The Selection and Role of Limit Reference Points for Pacific Herring (*Clupea pallasii*) in British Columbia, Canada

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Photo: Herring. Credit: DFO

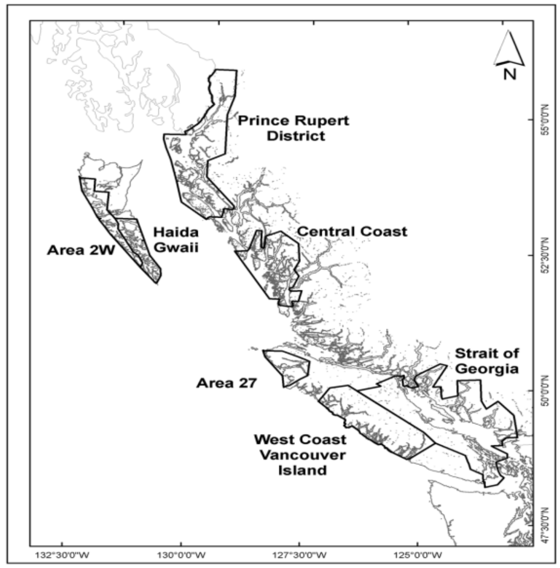

Figure 1: British Columbia Pacific Herring major stock areas: Haida Gwaii (HG), Prince Rupert District (PRD), Central Coast (CC), Strait of Georgia (SOG), West Coast of Vancouver Island (WCVI), and minor stock Area 2W and Area 27.

Context:

British Columbia's Pacific Herring (Clupea pallasii) fisheries are managed using a harvest strategy initially designed and adopted in 1986. The goal of the strategy is to allow for harvest opportunity while maintaining a minimum spawning biomass. The purpose of the minimum spawning biomass is to avoid compromising the reproductive potential of stocks and to facilitate timely recovery from low levels of spawning biomass. The strategy is implemented by coupling annual stock assessments and spawning biomass forecasts to a harvest control rule that specifies when management action is taken to reduce, or cease, commercial harvest. Despite the early adoption of a harvest control rule that anticipated requirements under the DFO Harvest Decision-making Framework Incorporating the Precautionary Approach (DFO 2009, hereafter called the DFO PA Framework), limit reference points have not been specified for Pacific Herring stocks in British Columbia (BC).

This Canadian Science Advisory Secretariat (CSAS), Regional Peer Review (RPR) was undertaken to review the role and selection of limit reference points for the major stocks of BC Pacific Herring. This work is a component of the commitment for renewal of the management framework for BC Pacific Herring in accordance with Canada's Sustainable Fisheries Framework, and to address requirements of the DFO PA Framework policy.

This Science Advisory Report is from the February 7–8, 2017 regional peer review on The Selection and Role of Limit Reference Points for Pacific Herring in British Columbia, Canada. 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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SUMMARY

- Limit reference points (LRPs) are defined as thresholds to states of serious harm to a fish stock where there may also be resultant impacts to the ecosystem, associated species and a long-term loss of fishing opportunities. Serious harm is considered to include irreversible and slowly reversible undesirable states.
- A LRP should be positioned before a state of serious harm occurs, rather than at the state of serious harm and must be avoided with high probability under the DFO Harvest Decision-making Framework Incorporating the Precautionary Approach (DFO 2009, hereafter called the DFO PA Framework).
- An evidence-based, production analysis approach, conditional on current data and stock assessment model assumptions, was used to evaluate whether the major Pacific Herring stocks in British Columbia show stock states consistent with signs of possible serious harm.
- Relationships between production and spawning biomass were examined to determine whether persistent low production and low biomass (LP-LB) states have occurred for the major stocks of Pacific Herring.
- The production analysis diagnosed recent LP-LB states for stocks in the Central Coast (CC), Haida Gwaii (HG) and West Coast of Vancouver Island (WCVI) management areas that were associated with persistent loss of benefits to resource users over a period from about one to two Pacific Herring generations (~6-11 years). Persistent LP-LB states were not diagnosed for stocks in the Prince Rupert District (PRD) and Strait of Georgia (SOG) management areas.
- The spawning biomass estimate that defined the upper boundary (frontier) of a persistent LP-LB state was interpreted as the threshold to possible serious harm for each Pacific Herring stock. A stock status-based LRP corresponding to the ratio of estimated spawning biomass (B_t) at the threshold to estimated unfished biomass (B_0) was selected, based on results for the CC, HG, and WCVI stocks, across two assessment model configurations.
- A spawning biomass-based LRP of $0.3B_0$ is recommended for the CC, HG, and WCVI stocks based on results of the production analysis *and* consistency with international best practice recommendations.
- A LRP of $0.3B_0$ is also recommended for the PRD and SOG stocks as it aligns with best practice recommendations, and because these stocks are geographically adjacent to stocks for which recent low LP-LB states were detected.
- The equilibrium replacement fishing mortality rate, F_{rep}, is considered a threshold for recruitment overfishing consistent with the concept of serious harm since it is a measure of the ability of a stock to replace itself over the long-term. Because of this, F_{rep} and spawning potential ratio proxies, F_{SPR30} and F_{SPR40}, were evaluated for each major stock, as were the equilibrium fishing mortalities associated with maximum sustainable yield, F_{MSY} and $F_{0.1}$.
- Estimates of F_{rep} and proxies were implausibly high for the major stocks of Pacific Herring, largely due to increasing estimates of natural mortality (M) over time (non-stationarity). In addition, the juxtaposition of selectivity and maturity schedules suggested that all fish could spawn at least once before becoming vulnerable to commercial fisheries. Results also implied that stocks need to be maintained close to the unfished biomass, B_0, to maintain population viability. Equilibrium reference points were rejected as candidates for LRPs due to numerous structural uncertainties that made their interpretation difficult.

- Experience with the current harvest strategy since 1986 indicates that persistent LP-LB states can occur when target harvest rates are set at or below 0.2 of the forecasted spawning biomass; for example, in the case of the CC, HG and WCVI stocks.
- A management strategy evaluation process, with engagement of managers and resource-users, is recommended to identify measurable objectives associated with both LRPs and target reference points for BC Pacific Herring. This process is needed for implementation of a closed loop simulation analysis to determine the expected performance of alternative management procedures with respect to providing acceptable performance and trade-offs in management outcomes related to the objectives.
- Ecosystem service requirements of Pacific Herring predators are poorly understood and measurable objectives for predators in BC are not specified. In the absence of quantitative models that represent hypotheses related to trophically dependent species, no adjustment of LRP recommendations for forage fish can be recommended at this time. Future development of operating models within a management strategy evaluation process may include ecosystem dynamics related to predator communities.
- Mechanisms to characterize serious harm to Pacific Herring stock in terms of states related to 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 other definitions of serious harm. Spatial operating models could also inform management options at finer spatial scales than the current major management areas.
- It is recommended that the development of both operating and assessment models should focus on the parameterization of natural mortality, estimates of maturity-at-age, and the effects of assumed prior probability distributions.
- The phasing-in of any new management procedure (i.e., changes to data collection, stock assessment models and/or harvest control rules) designed to avoid LRPs and achieve targets is recommended to mitigate short-term consequences to resource users.

INTRODUCTION

Biological limit and target reference points are commonly used to evaluate the status of fished populations in many fishery management jurisdictions. Although the BC Pacific Herring management system already meets some requirements of the DFO PA Framework, limit and target reference points related to biomass and limit fishing mortality rates have not been identified. A significant challenge to identifying biological limit reference points (LRPs) is linking them to the goal of avoiding "serious harm" that underpins international agreements and domestic fisheries policies. The DFO PA Framework states "*… the LRP represents the stock status below which serious harm is occurring to the stock. At this stock status level, there may also be resultant impacts to the ecosystem, associated species and a long-term loss of fishing opportunities.*" This policy statement establishes three considerations related to serious harm:

1. Serious harm applies not only to the stock of interest, but also to dependent species (e.g., predators) and other ecosystem resources (e.g., habitat);
2. A LRP should be positioned *before* a state of serious harm occurs, rather than *at* the state of serious harm (e.g., at a biomass level above the level where the possibility of serious harm exists or at a fishing mortality rate lower than one expected to produce serious harm); and
3. Long-term loss of benefits to resource users should be avoided.

LRPs are thresholds to serious harm that should be avoided with high probability. A LRP in isolation is not useful until the desired probability of avoiding the LRP is specified, as well as a time-frame for evaluating the success of management actions intended to fulfil the goal of avoiding the LRP, i.e., a measurable objective is fully specified. The purpose of an LRP is to separate management objectives from the operational control points (OCPs) where management actions are triggered. For example, a harvest control rule (HCR) consistent with the DFO PA Framework includes a biomass level where the harvest rate is reduced as stock biomass decreases. That biomass level is an OCP intended to encourage stock growth away from the LRP.

The harvest strategy for BC Pacific Herring introduced in 1986 anticipated the DFO PA Framework requirement for a harvest control rule with OCPs, and was founded on concepts consistent with avoiding serious harm. The Herring harvest strategy is intended to preserve a minimum spawning biomass to prevent deleterious low biomass levels where the reproductive potential of stocks may be compromised. Low biomass can result from overfishing, or from naturally occurring declines in abundance that are characteristic of small pelagic species. A second goal of the minimum spawning biomass is to facilitate timely recovery of stocks to higher abundance when declines occur. The minimum spawning biomass established in 1986 was specified as 25% of the unfished equilibrium spawning biomass, or $0.25B_0$. The HCR was intended to reduce the commercial fishing harvest rate to 0 when one-year forecasts indicated spawning biomass would be less than the estimate of $0.25B_0$. *Thus, the* $0.25B_0$ *level was implemented as an OCP where management action is taken, rather than as a LRP to be avoided with high probability.*

Although avoiding serious harm is cited as the basis for biologically based LRPs, practical experience shows that it is difficult to define states of serious harm until they become quite severe. Furthermore, considerable amounts of uncertainty need to be admitted for compliance with DFO PA Framework requirements. For example, for BC Pacific Herring, time-varying processes related to productivity affect the estimation of biological reference points (BRPs) and the management procedures put in place to avoid limits and achieve targets. Observed weight-at-age has declined for all five major stocks (DFO 2016). Assessment model estimates of natural mortality rate (M) vary over time, differ among stock areas, and for at least three of the major stocks have shown an increasing trend over about the last two decades (DFO 2016). Both these time-dependent processes influence the estimation of population scale and productivity parameters required for calculation of theoretical reference points, and can lead to biased estimates of reference points if not accurately accounted for. Unfortunately, there is no best practice established for doing this, although "dynamic" reference points are sometimes recommended. However, Cox et al. (2015[1]) determined that the use of dynamic reference points led to the progressive lowering of a conservation threshold for BC Pacific Herring such that risk to stocks would not be indicated when it was actually occurring.

Two types of analyses were undertaken to investigate possible serious harm for BC Pacific Herring stocks. The first analysis was based on interpreting a persistent low production and low biomass (LP-LB) stock state, as consistent with possible signs of serious harm under the DFO PA Framework policy interpretation. Depletion estimates, defined as the implied ratio of spawning biomass to unfished equilibrium spawning biomass (B_t/B_0) were evaluated in the context of investigating signs of serious harm. Sainsbury (2008) recommended $0.3B_{\text{unfished}}$ as a best practice biomass-based limit reference point. B_{unfished} is a dynamic, time-varying estimate

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[1] Cox, S.P., Benson, A.J., Cleary, J.S., and Taylor, N.G. 2015. Candidate limit reference points as a basis for choosing among alternate harvest control rules for Pacific Herring (*Clupea pallasii*) in British Columbia. CSAS Working Paper 2013PEL01 (Accepted WP, final revisions stage)

provided by model calculations based on the expected stock dynamics in the absence of a fishery. For stocks such as Pacific Herring that can exhibit significant fluctuations in productivity, coupled with decreasing weight and increasing natural mortality (e.g., DFO 2016), the $0.3B_{\text{unfished}}$ level could occur at very low levels of absolute abundance during periods of low productivity and may not serve as a precautionary limit consistent with the DFO PA Framework. Sainsbury noted that the equilibrium unfished spawning biomass (B_0) may be used as a proxy for B_{unfished}, if equilibrium assumptions are made.

A second analysis was based on avoiding serious harm framed in terms of avoiding recruitment overfishing (Myers et al 1994; Shelton and Rice 2002). Conceptually, recruitment overfishing can be defined as the state when fishing has sufficiently reduced the size of the spawning stock so that recruitment is compromised. A more intuitive definition of recruitment overfishing is that, on average, recruitment in a given year is insufficient for the population to replace itself. Previous authors have suggested using the replacement fishing mortality rate (F_{rep}) as a threshold for recruitment overfishing, defined as the fishing mortality rate that would result in the median juvenile survival rate (*recruits / spawning biomass*) observed in the stock recruitment data (Sissenwine and Shepherd 1987; Mace and Sissenwine 1993).

ANALYSIS

Stock Status and Production Relationships

Production relationships for the five major stocks of Pacific Herring in relation to spawning stock biomass were evaluated to determine whether there is evidence for stock states that show signs of persistent low production and low biomass (LP-LB) states, consistent with signs of possible serious harm. The analyses were conditional on current data and assessment model assumptions, based on median posterior density (MPD) outputs from two versions of an age-structured stock assessment model that differed in the treatment of spawn survey catchability parameters (q_1, q_2) for the surface survey period (1951-1987) and dive survey period (1988-2016), respectively. The two models are labelled AM1 (q_1 and q_2 estimated with prior probability distributions) and AM2 (q_1 estimated, q_2=1) and are described in DFO (2016). The primary difference between the AM1 and AM2 stock reconstructions is the decrease in biomass scale that results from fixing q_2=1. Plots representing trends over time in spawning biomass, natural mortality, production and production rate for the WCVI stock are included in the main body of this report (Figures 2 and 3). The corresponding graphical summaries for the other four major stocks are included in the Appendix (Figure 4 to Figure 11).

Time series trends of estimated spawning biomass for AM1 and AM2 show that the five major stocks of BC Pacific Herring simultaneously declined to historically low spawning biomass levels in the late 1960s before recovering (panel a, Figures 2 to 11). By the mid-2000s, the CC, HG, and WCVI stocks had again declined to low biomass levels similar to levels experienced during the collapse in the late 1960s. However, the characteristics of the stock dynamics differed between these periods. For example, stocks rapidly increased from low spawning biomass levels in the late 1960s within 3-4 years to above average levels of spawning biomass following cessation of commercial fishing and sustained relatively high spawning biomass when commercial fisheries were resumed until the mid-2000s. In contrast to the recovery of the late 1960s and early 1970s, recent low spawning biomass levels estimated for the CC, HG, and WCVI management areas have persisted over a period of about one to two Pacific Herring generations (6-11 years). Stocks in the PRD and SOG management areas also declined by the late 2000s, but not to levels estimated for the late 1960s, and spawning biomass in the SOG area has since increased to an estimated historic high level (DFO 2016).

Annual production (P_t) was calculated as the change in spawning biomass (B_t) from year *t* to *t*+1, and the catch (C_{t+1}) that was removed in year *t+1,* using the equation $P_t = B_{t+1} - B_t + C_{t+1}$ This is a modification of Hilborn (2001) to account for dynamics of the assessment model (Martell et al. 2012) which estimates end of year spawning biomass rather than beginning of year spawning biomass; and assumes that spawning biomass is observed after the catch is taken. Production estimates were calculated from estimated annual spawning biomass and catch for models AM1 and AM2 for *t*=1951 to 2015. The annual production *rate* (P_t/B_t) was also calculated.

Low stock biomass levels can be associated with deleterious outcomes such as recruitment overfishing, or can be exacerbated by increased natural mortality (e.g., due to predation) that reduces the capacity of a stock to recover. Therefore the persistence of low productivity, low biomass (LP-LB) states that lead to irreversible or slowly-reversible failure to recover, as well as the loss of benefits to resource users, was considered consistent with signs of possible serious harm. Visual inspection of phase plots showing the relationship between annual production and spawning biomass, and between annual production *rate* and spawning biomass was used to diagnose persistent LP-LB states (panels c and d, Figures 2 to 11). Depletion (D_t), defined as the ratio of estimated spawning biomass to unfished equilibrium biomass for a given year (i.e., B_t/B_0), was also calculated and evaluated across the time series (*t*=1951 to 2016), for both AM1 and AM2.

Conclusions from the examination of production relationships and estimates of depletion for the five major stocks include:

1. Production estimates trended to negative average levels (WCVI) or near zero levels (HG, CC) in advance of the decline in spawning biomass of the mid-2000s;
2. Recent and *persistent* LP-LB states occurred for stocks in the CC, HG, and WCVI management areas and were coincident with zero commercial harvest;
3. The loss of production occurred at relatively high (above average) levels of spawning biomass;
4. The decline in spawning biomass was preceded by declines in observed weight at age and increasing estimates of natural mortality that began about 1990;
5. The transition to a LP-LB state for the CC, HG and WCVI stocks was rapid, occurring in three years (less than one Pacific Herring generation);
6. The low biomass state of the late 1960s was not associated with persistent low productivity;
7. The LP-LB state persisted for six years (CC) to eleven years (HG and WCVI, model AM2), despite large commercial catch reductions, or cessation of commercial catches;
8. The estimated harvest rates were on average, less than the target harvest rate of 20% for CC, HG and WCVI (AM1 and AM2) or about 20% (PRD and SOG, model AM2) and were much less than estimated harvest rates during the 1960s;
9. During the time periods corresponding to LP-LB states for the CC, HG and WCVI stocks, estimated spawning biomass depletion levels averaged about $0.25B_0$ for model AM1 and were less than $0.25B_0$ for model AM2;
10. The PRD stock showed a modest decline in spawning biomass in the mid-2000s to about $0.3B_0$ but does not show a persistent LP-LB state; and

11. The SOG stock spawning biomass declined by more than 50% from 2000 to 2008-2010 to $0.4B_0$ or $0.5B_0$ (model AM1 and AM2, respectively) but has since increased to a historical high level of estimated spawning biomass and does not show a persistent LP-LB state.

The spawning biomass estimate that defined the upper boundary (frontier) of a persistent LP-LB state in the recent period was interpreted as the threshold to possible serious harm for each of the CC, HG and WCVI Pacific Herring stocks. For the CC, HG, and WCVI stocks, the frontiers of the LP-LB states were estimated to range from spawning depletion levels (D_{max}) of 0.244 (WCVI) to 0.328 (HG) for model AM1 and 0.174 (CC) to 0.284 (HG) for model AM2. These levels are comparable to maximum depletion levels (D_{max}) estimated for LB states for all five major stocks in the late 1960s, which ranged from 0.19 (HG) to 0.33 (WCVI) based on model AM1 and from 0.218 (PRD) to 0.289 (WCVI) for model AM2. The LP-LB states persisted from about one (CC) to two Pacific Herring generations (HG, WCVI) where generation time was estimated at about five years by Cleary et al. (2010). Summary results for the five major Pacific Herring management areas for models AM1 and AM2 are reported in Table 1 and Table 2, respectively.

The transition into the LP-LB state was rapid, usually occurring within three years from relatively large spawning biomass levels and coincident with negative production values. Based on results from model AM2, the CC stock was estimated to be at a spawning depletion of 0.47 in 2003 when production became negative and entered the LP-LB state by 2006. Similarly, the HG stock declined from an estimated spawning depletion level of 0.78 in 1998 into the LP-LB state by 2000 (model AM2 results). Finally, the WCVI stock declined into the LP-LB state by 2005 from an estimated depletion level of 0.69 in 2002 (model AM1 results). For CC, HG and WCVI stocks, the transition was coincident with negative production values.

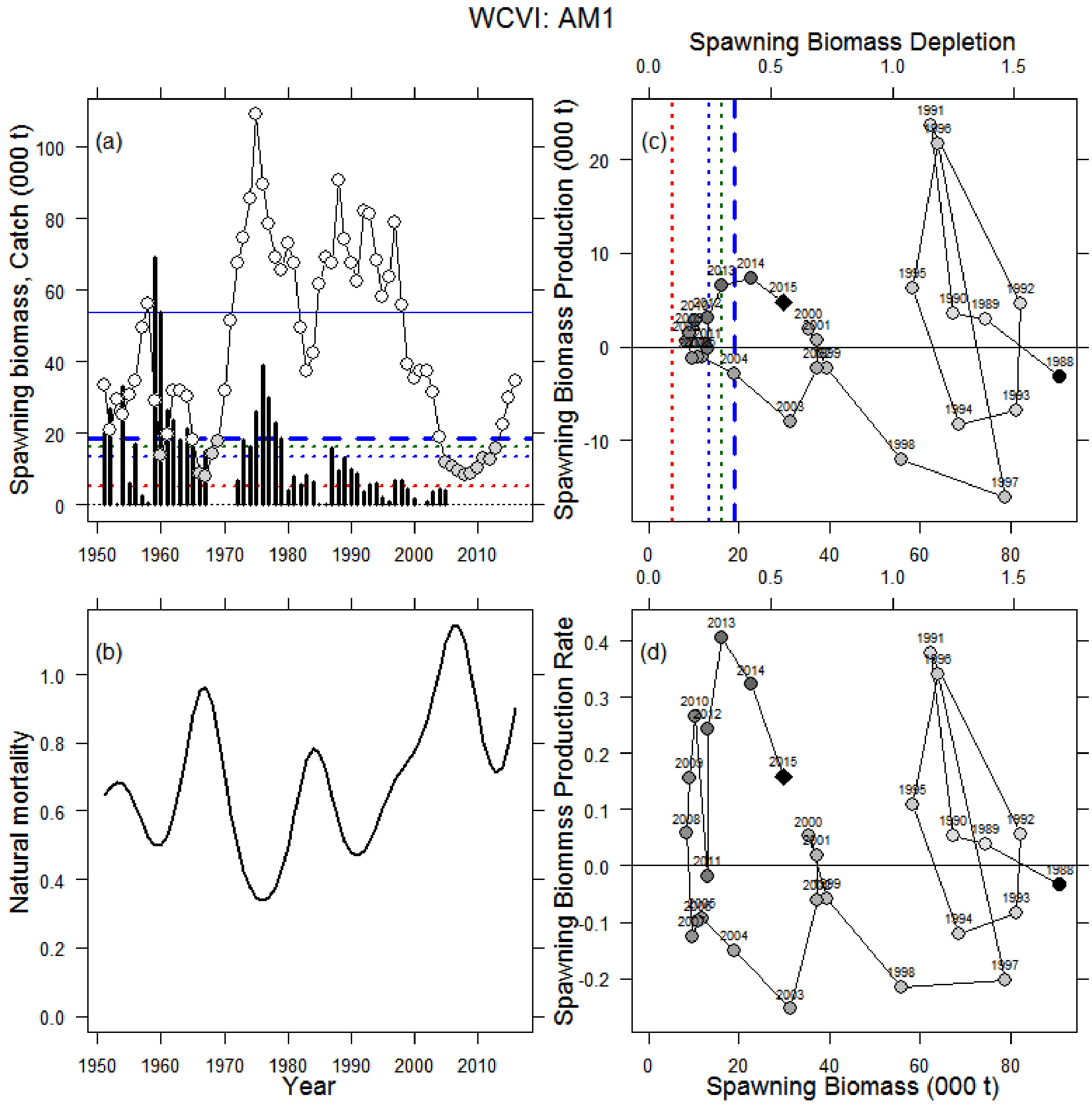

Figure 2: Assessment model AM1 parameter and production estimates for Pacific Herring in the WCVI management area. Panel (a) shows the 1951-2016 time series of estimated spawning biomass (circles) and catch (vertical bars). The lower 20% of spawning biomass estimates are shaded grey. Reference lines are shown at estimates of $0.1B_0$, (red dashed line) $0.25B_0$ (blue dashed line), $0.3B_0$ (green dashed line), the 1996 fixed cutoff value (thick blue long dashed line), and unfished spawning biomass (solid blue line). The time series of estimated natural mortality is shown in panel (b). Phase plots of spawning biomass production and spawning biomass production rate against spawning biomass are shown in panels (c) and (d), respectively, for 1988 (black circle) to 2015 (black diamond). Grey shading of the circles becomes darker in chronological order. Calendar years are indicated above each symbol. The axis scales at the top of panels (c,d) are in units of spawning biomass depletion, i.e., spawn biomass divided by the estimated unfished spawning biomass from the assessment model. For panel (c), reference lines are shown at estimates of $0.1B_0$, (red dashed line) $0.25B_0$ (blue dashed line), $0.3B_0$ (green dashed line), and the 1996 fixed cutoff value (thick blue long dashed line). All estimates quantities are based on maximum likelihood estimates (DFO 2016).

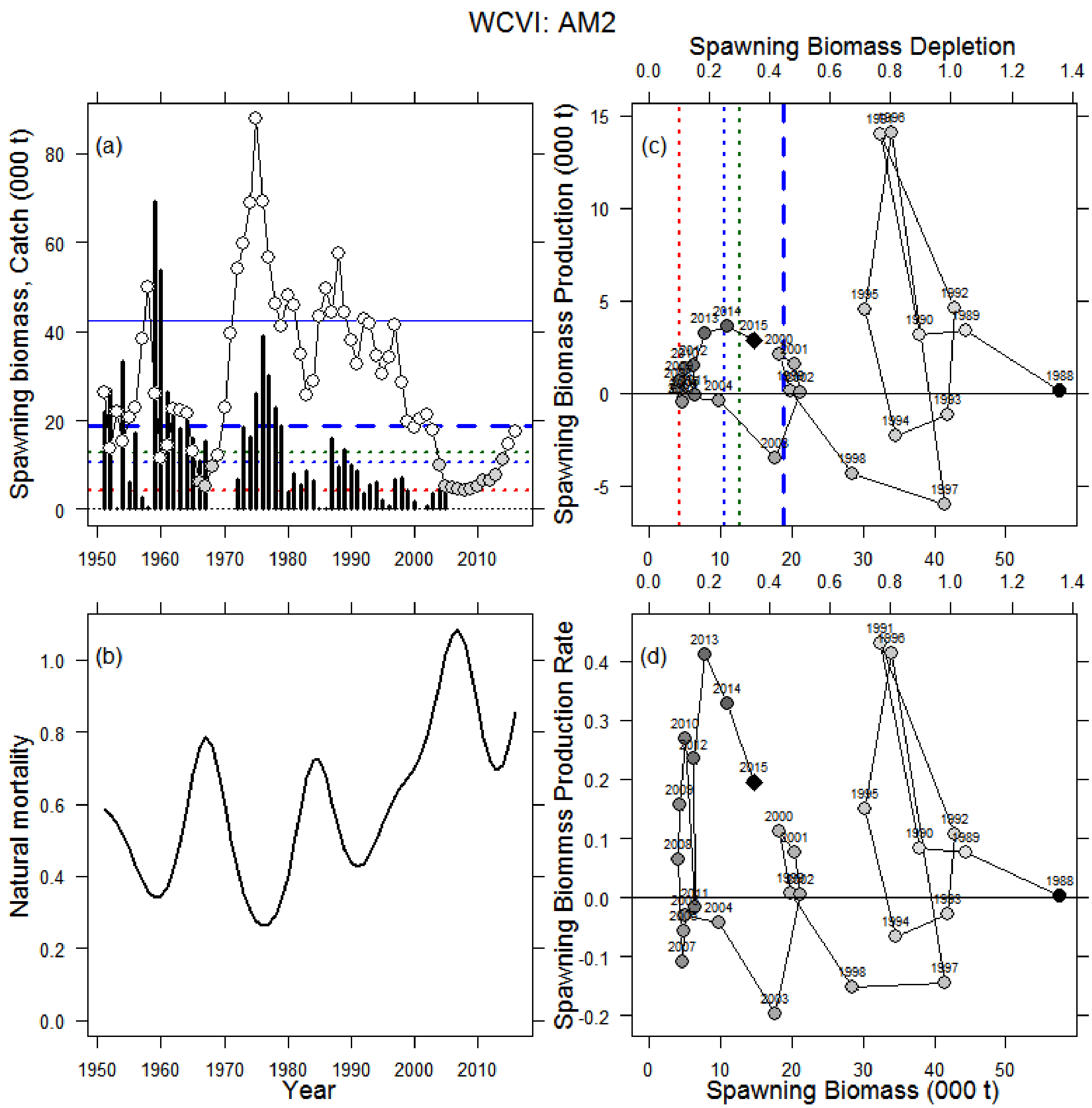

Figure 3: Assessment model AM2 parameter and production estimates for Pacific Herring in the WCVI management area. Description as for Figure 2.

Table 1: Summary of key results for stocks in all five major management areas for model AM1. Visual inspection of phase plots was used to interpret persistent clusters of early low biomass (LB) or recent low production and low biomass (LP-LB) states. The year of entry and sustained exit from the state determined the year ranges. For stocks in the PRD and SOG management areas, a LP-LB state was not diagnosed. The number of years (n) and minimum, average, and maximum spawning biomass depletion (D) values are reported for LB and LP-LB states. The column C=0 indicates the number of years of 0 catch following entry to the recent LP-LB state for stocks in the CC, HG, and WCVI management areas. Depletion levels are reported for spawning biomass (000s t, min, avg, max) and depletion corresponding to 25% of the unfished biomass. The average estimated harvest rate (DFO 2016) in years beginning in 1983 with positive catch is reported as U_{avg}.

	Early					Recent								
Stock	LB Range	n	D_{min}	D_{avg}	D_{max}	LP-LB Range	n	C=0	D_{min}	D_{avg}	D_{max}	$B_{0.25}$	$D_{0.25}$	U_{avg}
CC	1964-1969	6	0.126	0.194	0.260	2006-2011	6	6	0.195	0.245	0.282	14.348	0.250	0.12
HG	1965-1969	5	0.078	0.140	0.188	2000-2008	9	13	0.239	0.279	0.328	9.244	0.250	0.07
WCVI	1966-1969	4	0.149	0.228	0.333	2005-2012	8	10	0.158	0.200	0.244	13.462	0.250	0.09
PRD	1967-1972	6	0.169	0.208	0.238	na	-	-	-	-	-	13.400	0.250	0.18
SOG	1966-1969	4	0.119	0.172	0.227	na	-	-	-	-	-	36.600	0.250	0.13

Table 2: Summary of key results for stocks in all five major management areas for model AM2. Description as for Table 4 but the fixed 1996 cutoff value and associated spawning stock depletion levels are reported as B_{Cutoff} *and* D_{Cutoff}.

	Early					Recent								
Stock	LB Range	n	D_{min}	D_{avg}	D_{max}	LP-LB Range	n	C=0	D_{min}	D_{avg}	D_{max}	B_{Cutoff}	D_{Cutoff}	U_{avg}
CC	1964-1969	6	0.126	0.184	0.256	2006-2011	6	6	0.126	0.159	0.174	17.600	0.345	0.17
HG	1965-1969	5	0.087	0.168	0.225	2000-2010	11	13	0.179	0.222	0.284	10.700	0.447	0.11
WCVI	1966-1969	4	0.121	0.197	0.289	2004-2014	11	10	0.098	0.150	0.262	18.800	0.444	0.15
PRD	1967-1972	6	0.154	0.191	0.218	na	-	-	-	-	-	12.100	0.227	0.20
SOG	1965-1970	6	0.077	0.167	0.252	na	-	-	-	-	-	21.200	0.192	0.22

Equilibrium Reference Points

For each of the major BC Pacific Herring stocks, the equilibrium replacement fishing mortality rate (F_{rep}), the spawning potential ratio proxies (F_{SPR30} and F_{SPR40}), and the equilibrium fishing mortalities associated with maximum sustainable yield (F_{MSY} and $F_{0.1}$) were evaluated (Table 3). F_{rep} is considered a threshold for recruitment overfishing consistent with the concept of serious harm since it is a measure of the ability of a stock to replace itself over the long-term (Sissenwine and Shepherd 1987; Mace and Sissenwine 1993). The equilibrium results are difficult to interpret due to the high values of F associated with some reference points. The estimates of F_{rep} (ranging from 0.26 to 0.41), and F_{MSY} (ranging from 0.45 to 0.78) suggest that all stocks can be fished at high rates and maintain high values of depletion, which is inconsistent with the evidence from the stock assessment reconstructions. Estimates of F_{MSY} were high partly due to the high values of M used in the analysis (long-term average of the time series of M), and partly because the maturity-at-age schedule, as estimated from field studies, is located to the left of model-estimated commercial selectivity-at-age schedules. This means that for all stocks, 50% maturity is estimated to occur at a much younger age than 50% selectivity, which essentially guarantees a large component of the Pacific Herring population can spawn at least once before becoming vulnerable to the fishery. Therefore, the analysis produced implausibly high estimates of sustainable fishing mortality rates. This outcome was markedly so for the HG stock, evidenced by the highest estimate of F_{MSY} among all stocks, which is counter-intuitive since the HG stock has not shown evidence of sustained increase in spawning biomass, even in the absence of fishing.

As indicated by the examination of production relationships, the productivity regime for BC Pacific Herring appears to have shifted in recent years, with none of the CC, HG or WCVI stocks showing similar rates of recovery from low stock size to the recoveries observed after the collapses of the 1960s. This could be due to increasing adult natural mortality in recent years (e.g., panel b, Figures 2 and 3), in which case the apparent shift in in productivity would be driven by reduced productivity in the adult component of the population rather than by recruitment. In this case, a LRP based on F_{rep} may not protect against persistent LP-LB states.

Table 3: Summary of key equilibrium fishing mortality results for all management areas based on model AM1. F > 4 essentially implies a harvest rate (U) approaching 1, where U and instantaneous fishing mortality rate F are related by $U = 1 – e^{-F}$. This implies that virtually all of the vulnerable biomass could be harvested because all fish have had a chance to spawn at least once before being vulnerable to harvest. This result is a possible artefact of the structural assumptions of the model, affecting estimates of natural mortality and selectivity, or of the method to estimate maturity at age.

	F_{rep}	F_{MSY}	F_{SPR40}	F_{SPR30}	$F_{0.1}$
CC	0.41	0.54	2.02	> 4	0.82
HG	0.26	0.78	> 4	> 4	1.74
PRD	0.30	0.45	1.33	2.89	0.64
SOG	0.39	0.55	> 4	> 4	1.62
WCVI	0.39	0.56	> 4	> 4	1.42

Ecosystem and Forage Fish Considerations

The need for a multi-species definition for serious harm for forage fish is considered in both international and domestic policies. However, policies are not prescriptive as to how to define biological limits or targets for forage fish. For example, the United States National Oceanic and Atmospheric Administration (NOAA) *Fisheries Ecosystem-based Fisheries Management* Road

Map (NOAA 2016) includes a requirement to 'Develop and monitor ecosystem-level reference points' (Principle 5), including understanding predator-prey relationships and forage fish dynamics. The DFO *Policy of New Fisheries for Forage Species* states reference points should ensure that fisheries do not reduce the forage species population to levels where either its productivity, or the productivity of predators on it, would be reduced. The implications are that consideration must also be given to dependent species when defining serious harm.

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. Published ecosystem models most commonly describe biomass targets for forage fish, rather than biological limits, and require quantitative descriptions of predator-prey relationships for forage fish. The role of BC Pacific Herring as a forage fish is well known, but the ecosystem service requirements of their predators are poorly understood, predator-prey functional relationships are not well-defined, and objectives for predator species are not quantified. 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.

Sources of Uncertainty

All production and equilibrium reference point estimates are conditional on the data and outputs of models AM1 and AM2 described by DFO (2016). Models AM1 and AM2 differ only by parameter uncertainty related to dive survey catchability. Therefore, structural uncertainties related to alternative hypotheses of population and fishery dynamics are not considered.

Productivity in current stock assessment models is fundamentally driven by assumptions about natural mortality; stock-recruitment relationships and parameters (i.e., steepness); observed changes in size-at-age; the specification of maturity-at-age; and interpretation of the spawn index. There is uncertainty associated with confounding interactions among model parameters used to express these processes.

The analysis of equilibrium reference points resulted in equilibrium fishing mortality rates that are too aggressive for BC Pacific Herring, and imply that relatively high spawning biomass levels can be achieved at those rates. This result is contrary to observations for all five major stocks. The estimation of sustainable fishing mortality rates depends on knowledge of the relationship between stock and recruitment. Unfortunately this relationship is one of the most uncertain processes in stock assessment and may be dependent on prior probability distributions assumed/selected for the steepness parameter. Difficulties in estimating the stock-recruit relationship and its relative influence on stock productivity is exacerbated by non-stationary processes such as those that are likely to apply to BC Pacific Herring, particularly the magnitude of the rate of increase in M. The current structural assumptions about time-varying mortality within the stock assessment (DFO 2016) may create confounding among estimates of steepness, selectivity, survey catchabilities and other stock assessment model parameters. This challenge, coupled with the relative alignment of maturity-at-age and commercial fishery selectivity, means that future consideration of traditional equilibrium reference points should be based on results of simulation testing with operating models that represent a wide range of plausible structural hypotheses for Pacific Herring population, fishery and ecosystem dynamics.

If future declines in the abundance of BC Pacific Herring stocks result in LP-LB states, both the level and duration of such states are uncertain. For example, there is no guarantee that a re-occurrence of recent LP-LB states diagnosed for the CC, HG, and WCVI stocks would occur at the same biomass and production levels, or have the same duration.

Population, ecosystem and fishery dynamics associated with states of possible serious harm related to the spatial distribution, stock structure, and genetic diversity of BC Pacific Herring stocks 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 other definitions of serious harm. Spatial operating models could also inform management options at finer spatial scales than the current major management areas. Similarly, future development of operating models that incorporate ecosystem dynamics such as quantified functional relationships between forage species and their predators, could improve understanding of the performance of candidate LRPs with respect to forage fish considerations.

CONCLUSIONS AND ADVICE

The DFO PA Framework is clear that LRPs must be positioned before a state of possible serious harm is reached (i.e., at a higher spawning biomass level, or lower fishing mortality rate, than states coincident with possible serious harm). However, there is little policy or scientific guidance as to how far above the state of possible serious harm a biomass-based LRP should be positioned in order to avoid serious harm with high probability, particularly in the presence of non-stationary processes such as those that exist for BC Pacific Herring. Cox et al (2015[1]) determined that the use of dynamic reference points led to the progressive lowering of a conservation threshold for BC Pacific Herring, such that risk to stocks could be underestimated. Sainsbury (2008) recommended $0.3B_{\text{unfished}}$ as a best practice biomass-based limit reference point. However, because $0.3B_{\text{unfished}}$ is a dynamic estimate, $0.3B_0$ (an equilibrium proxy for $0.3B_{\text{unfished}}$) was considered here instead.

The approach taken to evaluating possible serious harm for BC Pacific Herring stocks was evidence-based, conditional on current data and assumptions inherent in assessment models AM1 and AM2 (DFO 2016). A persistent LP-LB state was interpreted for BC Pacific Herring as being consistent with signs of possible serious harm, defined as exhibiting an irreversible or slowly-reversible state, low production, and historical (or near historical) low spawning biomass. Recent LP-LB states were diagnosed for stocks in the Central Coast (CC), Haida Gwaii (HG) and West Coast of Vancouver Island (WCVI) management areas that were associated with persistent loss of benefits to resource users over a period from about one to two Pacific Herring generations (~6-11 years). Persistent LP-LB states were not diagnosed for stocks in the Prince Rupert District (PRD) and Strait of Georgia (SOG) management areas. The upper spawning biomass frontier of persistent LP-LB states for stocks in the CC, HG and WCVI management areas was considered to be a threshold to a state consistent with signs of possible serious harm. An LRP of $0.3B_0$ is within the range of the frontier of the LP-LB states for the CC, HG and WCVI stocks based on model AM1. For model AM2, the frontier of the LP-LB state is estimated to be lower by approximately 0.13 to 0.02 depletion units, depending on the stock.

Science advisory conclusions and recommendations are listed below:

- A spawning biomass-based LRP of $0.3B_0$ is recommended for the CC, HG, and WCVI stocks based on results of the production analysis *and* consistency with international best practice recommendations.
- A LRP of $0.3B_0$ is recommended for the PRD and SOG stocks as it aligns with best practice recommendations and because these stocks are geographically adjacent to stocks for which recent low LP-LB states were diagnosed.

- Equilibrium reference points associated with the recent analysis are not recommended. Estimates of F_{rep} and proxies were implausibly high due to high long-term average estimates of natural mortality, and the juxtaposition of the maturity and selectivity ogives.
- A management strategy evaluation process, with engagement of managers and resource-users, is recommended to identify measurable objectives associated with both LRPs and target reference points for BC Pacific Herring. This process is needed for implementation of a closed loop simulation analysis to determine the expected performance of alternative management procedures with respect to providing acceptable performance and trade-offs in management outcomes related to the objectives.
- Ecosystem service requirements of Pacific Herring predators are poorly understood and objectives for predators are not quantified. In the absence of quantitative models that represent hypotheses related to dependent species, no adjustment of LRP recommendations for forage fish can be recommended at this time. Future development of operating models within a management strategy evaluation process may include ecosystem dynamics related to predator communities.
- Future development of population dynamics models that include spatial dynamics and/or stock structure may lead to candidate LRPs and performance indicators that characterize other definitions of serious harm.
- It is recommended that the development of both operating and assessment models should focus on the parameterization of natural mortality, estimates of maturity-at-age, and the effects of prior probability distributions for key parameters in the stock assessment models.
- The phasing-in of any new management procedure (i.e., changes to data collection, stock assessment models and/or harvest control rules) designed to avoid LRPs and achieve targets is recommended to mitigate short-term consequences to resource users.

SOURCES OF INFORMATION

This Science Advisory Report is from the February 7-8, 2017 Regional Peer Review of The Selection and Role of Limit Reference Points for Pacific Herring (*Clupea pallasii*) in British Columbia, Canada. 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 A. FIGURES

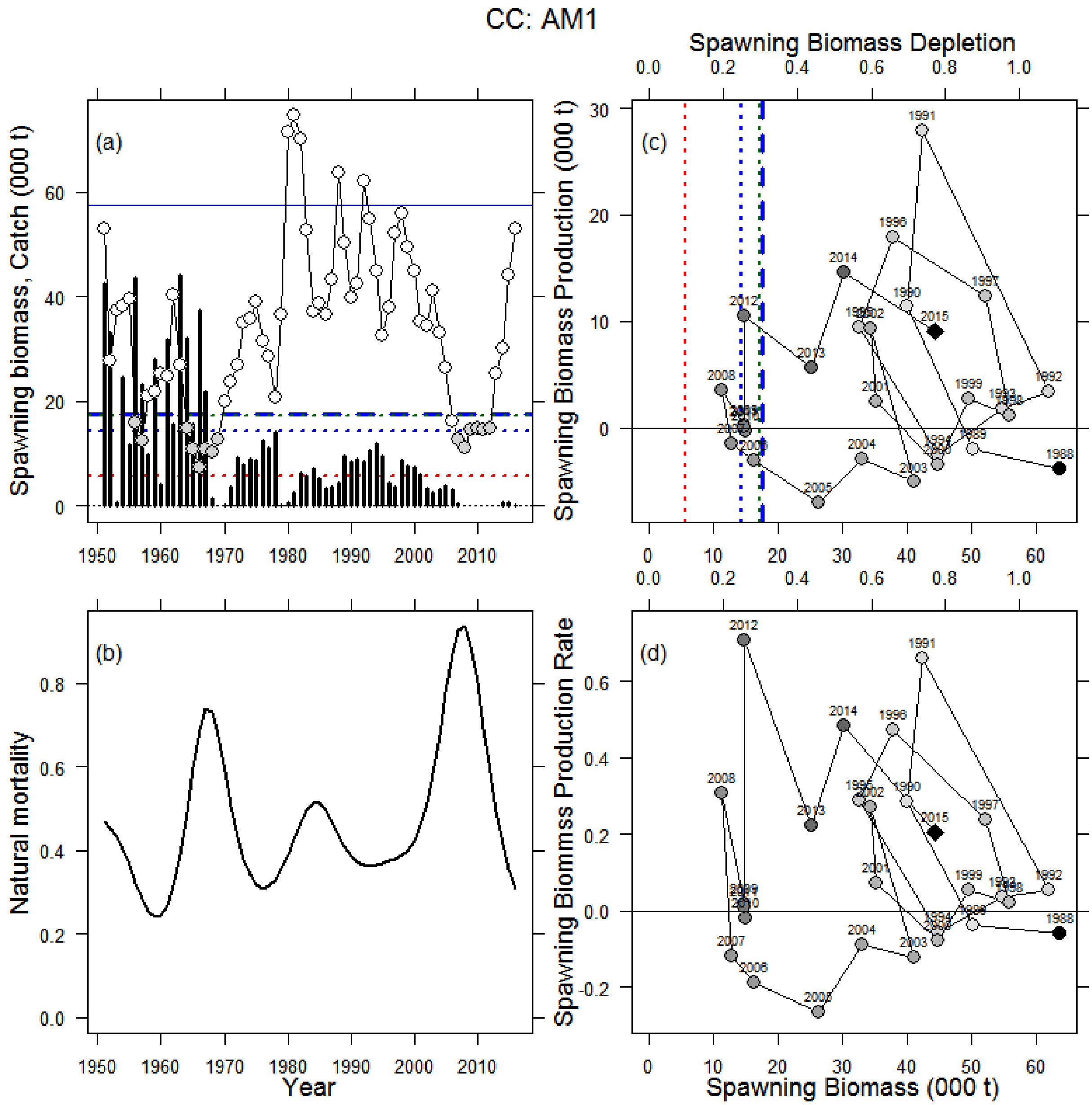

Figure 4: Assessment model AM1 parameter and production estimates for Pacific Herring in the CC management area. Description as for Figure 2.

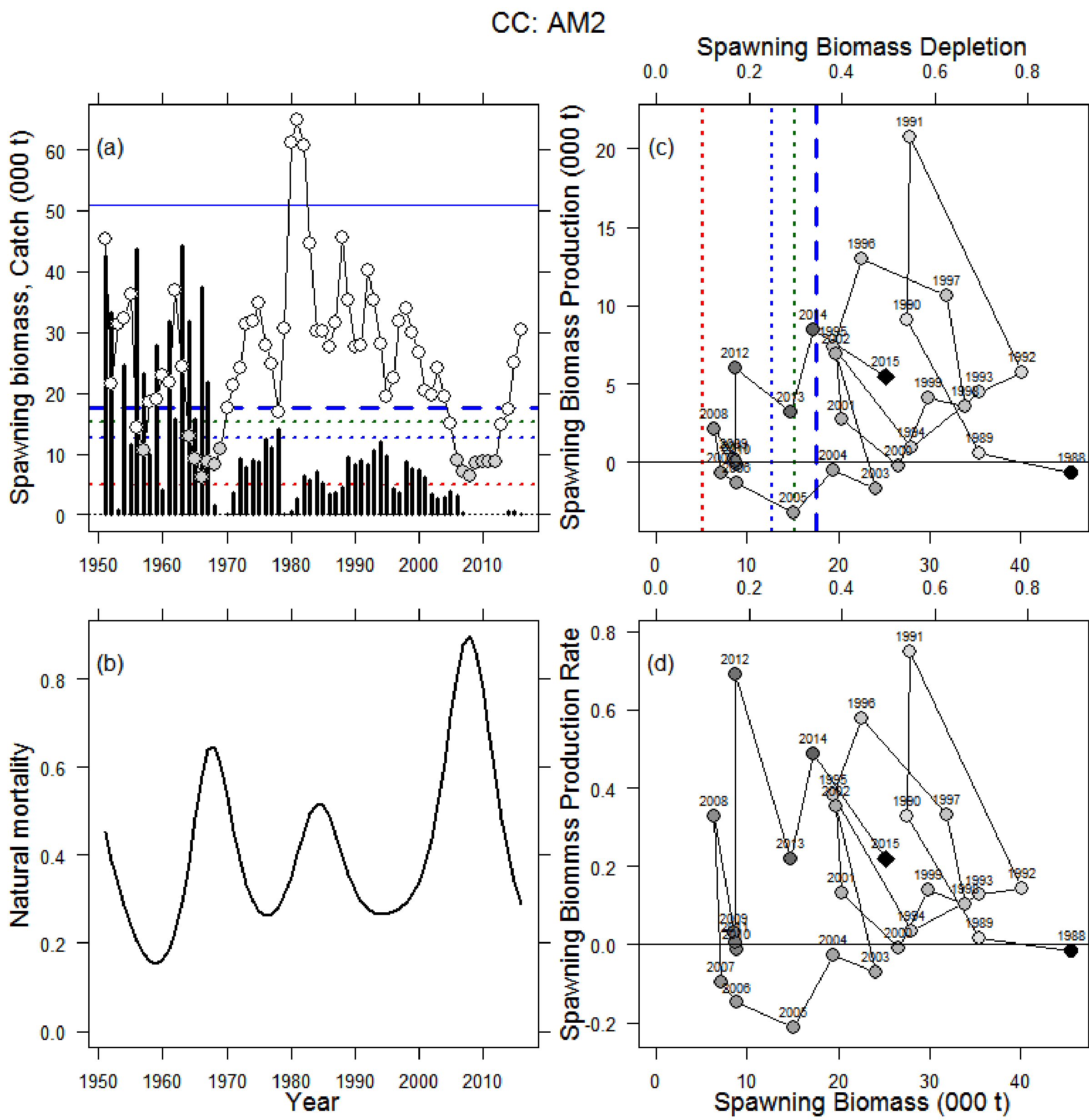

Figure 5: Assessment model AM2 parameter and production estimates for Pacific Herring in the CC management area. Description as for Figure 2.

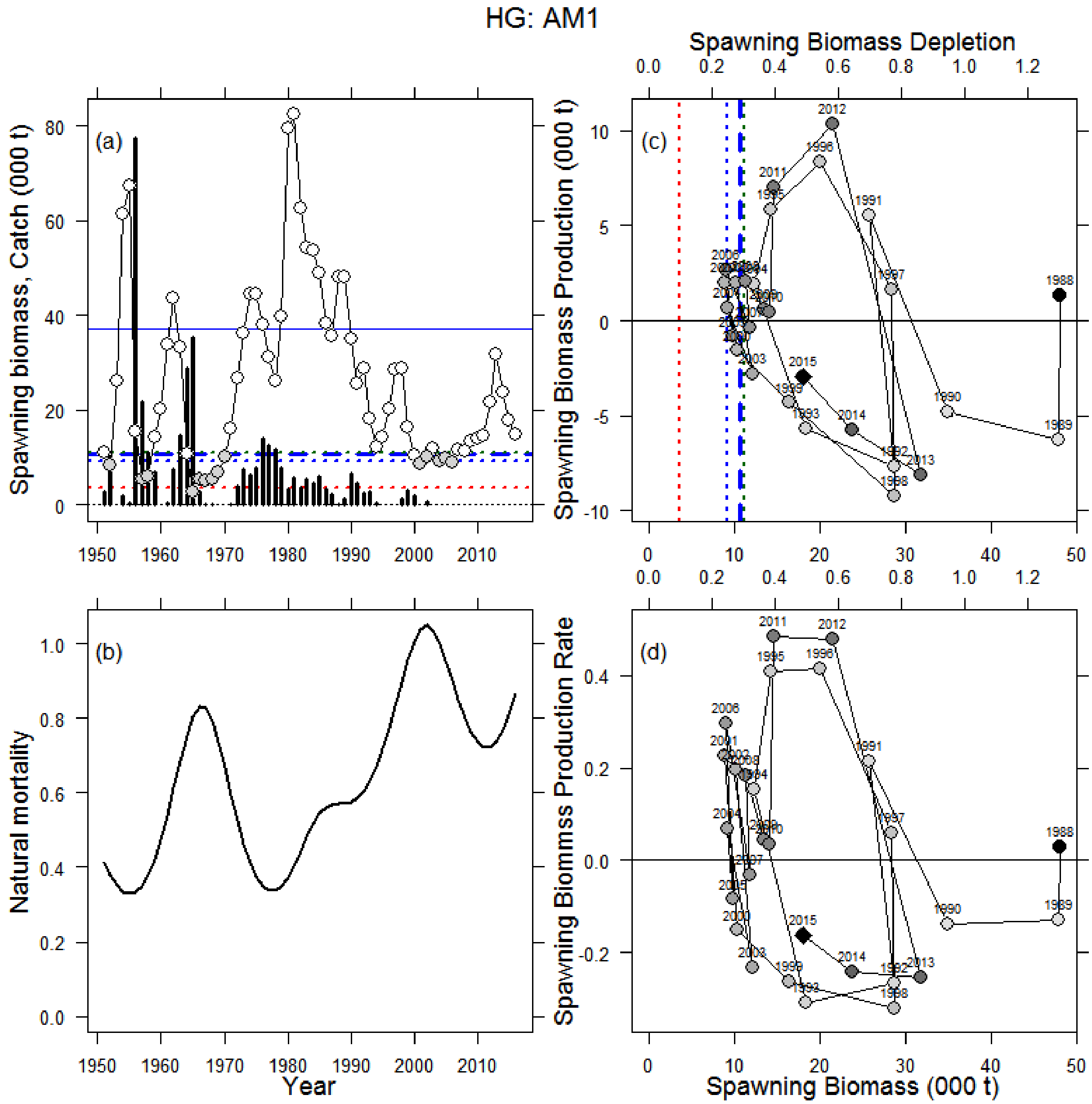

Figure 6: Assessment model AM1 parameter and production estimates for Pacific Herring in the HG management area. Description as for Figure 2.

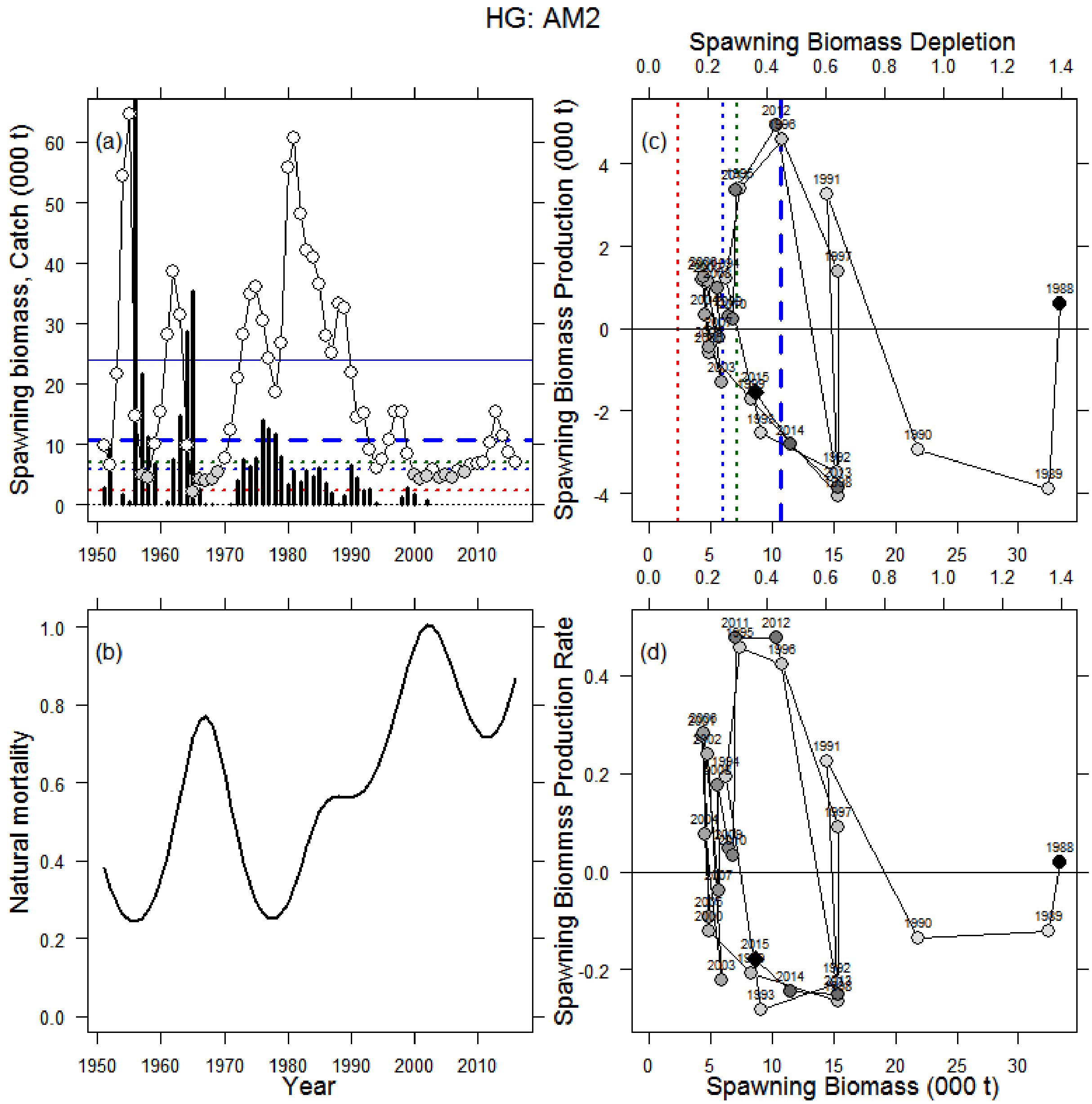

Figure 7: Assessment model AM2 parameter and production estimates for Pacific Herring in the HG management area. Description as for Figure 2.

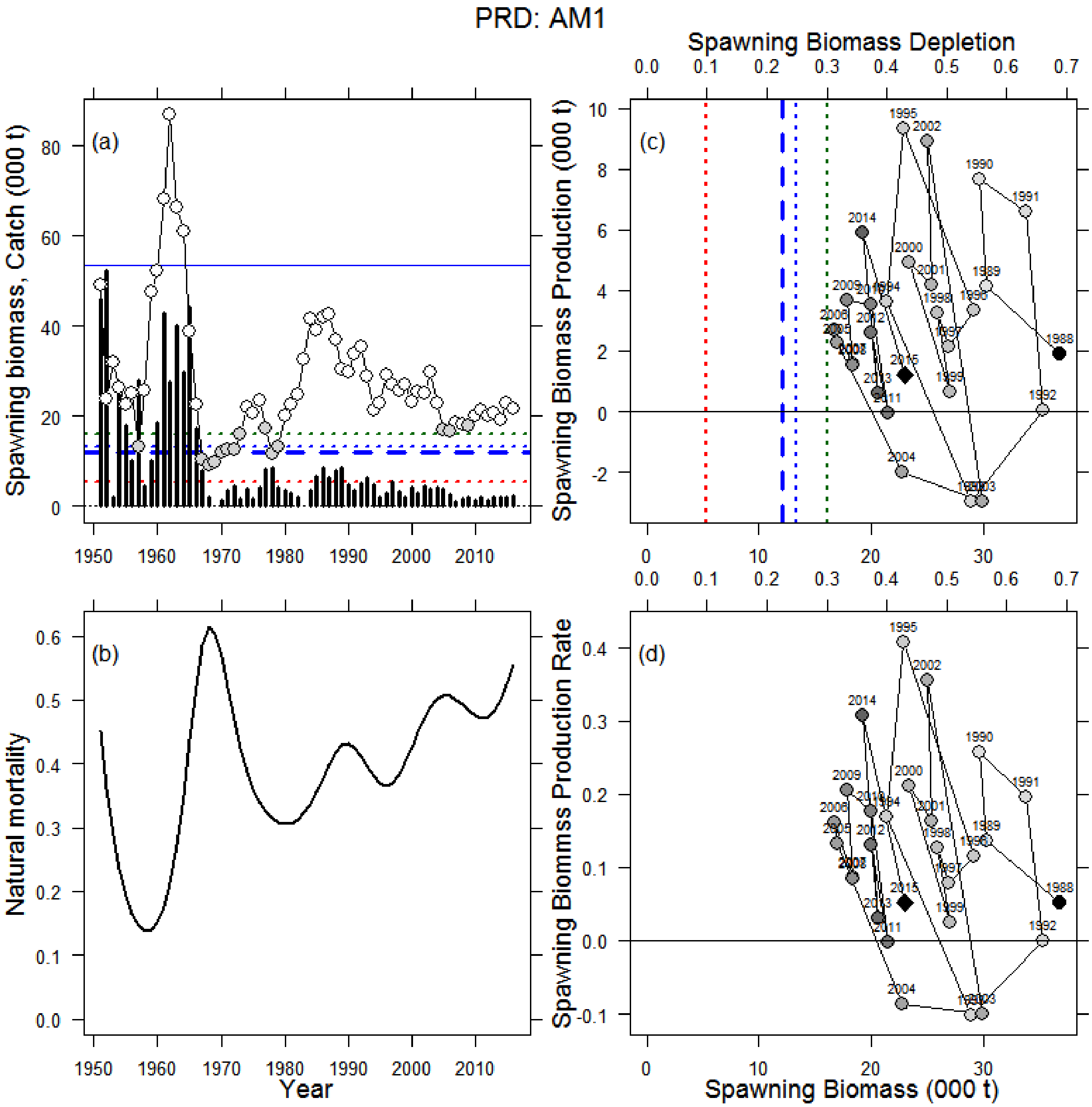

Figure 8: Assessment model AM1 parameter and production estimates for Pacific Herring in the PRD management area. Description as for Figure 2.

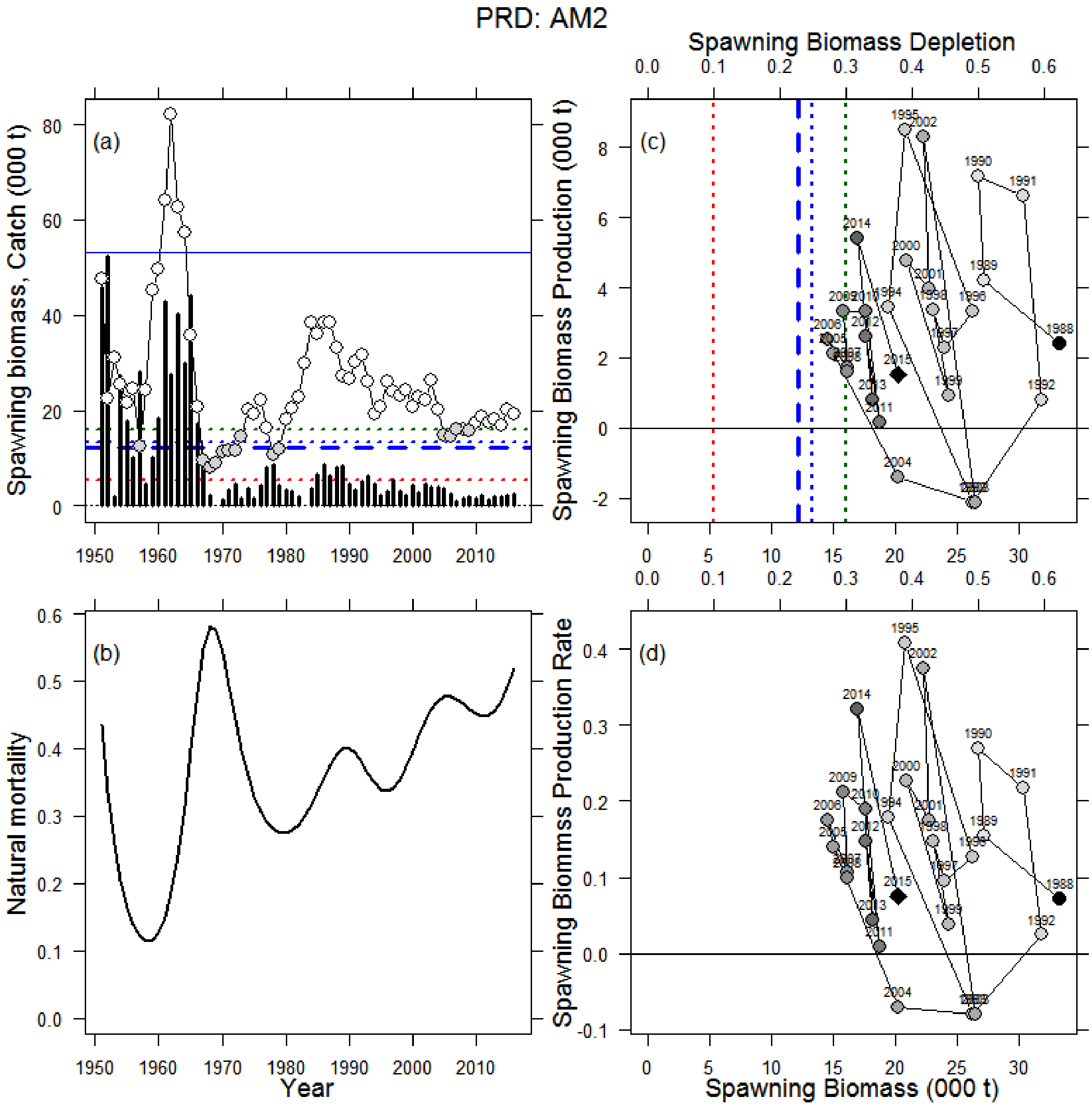

Figure 9: Assessment model AM2 parameter and production estimates for Pacific Herring in the PRD management area. Description as for Figure 2.

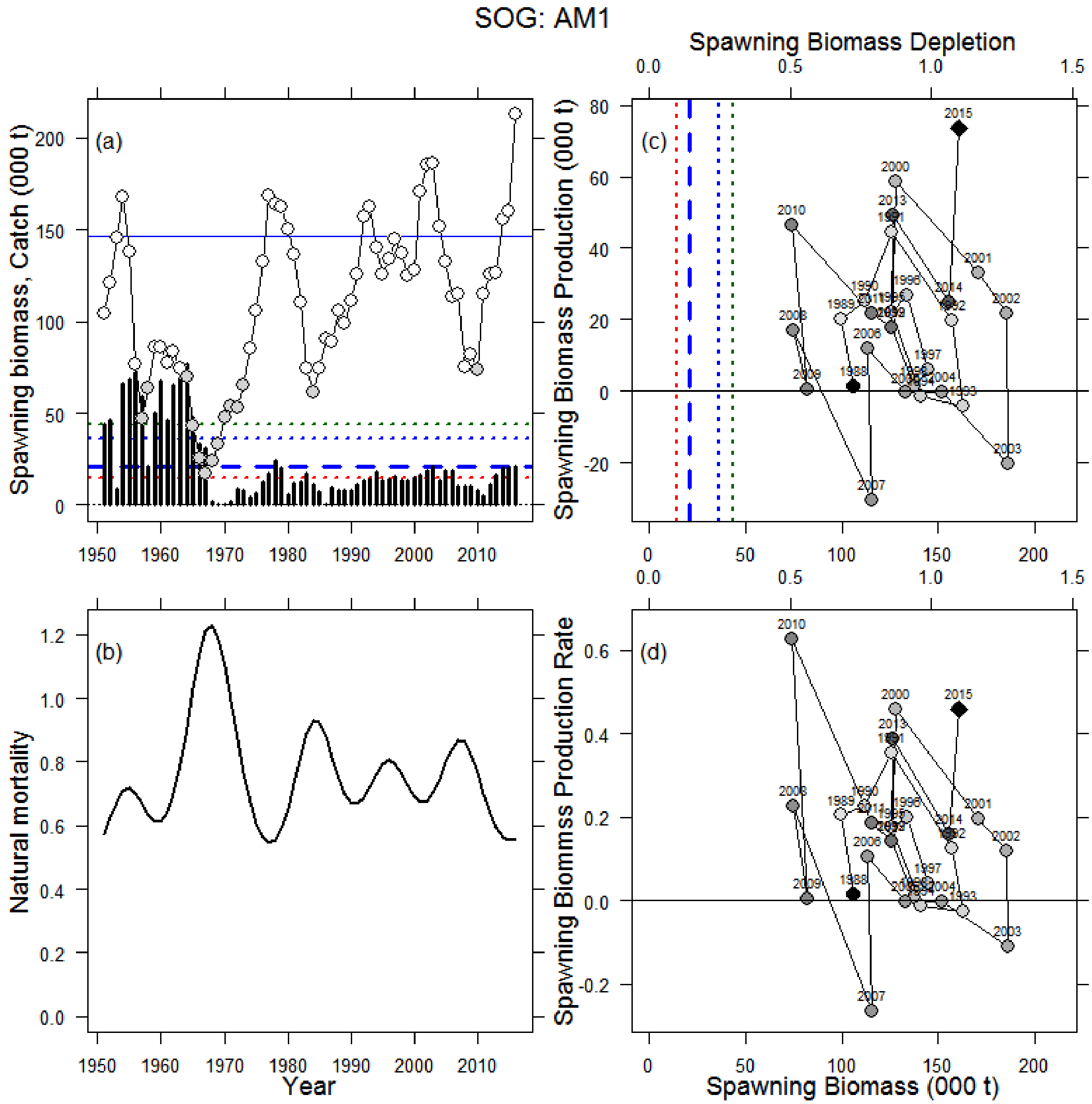

Figure 10: Assessment model AM1 parameter and production estimates for Pacific Herring in the SOG management area. Description as for Figure 2.

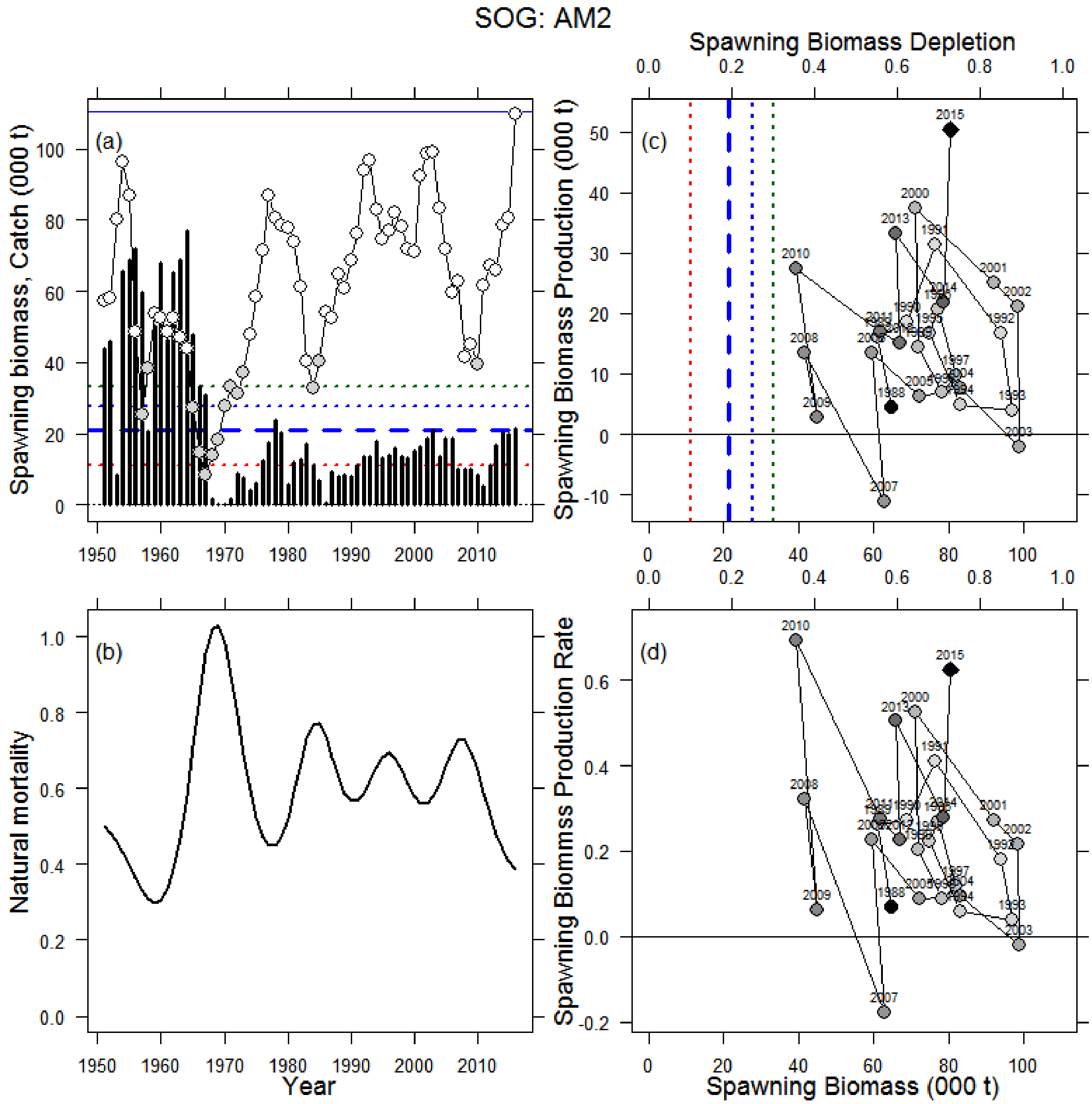

Figure 11: Assessment model AM2 parameter and production estimates for Pacific Herring in the SOG management area. Description as for Figure 2.

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