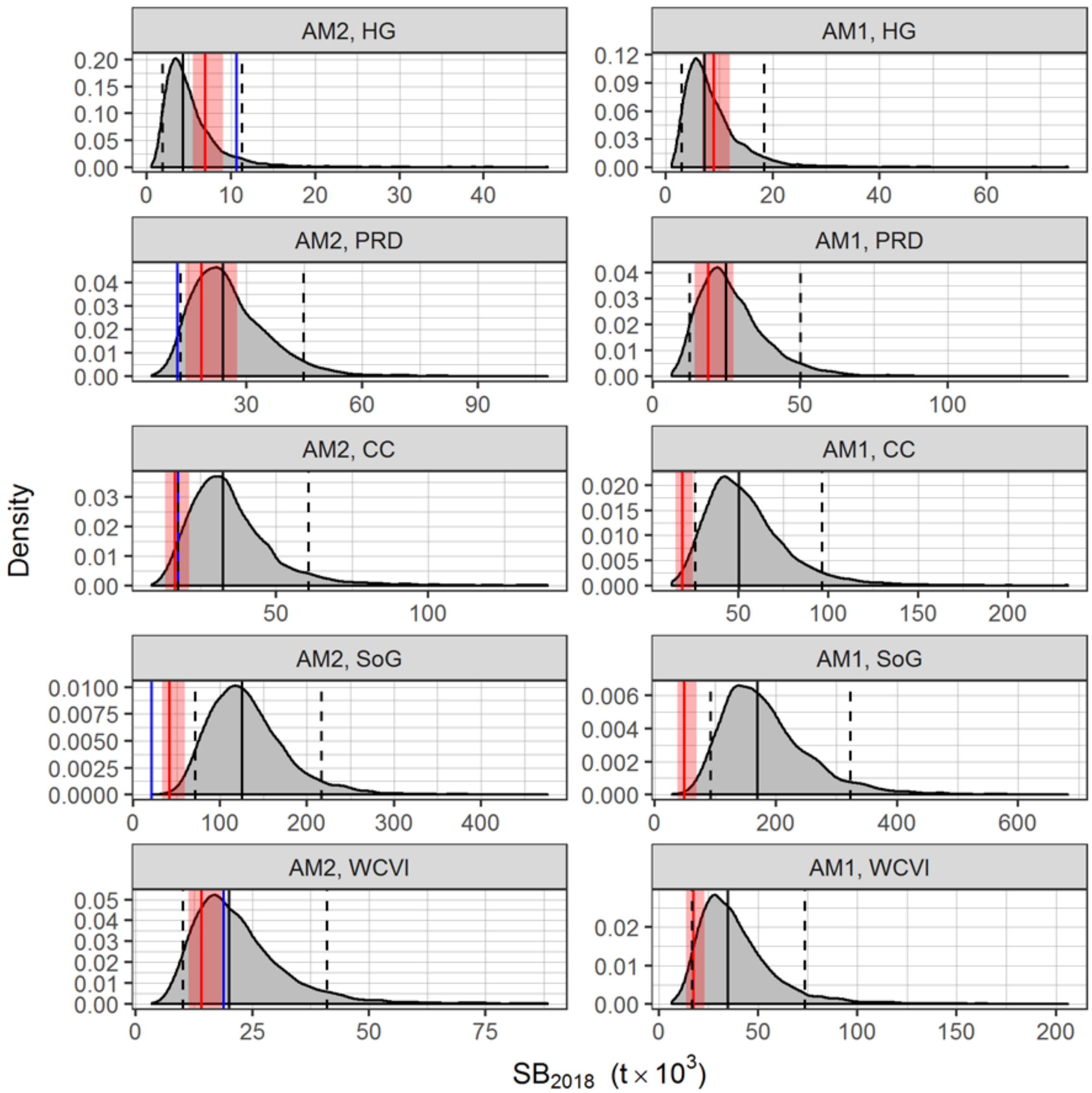

Figure 12. Predicted spawning biomass assuming no fishing in 2018, SB_{2018} in thousands of tonnes, t for Pacific Herring in the major stock assessment regions for models AM2 and AM1. Vertical black lines indicate medians (solid) and 90% credible intervals (dashed) for SB_{2018}. Vertical red lines indicate medians, and red shading indicates 90% credible intervals for the limit reference point (LRP), $0.3SB_0$, where SB_0 is the estimated unfished biomass. If present, vertical blue lines indicate 1996 fixed cutoffs, AM2 plots only (HG: 10,700 t, PRD: 12,100 t, CC: 17,600 t, SOG: 21,200 t, WCVI: 18,800 t).

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