Assessment of the Pacific halibut (*Hippoglossus stenolepis*) stock at the end of 2017

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PURPOSE

To provide the Commission with a detailed report of the 2017 stock assessment analysis.

ABSTRACT

This stock assessment reports the status of the Pacific halibut (*Hippoglossus stenolepis*) resource in the International Pacific Halibut Commission (IPHC) Convention Area at the end of 2017. Coastwide mortality (removals; including all sizes of Pacific halibut) from all sources in 2017 were estimated to be 42.4 million pounds[1] (~19,200 t), up slightly from 41.8 million pounds (~18,960 t) in 2016. In addition to the removals, the assessment includes data from both fishery dependent and fishery independent sources, as well as auxiliary biological information. The IPHC's 2017 fishery-independent setline survey (FISS or setline survey) detailed a coastwide aggregate legal (O32) Weight-Per-Unit-Effort (WPUE) which was 10% lower than the value observed in 2016. Numbers-Per-Unit-Effort (NPUE) showed a 24% decrease from 2016 to 2017. Coastwide commercial fishery WPUE was up 5% (projected to be only 3% when logbook data are complete) over the same period. Age distributions in 2017 from both the setline survey and fishery remained similar to those observed in 2011-16, but with somewhat fewer fish younger than the 2005 cohort (age-12), indicating that subsequent coastwide recent recruitment events have been lower than those in previous years. At the coastwide level, individual size-at-age continues to be very low relative to the rest of the time-series, and there has been little clear change over the last several years.

This stock assessment consists of four equally-weighted models, two long time-series models, and two short time-series models either using data sets by geographical region, or aggregating all data series into coastwide summaries; these models are structurally unchanged since the most recent detailed scientific review in 2015. Results are based on the approximate probability distributions derived from the ensemble of models, thereby incorporating the uncertainty within each model as well as the uncertainty among models. The results at the end of 2017 indicate that the Pacific halibut stock declined continuously from the late 1990s to around 2010, as a result of decreasing size-at-age, as well as somewhat weaker recruitment strengths than those observed during the 1980s. Since the estimated female spawning biomass (SB) stabilized near 200 million pounds (~90,100 t) in 2010, the stock is estimated to have been increasing gradually to 2017. The SB at the beginning of 2018 is estimated to be 202 million pounds (~91,600 t), with an approximate 95% confidence interval ranging from 148 to 256 million pounds (~67,100-116,100 t). Pacific halibut recruitment estimates show the largest recent cohorts in 1999 and 2005; cohorts from 2006 through 2013 are estimated to be smaller than any recruitment from 1999-2005. This indicates a high probability of decline in both the stock and fishery yield as recent recruitments become increasingly important to the age range over which much of the harvest and spawning takes place.

A comparison of the median 2018 ensemble SB to reference levels specified by the interim management procedure suggests that the stock is currently at 40% (approximate 95% credible range = 26-60%) of specified unfished levels (relative to the SB specified by the current

[1] All weights in the document are 'net' weights; head-off and entrails removed approximately 75% of round weight.

management procedure). However, the probability distribution indicates considerable uncertainty, with a 6/100 (6%) probability the stock is below the $SB_{30\%}$ level. Stock projections were conducted using the integrated results from the stock assessment ensemble, details of Regulatory Area-specific catch sharing plans and estimates of removals from the 2017 directed fisheries and other sources of mortality where these values are projected for 2018. A more detailed harvest decision table including a finer grid of management alternatives and additional risk metrics is reported. The stock is projected to decrease gradually over the period from 2018-20 for removals around the reference SPR (46%) level (31 million pounds, ~14,060 t). There is a relatively small chance (<21/100; 21%) that the stock will decline below the threshold reference point (SB30%) in projections for all the levels of TCEY up to 40 million pounds (~18,100 t) evaluated over three years; for TCEYs exceeding that level, the probability begins to increase rapidly. Major sources of uncertainty, retrospective analyses and sensitivity analyses exploring current research avenues are included in this document.

INTRODUCTION

This stock assessment reports the status of the Pacific halibut (*Hippoglossus stenolepis*) resource in the International Pacific Halibut Commission (IPHC) Convention Area at the end of 2017. As in recent stock assessments, the resource is modelled as a single stock extending from northern California to the Aleutian Islands and Bering Sea, including all inside waters of the Strait of Georgia and Puget Sound, but excludes known extremities in the western Bering Sea within the Russian Exclusive Economic Zone. The stock assessment provides a brief summary of recently collected data; a more detailed treatment of data sources included in the assessment and used for other analyses supporting harvest policy calculations is provided in document IPHC-2018-AM094-09. Results include current model estimates of stock size and trend reflecting all available data. Specific management information is summarized via a decision table reporting the estimated risks associated with alternative management actions. A concise summary of the assessment and management information is provided in document IPHC-2018-AM094-08. Catch tables detailing Regulatory Area-specific projections are provided separately in IPHC-2018-AM094-11.

DATA SOURCES

Each year, the data sources used to support this assessment are updated to include newly available information, and refined to reflect the most current and accurate information available to the IPHC. Major reprocessing and development of supplementary data sources was conducted in 2013 and 2015 (Stewart 2014, 2016, Stewart and Martell 2016). In 2016, a model-based estimator was introduced for the IPHC fishery-independent setline survey (Stewart 2017b, Webster 2017). For 2017, the model-based estimator was extended to include fishery-independent setline survey data from 1993-97, and survey age data collected at expansion stations from 2014-2017 were added to existing samples from the annually surveyed stations. All available information was finalized on 11 November 2017 in order to provide adequate time for analysis and modeling. As has been the case in all years, some data are incomplete, or include projections for the remainder of the year. These include commercial fishery WPUE, commercial fishery age composition data, and 2017 removals for all fisheries still operating after 11 November 2017. All preliminary data series in the assessment will be fully updated in 2018.

Data are initially compiled by management area and then aggregated to the coastwide level and to four geographical regions: Region 2 (2A, 2B, and 2C), Region 3 (3A, 3B), Region 4 (4A, 4CDE) and Region 4B. In addition to the removals (including all sizes of Pacific halibut), the assessment includes data from both fishery dependent and fishery independent sources as well as auxiliary biological information. Primary sources of information for this assessment include indices of abundance from the annual setline survey and commercial Catch-Per-Unit-Effort (numbers and weight), and biological summaries (length-, weight-, and age-composition data). In aggregate, the historical time series of data available for this assessment represents a considerable resource for analysis. The range of relative data quality and geographical scope are also considerable, with the most complete information available only in recent years (Figure 1). A detailed summary of input data used in this stock assessment can be found in IPHC-2018-AM094-09.

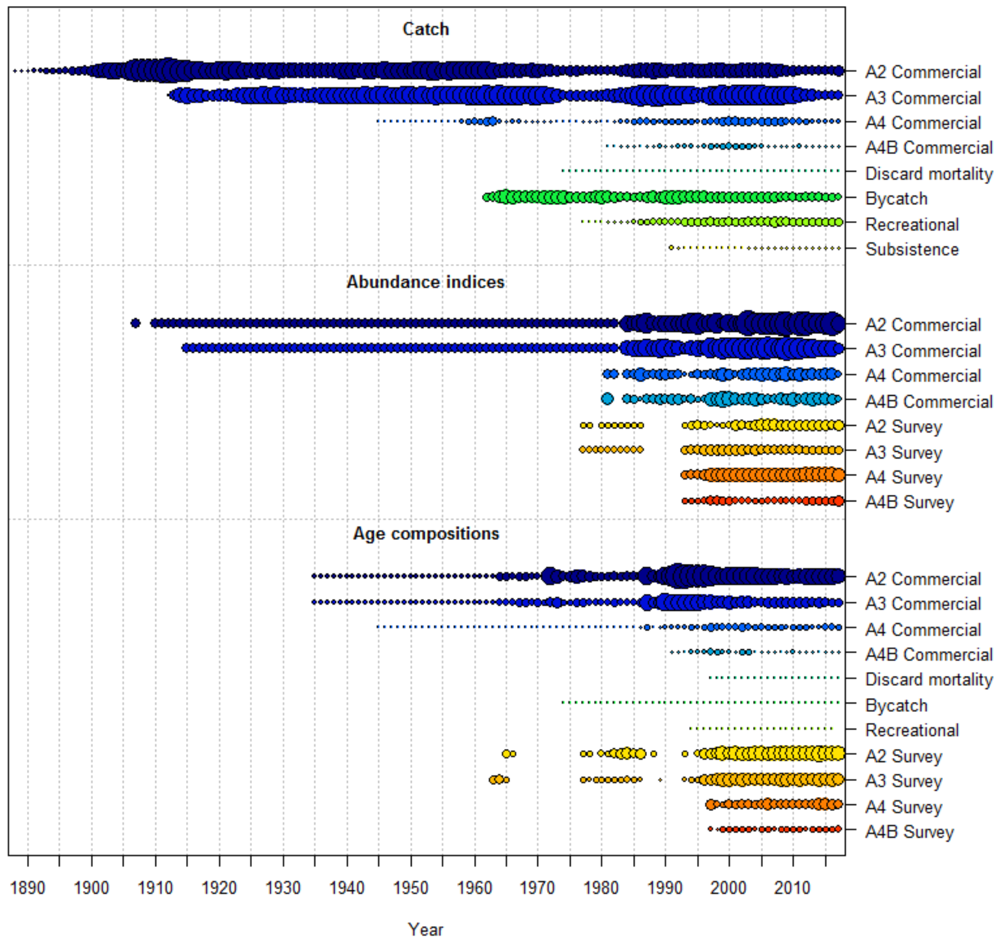

FIGURE 1. Overview of data sources. Circle areas are proportional to magnitude (catches) or the relative precision of the data (indices of abundance and age composition data).

Briefly, known Pacific halibut removals (mortality) consist of target fishery landings and discard mortality (including research), recreational fisheries, subsistence, and bycatch mortality in fisheries targeting other species (where Pacific halibut retention is prohibited). Over the period 1918-2017 removals have totaled 7.2 billion pounds (~3.2 million t), ranging annually from 34 to 100 million pounds (16,000-45,000 t) with an annual average of 63 million pounds (~29,000 t). Annual removals were above this long-term average from 1985 through 2010 and have been relatively stable near 42 million pounds (~19,000 t) since 2014. Coastwide commercial Pacific halibut fishery landings in 2017 were approximately 26.2 million pounds (~11,900 t), up from a low of 23.7 million pounds (~10,700 t) in 2014. Bycatch mortality was estimated to be 6.0 million pounds in 2017 (~2,720 t)[2], the lowest level in the estimated time series, beginning with the arrival of foreign fishing fleets in 1962, and just over one million pounds (~450 t) less than estimated for 2016. The total recreational removals was estimated to be 8.1 million pounds (~3,675 t), up 10% from 2016. Removals from all sources in 2017 were estimated to be 42.4 million pounds (~19,200 t), up slightly from 41.8 million pounds in 2016 (~18,960 t).

The 2017 IPHC's fishery-independent setline survey detailed a coastwide aggregate legal (O32) WPUE which was 10% lower than the value observed in 2016, with individual Regulatory Areas varying from a 1% increase (Area 2C) to a 32% decrease (Area 3B). Setline survey NPUE showed a more pronounced decrease from 2016 to 2017 (24% coastwide), with individual Regulatory Areas ranging from a 1% increase (Area 4A) to a 44% decrease (Area 2A). Commercial fishery WPUE (based on extensive, but still incomplete logbook records available for this assessment) was slightly increased (5%) at the coastwide level with mixed trends among Regulatory Areas. Based on review by the IPHC's Scientific Review Board (SRB), a bias correction for each Regulatory Area was developed using the last five years of post-assessment revisions resulting from additional logbooks available after the assessment deadline in early November. Applying these corrections reduced the increase in coastwide commercial fishery WPUE to only 3% and negative trends were predicted for all Areas except Area 4D (+71%), Area 4C (+20%) and Area 3A (+6%). Tribal and non-tribal commercial fishery trends in Area 2A are reported separately this year in response to important differences in the timing and spatial extent of the two components. Tribal fishery WPUE has been increasing since 2014 in that Area, and non-tribal WPUE has been declining over the same period, although a small increase (5%) from 2016 to 2017 was observed. The very large increase in WPUE observed in Area 4D appears to be a function of much higher catch-rates around St. Matthew Island (also observed in the setline survey) and a shift of 25% of the catch previously occurring along the shelf-edge to the waters around that island in 2017. Age distributions in 2017 show a 2005 cohort somewhat stronger than those in adjacent years, and weak recruitments from 2006 onward. At the coastwide level, individual size-at-age continues to be very low relative to the rest of the time-series, and there has been little change over the last several years.

STOCK ASSESSMENT

Creating robust, stable, and well-performing stock assessment models for the Pacific halibut stock has historically proven to be problematic due to the highly dynamic nature of the biology, distribution, and fisheries (Stewart and Martell 2014). The stock assessment for Pacific halibut has evolved through many different modeling approaches over the last 30 years (Clark 2003). These changes have reflected improvements in fisheries analysis methods, changes in model assumptions, and responses to recurrent retrospective biases and other lack-of-fit metrics (Stewart and Martell 2014). Although recent modelling efforts have created some new alternatives, no single model satisfactorily approximates all aspects of the available data and scientific understanding. Building on simpler approaches in 2012 and 2013, in 2014, an ensemble of four stock assessment models representing a two-way cross of short vs. long time series', and aggregated coastwide vs. Areas-As-Fleets (AAF) models was used to explore the range of plausible current stock estimates. AAF models are commonly applied when biological differences among areas or sampling programs make coastwide summary of data sources

[2] The IPHC receives a preliminary estimate of the current year's bycatch mortality from the National Marine Fisheries Service Alaska Regional Office in early November.

problematic (Waterhouse et al. 2014). AAF models continue to treat the population dynamics as a single aggregate stock, but fit to each of the spatial datasets individually, allowing for differences in selectivity and catchability of the fishery and survey among regions. In addition, the AAF models more easily accommodate temporal and spatial trends in where and how data have been collected, and fishery catches have occurred. This is achieved through explicitly, accounting for missing information in some years, rather than making assumptions to expand incomplete observations to the coastwide level. These four models are structurally unchanged since the most recent detailed scientific review in 2015 (Stewart and Martell 2016). Each of these models (and many alternatives explored during development) has shown a similar historical pattern: a stock declining from the late 1990s, with several years of relative stability at the end of the time-series.

The ensemble approach recognizes that there is no “perfect” assessment model, and that a robust risk assessment can be best achieved via the inclusion of multiple models in the estimation of management quantities and the uncertainty about these quantities (Stewart and Martell 2015a). This stock assessment is based on the approximate probability distributions derived from an ensemble of models, thereby incorporating the uncertainty within each model as well as the uncertainty among models. This approach reduces potential for abrupt changes in management quantities as improvements and additional data are added to individual models, and provides a more realistic perception of uncertainty than any single model, and therefore a stronger basis for risk assessment.

This stock assessment is implemented using the generalized software stock synthesis, a widely used modeling platform developed at the National Marine Fisheries Service (Methot and Wetzel 2013). This combination of models included a broad suite of structural and parameter uncertainty, including natural mortality rates (estimated in the long time-series models, fixed in the short time-series models), environmental effects on recruitment (estimated in the long time-series models), fishery and survey selectivity (by region in the AAF models) and other model parameters. These sources of uncertainty have historically been very important to the understanding of the stock, as well as the annual assessment results (Clark and Parma 1999, Clark and Hare 2006, Stewart and Martell 2016). The benefits of the long time-series models include historical perspective on recent trends and biomass levels; however, these benefits come at a computational and complexity cost. The short time-series models make fewer assumptions about the properties of less comprehensive historical data, but they suffer from much less information in the short data series as well as little context for current dynamics.

Each of the models in the ensemble was equally weighted, and differences in uncertainty within models propagated in the integration of results. In the future, it may be desirable to develop a method for weighting models based on the lack-of-fit to key data sources, retrospective patterns within models, as well as consistency of the results with biological understanding. Evaluation of alternative weighting approaches was presented to the IPHC Scientific Review Board (SRB) in 2015, 2016 and 2017 (Stewart 2017), but did not suggest a change to the equal weights that have been applied; therefore, that assumption is retained. It is also anticipated that additional models or variations of existing models will be evaluated for potential inclusion into the ensemble in future years. In this manner, the ensemble approach can be transparently improved in the future as additional approaches and refinements become available.

COMPARISON WITH PREVIOUS ASSESSMENTS

Comparison of this year's results with previous stock assessments indicates that the estimates of spawning biomass from the 2017 ensemble remain consistent with those from 2012-16. Each of the previous assessment values lie inside the predicted 50% interval of the ensemble in recent years (Figure 2). Models prior to 2012, which had shown a problematic retrospective pattern, suggested terminal stock trends and sizes in the mid-2000s that are no longer considered plausible. The estimates from these models for the late 1990s now occur at the lower edge of the plausible range: all four of the current models suggest a larger spawning biomass during that period. Point estimates for the 2017 SB from the 2016 ensemble (Stewart and Hicks 2017) were slightly higher than the current results, but statistically very similar given the degree of uncertainty (Table 1). The level of fishing intensity (measured via the Spawning Potential Ratio, SPR) projected for 2017 was $F_{45\%}$; however, in retrospect (based on revised recent year-class strengths) a higher level of fishing intensity ($F_{40\%}$) is estimated in this year's assessment (Table 1).

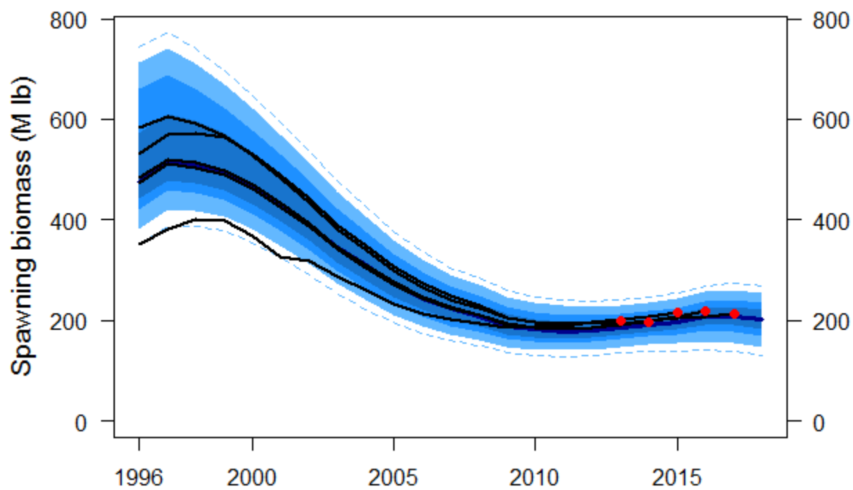

FIGURE 2. Retrospective comparison among recent IPHC stock assessments. Black lines indicate estimates of spawning biomass from assessments conducted from 2012-2016 with the terminal estimate shown as a point, the shaded distribution denotes the 2017 ensemble: the dark blue line indicates the median (or "50:50 line") with an equal probability of the estimate falling above or below that level; colored bands moving away from the median indicate the intervals containing 50/100, 75/100, and 95/100 estimates; dashed lines indicating the 99/100 interval.

TABLE 1. Comparison of 2017 median ensemble beginning-of-year spawning biomass (Mlb, with relative 95% confidence intervals) and Spawning Potential Ratio estimates from the 2016 and current assessments.

Quantity	2016 Assessment	2017 Assessment
2017 Spawning biomass	212 (153-286)	208 (156-261)
2017 SPR	45%	40%

BIOMASS, RECRUITMENT, AND REFERENCE POINT RESULTS

Ensemble

The results of the 2016 stock assessment indicate that the Pacific halibut stock declined continuously from the late 1990s to 2011(Figure 2, Table 2). The differences among the individual models contributing to the ensemble are most pronounced prior to the early 2000s (Figure 3). However, current stock size estimates (at the beginning of 2018) also differ substantially among the four models (Figure 4). The differences in both scale and recent trend reflect the structural assumptions, e.g., higher natural mortality estimated in the long coastwide model and dome-shaped selectivity for Regions 2 and 3 in the AAF models. Differences are also apparent in the recent recruitment estimates, which suggest larger recruitments in 1999 and 2005 than in other recent years (Figure 5, Table 2). These recent recruitments are much lower than the 1987 cohort, and in the coastwide long model below those in the late 1970s and early 1980s (Figure 6). Recruitments from 2006-13 are all estimated to be below those from 1999-2005. This is particularly important for near-term trends in fishery yield as well as spawning biomass, as Pacific halibut born in 2006 will be 50% mature in 2018, and will be fully available to the directed fisheries. The differing effects of these reduced recruitments on fishery yield are illustrated in the estimated declines in age-8+ biomass, which start earlier and are more pronounced than those seen for spawning biomass (Figure 7, Table 2). Recruitment estimates after 2010 remain poorly informed by information from the fishery and survey data, and are therefore highly uncertain.

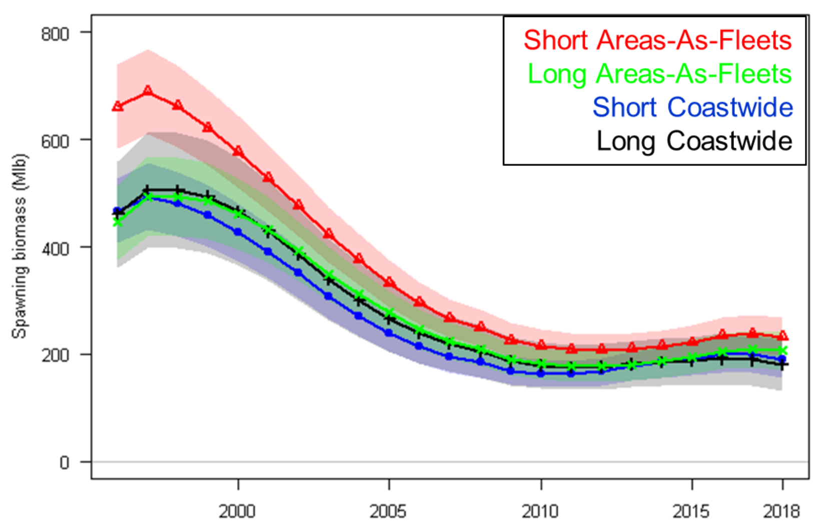

FIGURE 3. Estimated spawning biomass trends (1996-2018) based on the four individual models included in the 2017 stock assessment ensemble. Solid lines indicate the maximum likelihood estimates; shaded intervals indicate approximate 95% confidence intervals.

In addition to recruitment trends, observed decreases in size-at-age have also been an important contributor to recent stock declines. The results of the 2017 stock assessment indicate that the Pacific halibut stock declined continuously from the late 1990s to around 2010 (Figure 3). That trend is estimated to have been largely a result of decreasing size-at-age, as well as somewhat weaker recruitment strengths than those observed during the 1980s. Since the estimated female spawning biomass (SB) stabilized near 180 million pounds (~81,600 t) in 2011 the stock is estimated to have increased gradually to 2017. The SB at the beginning of 2018 is estimated to be 202 million pounds (~91,600 t), with an approximate 95% confidence interval ranging from 148 to 256 million pounds (~67,100-116,100 t; Figure 8, Table 2).

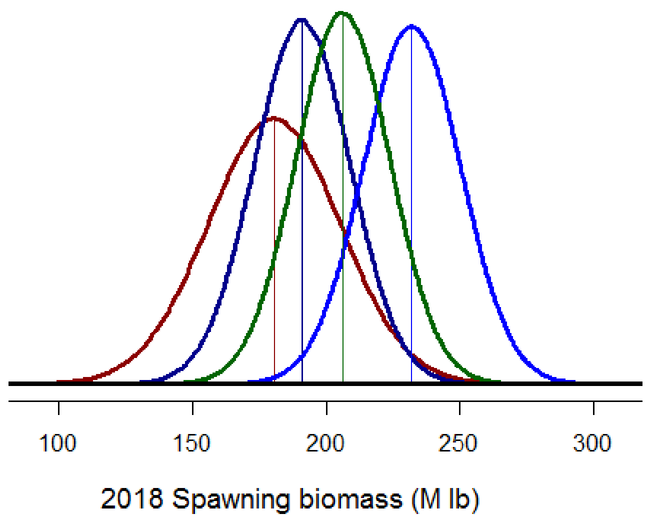

FIGURE 4. Distribution of individual model estimates for the 2017 spawning biomass. Vertical lines indicate the median values.

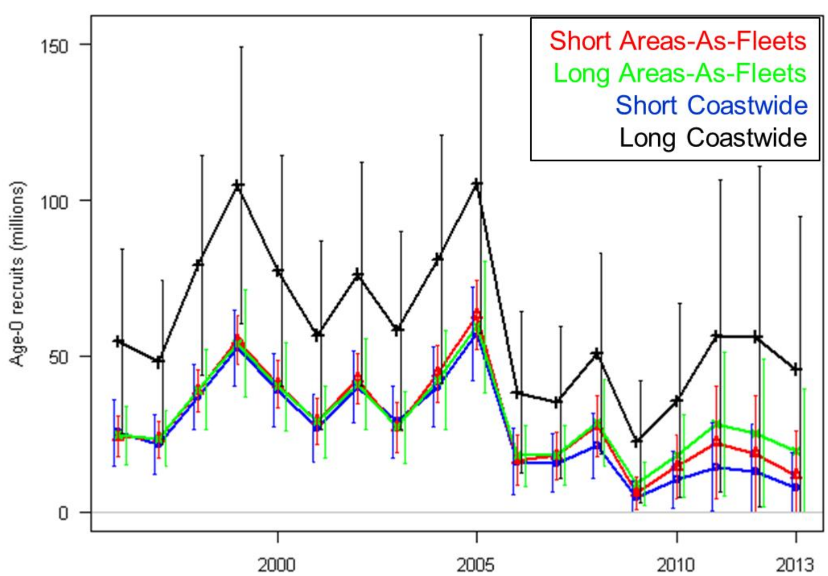

FIGURE 5. Estimated age-0 recruitment trends (1996-2013) based on the four individual models included in the 2017 stock assessment ensemble. Series indicate the maximum likelihood estimates; vertical lines indicate approximate 95% confidence intervals.

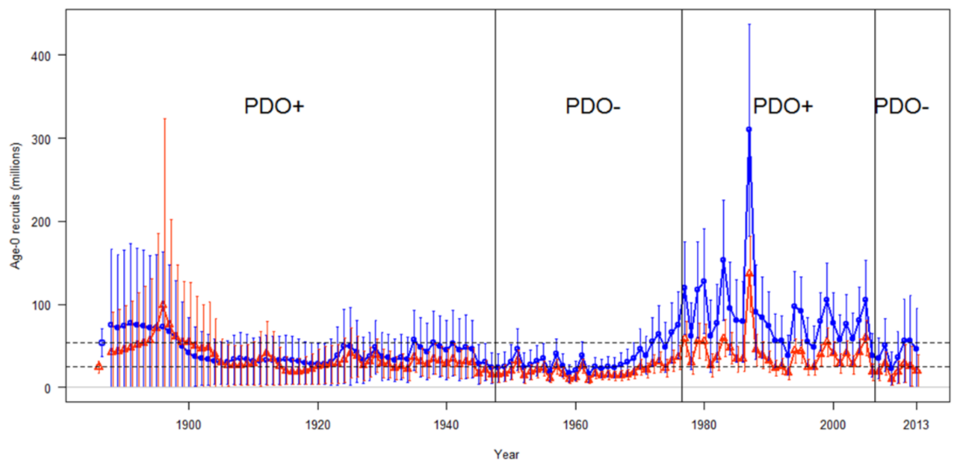

FIGURE 6. Trend in historical recruitment strengths (by birth year) estimated by the two long time-series models, including the effects of the Pacific Decadal Oscillation (PDO) regimes.

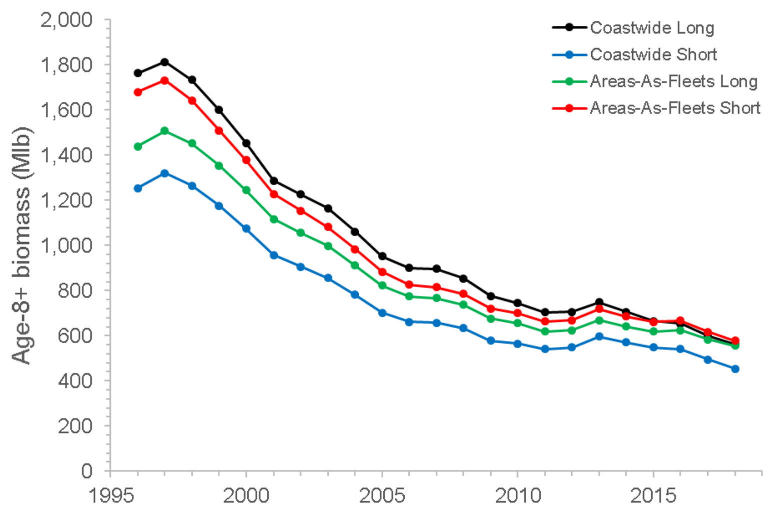

FIGURE 7. Estimated age-8+ biomass trends (1996-2013) based on the four individual models included in the 2017 stock assessment ensemble. Note that confidence intervals for these estimates are not currently available but are likely larger than those observed for spawning biomass.

TABLE 2. Recent median spawning biomass (millions lbs) and fishing intensity (based on median Spawning Potential Ratio, where smaller values indicate higher fishing intensity) from the 2017 stock assessment ensemble, and Age-0 recruitment (millions) and age-8+ biomass (millions lbs) estimates from the individual models (CW=coastwide, AAF=Areas-As-Fleets) comprising the ensemble.

		Fishing	Recruitment				Age-8+ biomass			
Year	Spawning biomass	intensity ($F_{XX\%}$)	CW Long	CW Short	AAF Long	AAF Short	CW Long	CW Short	AAF Long	AAF Short
1996	475	48%	54.7	25.4	24.6	24.2	1,763	1,253	1,440	1,680
1997	514	43%	48.1	21.7	23.6	23.4	1,814	1,321	1,508	1,732
1998	509	41%	79.2	37.0	39.2	38.9	1,735	1,265	1,452	1,643
1999	495	39%	104.8	52.4	53.9	55.0	1,601	1,176	1,354	1,510
2000	467	39%	77.4	39.1	40.2	41.0	1,454	1,075	1,244	1,378
2001	433	36%	56.7	27.0	28.9	29.0	1,287	957	1,118	1,227
2002	392	32%	76.3	40.1	41.0	42.6	1,227	907	1,057	1,154
2003	347	29%	58.2	29.0	27.2	27.1	1,166	855	999	1,082
2004	309	26%	81.0	40.1	42.3	44.3	1,062	782	911	983
2005	274	24%	105.1	57.2	59.4	63.2	953	701	823	884
2006	245	24%	38.4	16.1	18.1	16.6	900	661	774	827
2007	223	24%	35.1	15.7	18.1	18.1	896	658	767	816
2008	208	24%	50.8	21.3	28.8	27.6	854	634	737	786
2009	190	25%	22.5	4.8	9.2	6.0	776	578	675	721
2010	182	25%	35.7	10.5	18.0	14.6	745	565	655	700
2011	179	29%	56.4	14.5	28.2	22.3	705	541	619	663
2012	180	34%	56.2	13.1	25.3	18.6	706	549	623	668
2013	186	36%	45.8	7.8	19.5	11.8	749	596	669	718
2014	192	41%	NA	NA	NA	NA	706	571	641	686
2015	198	42%	NA	NA	NA	NA	665	548	618	662
2016	207	42%	NA	NA	NA	NA	654	541	625	666
2017	208	40%	NA	NA	NA	NA	599	494	584	617
2018	202	NA	NA	NA	NA	NA	562	454	556	579

Long time-series models

The two long time-series models provided different perceptions of current vs. historical stock sizes (Figure 9). The AAF model suggests that the stock is at 35% of the equilibrium unfished stock size used in the interim management procedure; however, the model estimates that current spawning biomass is at only 96% of the historically low levels estimated for the 1970s. The coastwide model suggests that the stock is at 48% of the equilibrium unfished stock size; however, the current spawning biomass is estimated to be at 216% of the minimum values estimated for the 1970s. These differences represent considerable uncertainty in both the current stock size and trend. Recent differences are likely attributable to the separation of signals from each region (particularly Region 2, with the longest time-series of data), and allowance for different properties in each region’s fishery and survey. Historical differences appear to be due to the differing assumptions regarding connectivity between Regions 2 and 3 and Regions 4 during the early part of the 1900s when there are no data available from Area 4 (Stewart and Martell 2016).

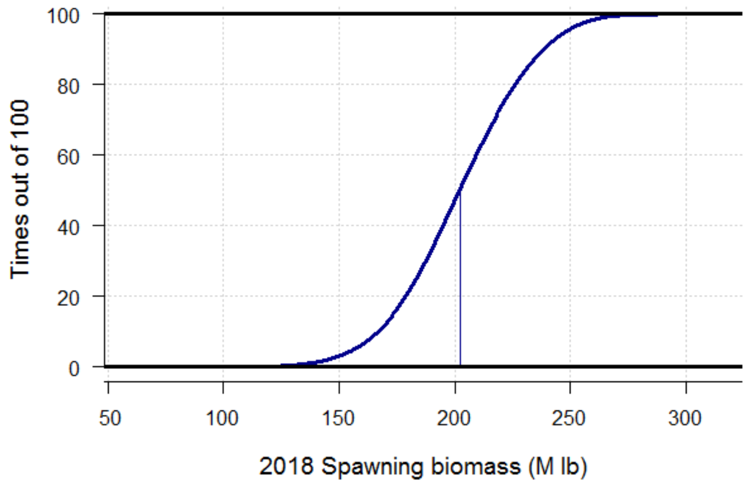

FIGURE 8. Cumulative distribution of the estimated spawning biomass from the ensemble at the beginning of 2018. Curve represents the estimated probability that the biomass is less than or equal to the value on the x-axis; vertical line represents the median (202 million pounds; ~91,600 t).

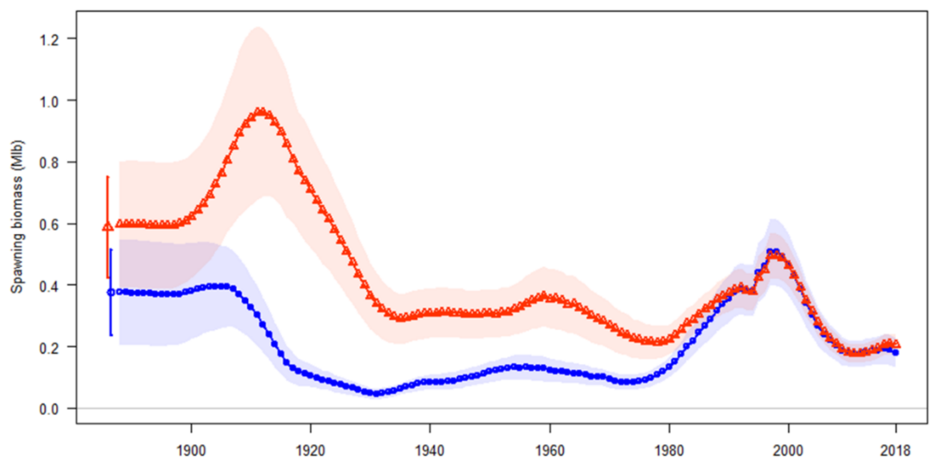

FIGURE 9. Spawning biomass estimates from the two long time-series models. Shaded region indicates the approximate 95% within-model interval. The red (upper) series is the AAF model and the blue (lower) series is the coastwide model.

Ecosystem conditions

Based on the two long time-series models, average Pacific halibut recruitment is estimated to be higher (41 and 76% for the coastwide and AAF models respectively) during favorable Pacific Decadal Oscillation (PDO) regimes, a widely used indicator of productivity in the north Pacific. Historically, these regimes included positive conditions prior to 1947, poor conditions from 1947-77, positive conditions from 1978-2006, and poor conditions from 2007-13. Annual average PDO values from 2014 through October 2016 have been positive; however, many other environmental indicators, current and temperature patterns have been anomalous relative to historical periods. Further, observed declines in Pacific cod (*Gadus macrocephalus*) in the Gulf of Alaska, seabird mortality events and other conditions suggest that historical patterns of productivity related to the PDO may not be relevant to the most recent few years.

Reference points

A comparison of the median 2018 ensemble SB to reference levels specified by the interim management procedure suggests that the stock is currently at 40% (approximate 95% credible range = 26-60%) of specified unfished levels (relative to the SB specified by the interim management procedure; Figure 10). The probability that the stock is below the $SB_{30\%}$ level is estimated to be 6%, with less than a 1% chance that the stock is below $SB_{20\%}$. Consistent with the interim management procedure (while improvements are ongoing), estimates of spawning biomass are compared to equilibrium values representing poor recruitment regimes and relatively large size-at-age. Alternative reference points include the spawning biomass estimated to have occurred at the lowest point in the historical time-series (1977-78), as well as the spawning biomass that would be estimated to occur at present (given recent recruitment and biology) in the absence of fishing (dynamic SB0; Hicks and Stewart 2017). The estimates of current spawning biomass relative to the dynamic reference point range from 26-43% among the four stock assessment models, with an average value of 33%. Relatively large differences among models reflect both the uncertainty in historical dynamics as well as the importance of spatial patterns in the data and population processes, for which all of the models represent only simple approximations. All sources of estimated removals for 2017 correspond to a fishing intensity point estimate of $F_{40\%}$ (Table 2, Figure 11). The 95% interval of this distribution is considerable ($F_{58\%}$-$F_{29\%}$), and slightly irregular, reflecting the different distributions estimated within each of the individual models. Harvest levels of this magnitude are generally at or below target rates for many similar stocks. The recent time-series shows that the 2017 estimate corresponds to slightly higher fishing intensity than 2014-2016, but below values from 2000-2013 (Figure 12).

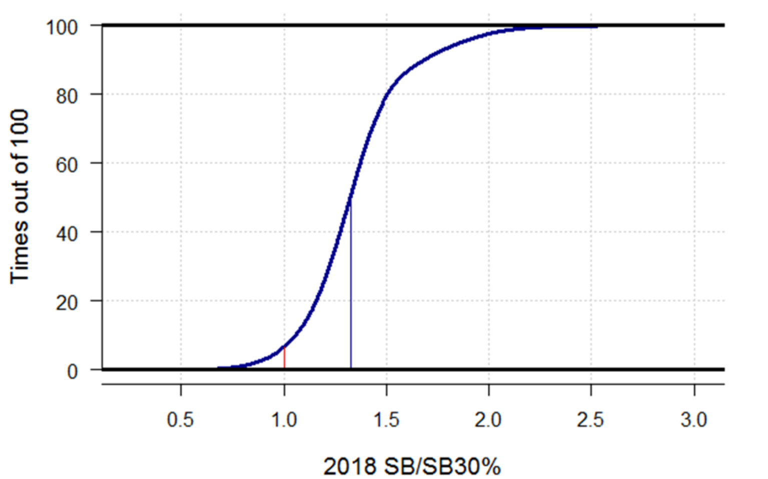

FIGURE 10. Cumulative distribution of 2018 ensemble spawning biomass estimates relative to the SB30% reference point. Curve represents the estimated probability that the biomass is less than or equal to the value on the x-axis. Vertical lines indicate the median value (40%), and the value corresponding to the IPHC's harvest policy threshold.

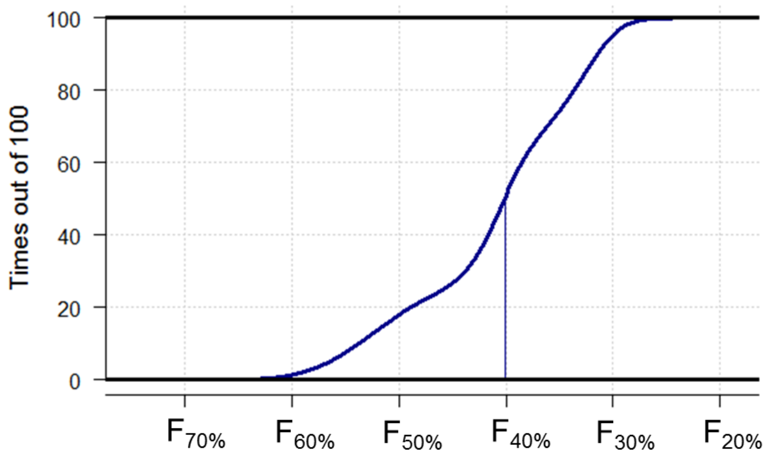

FIGURE 11. Cumulative distribution of the estimated relative fishing intensity (based on the Spawning Potential Ratio) estimated to have occurred in 2017. Curve represents the estimated probability that the fishing intensity is less than or equal to the value on the x-axis. Vertical line indicates the median value (F40%).

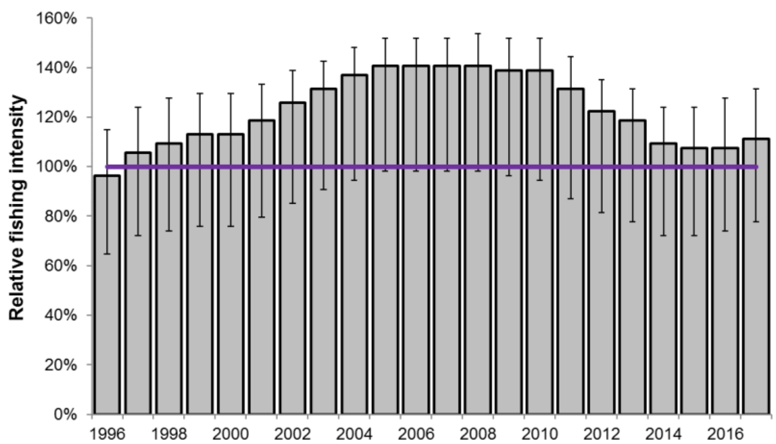

FIGURE 12. Recent estimated fishing intensity (based on the Spawning Potential Ratio) relative to the SPR=46% reference level (horizontal line). Vertical lines indicate approximate credible intervals from the stock assessment ensemble.

Major Sources of Uncertainty

This stock assessment includes uncertainty associated with estimation of model parameters, treatment of the data sources (e.g., short and long time-series), natural mortality (fixed vs. estimated), approach to spatial structure in the data, and other differences among the models included in the ensemble. Although this is an improvement over the use of a single assessment model, there are important sources of uncertainty that are not included.

Two uncertainties in our current understanding of the Pacific halibut resource are:

1) The sex-ratio of the commercial catch (not sampled due to the dressing of fish at sea), which serves to set the scale of the estimated female abundance in tandem with assumptions regarding natural mortality. Voluntary marking in tandem with genetic sampling of all Pacific halibut sampled from the commercial landings will allow an

estimate of the 2017 landings to be available for the next stock assessment. It will take several years to generate enough information on the sex ratio of the landings to begin to meaningfully inform the stock assessment models; however, this represents a crucial step toward addressing this source of uncertainty for future stock assessments. The uncertainty in the historical time-series will remain.

2) The treatment of spatial dynamics and movement rates among Regulatory Areas, which are represented via Regions in the coastwide and AAF approaches, and have large implications for the current stock trend. In addition, movement rates for adult and younger Pacific halibut (roughly ages 0-6, which were not well-represented in the PIT-tagging study), particularly to and from Region 4, are necessary for parameterizing a spatially explicit stock assessment. Current understanding of these rates has now been summarized, but remains problematic for tactical stock assessment modelling.

Other important contributors to assessment uncertainty and potential bias include recruitment, size-at-age, and fishery removals. The link between Pacific halibut recruitment strengths and environmental conditions remains poorly understood, and there is no guarantee that observed correlations will continue in the future. Therefore, recruitment variability remains a substantial source of uncertainty in current stock estimates due to the lag between birth year and direct observation in the fishery and survey data (6-10 years). Reduced size-at-age relative to levels observed in the 1970s is the most important driver of recent stock trends, but its cause also remains unknown. The historical record suggests that size-at-age changes relatively slowly; therefore, although projection of future values is highly uncertain, near-term values are unlikely to be substantially different than those currently observed. Data suggest that the decreasing trend in size-at-age has slowed and coastwide values have been relatively stable over the last decade. Like most stock assessments, estimated removals from the stock are assumed to be accurate. Therefore uncertainty due to bycatch mortality estimation (observer sampling and representativeness), discard mortality rates, and any other unreported sources of removals in either directed or non-directed fisheries could create bias in this assessment. Ongoing research on these topics may help to inform our understanding of these processes in the long-term, but in the near-future it appears likely that a high degree of uncertainty in both stock scale and trend will continue to be an integral part of the annual management process.

This stock assessment contains a broader representation of uncertainty in stock levels relative to analyses for many other species. Although the data available for this stock assessment has narrowed both the historical and projected confidence intervals for stock size and trend relative to last year’s assessment and projections, the considerable remaining uncertainty can be seen in the distribution for spawning biomass estimated at the beginning of 2018 (Figure 8), such that the small differences between the estimate from the 2017 and recent assessments (Table 1, Figure 2) are not statistically significant.

Since 2012, natural mortality has been an important source of uncertainty that is included in the stock assessment. In 2012, three fixed levels were used to bracket the plausible range of values. In 2013, the three models contributing to the ensemble included both fixed and estimated values of natural mortality. In the current ensemble, the models again span both fixed (0.15/year for female Pacific halibut) and estimated values. The female value estimated in the long AAF model (0.15) differs substantially from the value estimated in the coastwide model (0.22). This discrepancy contributes to the difference in scale and productivity for the two models, but is not easily reconciled at present. Although this uncertainty is directly incorporated into the ensemble results, it remains an avenue for future investigation.

Future expansion of the ensemble approach will continue to improve uncertainty estimates, and create assessment results that are robust to changes in individual models, data sets, and other sources of historical changes in stock assessment results from year to year.

SENSITIVITY AND RETROSPECTIVE ANALYSES

A wide range of sensitivity analyses were conducted during the development of the 2015 stock assessment (Stewart and Martell 2016). These efforts form the primary basis for the identification of important sources of uncertainty outlined above. The most important contributors to estimates of both population trend and scale included: the sex-ratio of the commercial catch, the treatment of historical selectivity in the long time-series models, and natural mortality. Several sensitivity analyses were revisited this year in order to update and illustrate their importance, particularly with regard to the IPHC's research program.

The first sensitivity conducted for this assessment was an investigation into the potential effects of a downward trend in spawning output for the Pacific halibut stock. This could be caused by a change in the underlying fecundity or maturity schedules, or by a trend in the rate of skip-spawning (where a reproductively mature fish does not actually spawn in a particular year). To implement this sensitivity, a reduction in spawning output was added to the assessment beginning in 2002 and ending with 10% less spawning output in 2017 (a 15-year trend). When compared with the short coastwide model included in the ensemble, the change in maturity results in a nearly proportional decrease in the estimate of spawning biomass over the same period, leading to a bias in recent trend and scale of the current stock (Figure 13). This result illustrates the importance of ongoing research into factors influencing reproductive biology and success for Pacific halibut.

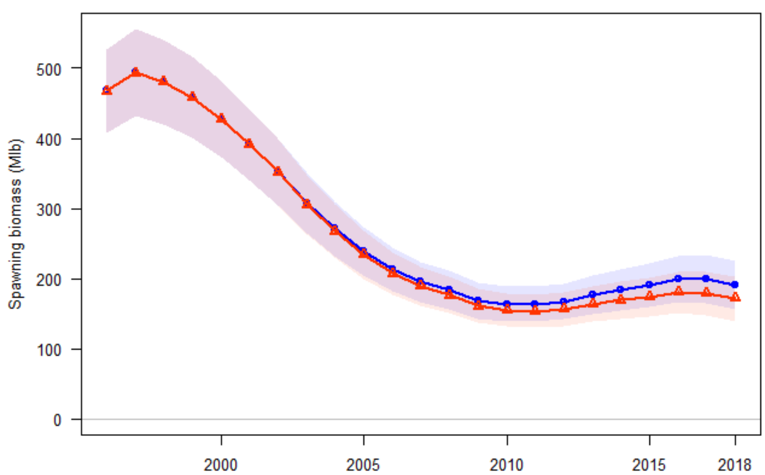

FIGURE 13. Spawning biomass estimates from a sensitivity analysis using the short coastwide model to evaluate the effect of a 10% decrease in spawning output over the last 15 years (lower series) with the results included in the ensemble (upper series). Shaded region indicates the approximate 95% within-model interval.

Currently, the survey is assumed to be a reasonable proxy for relative fishery selectivity of the oldest male and female Pacific halibut. The second sensitivity examined the effect of higher or lower relative fishery selectivity of males (using the coastwide short model); effectively testing the sensitivity to the assumption of sex-ratio of the commercial catch. A decrease in relative selectivity for males was found to result in larger absolute levels of spawning biomass, but little effect on trend, given a constant assumption over time (Figure 14). An increase in the relative selectivity of males did not produce greatly differing results for this model. It is likely that trends in sex-ratio could result in a bias to the estimated stock trends if it were unaccounted for. This sensitivity illustrates the importance of ongoing efforts to directly measure the sex-ratio of the commercial catch through marking at sea and genetic validation.

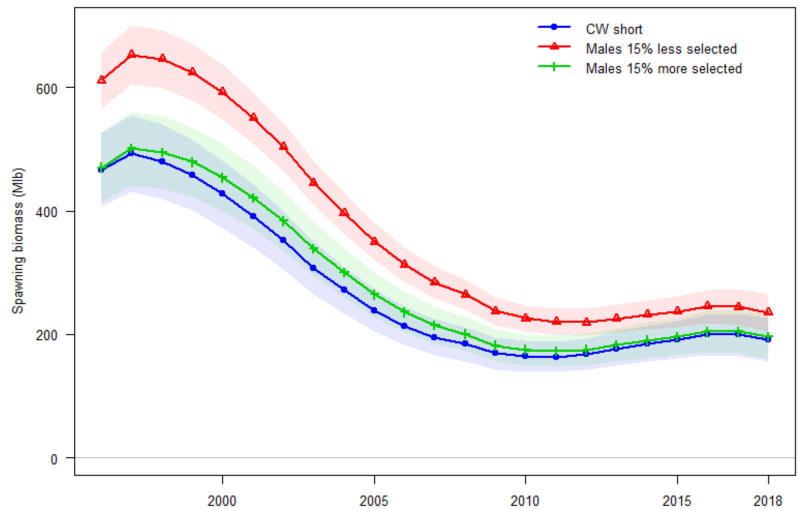

FIGURE 14. Spawning biomass estimates from a sensitivity analysis using the coastwide short model to evaluate the effect of a 15% change (+/-) in the relative selectivity for male halibut in the commercial fishery with the results included in the ensemble (middle series). Shaded region indicates the approximate 95% within-model intervals.

The third sensitivity added for this assessment explored the effect of additional unobserved mortality on the halibut stock. The sensitivity included two tests: 1) a 20% increase in mortality over the whole time-series, and 2) a trend of increasing mortality to 20% over the most recent 15 years. Unobserved mortality increases the estimate of stock size (Figure 15), and the trend causes a very small bias at the terminal end of the series, but mainly results in a small bias as well (Figure 16). Both of these results are relevant to both the stock assessment and harvest policy development, if unobserved mortality were occurring.

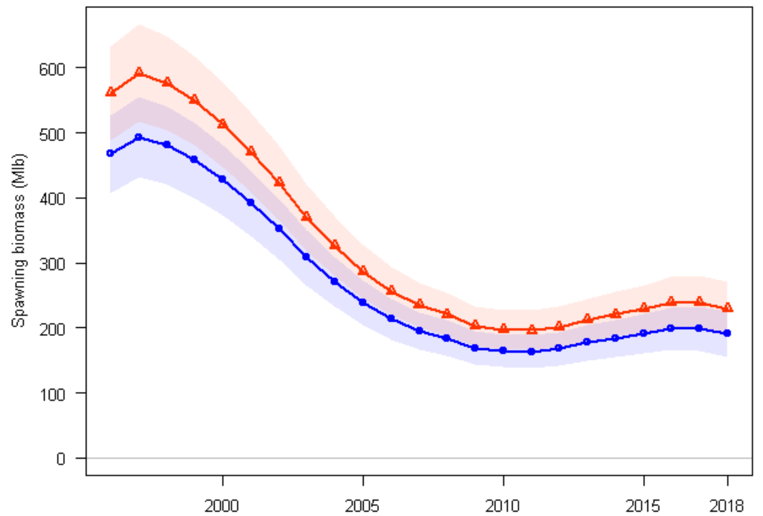

FIGURE 13. Spawning biomass estimates from a sensitivity analysis using the coastwide short model to evaluate the effect of a 20% increase in the total mortality from all sources (upper series), compared to the estimate used in the ensemble (lower series). Shaded region indicates the approximate 95% within-model intervals.

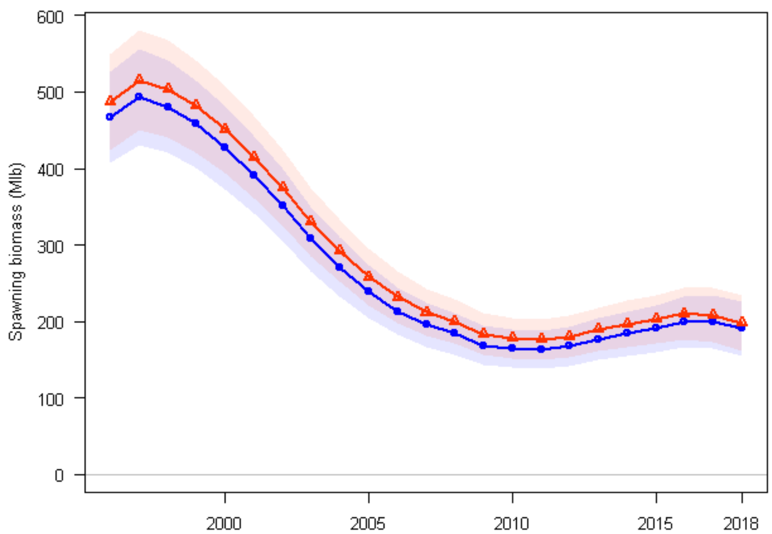

FIGURE 14. Spawning biomass estimates from a sensitivity analysis using the coastwide short model to evaluate the effect of a trend of a 20% increase in the total mortality from all sources over the last 15 years (upper series), compared to the estimate used in the ensemble (lower series). Shaded region indicates the approximate 95% within-model intervals.

A retrospective analysis was performed for each of the individual models contributing to this assessment. Both long time-series models showed little pattern in the most recent years, but slightly higher estimates as additional data were removed from each (Figure 15); however terminal biomass estimates remained inside the confidence intervals for the full model result over three of five years of the retrospective analysis. The short time-series models showed similar but slightly larger retrospective behavior (Figure 16), being inside the confidence intervals three to four of five years. This is not unexpected for short time-series models where there is a greater proportion of the total information available contained in each year's data.

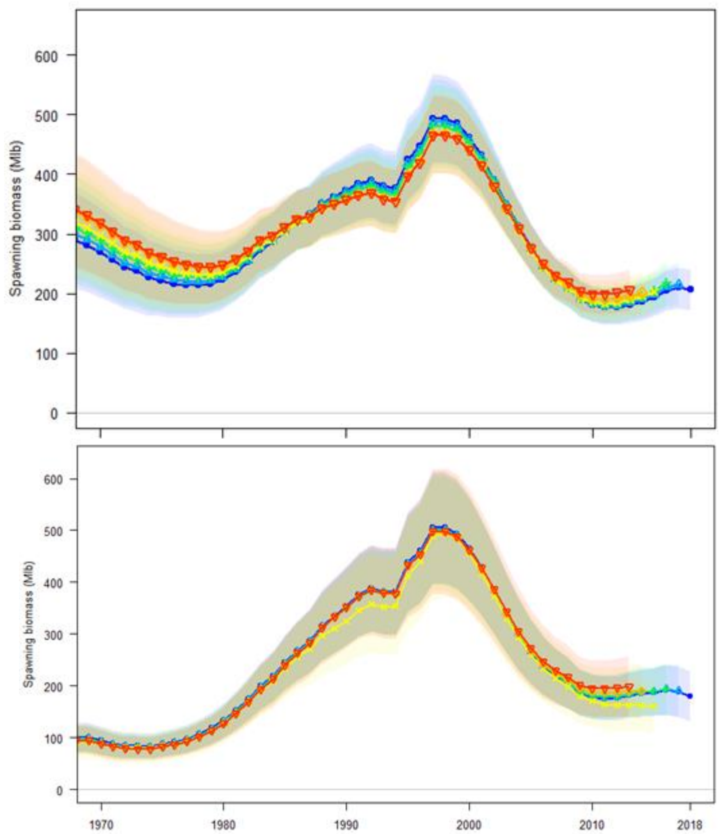

FIGURE 15. Results of the retrospective analysis on spawning biomass estimates using the Areas-as-fleets long (upper panel) and coastwide long (lower panel) time-series models and sequentially removing one year of data for five years. Dashed lines and shaded regions indicate within-model 95% intervals.

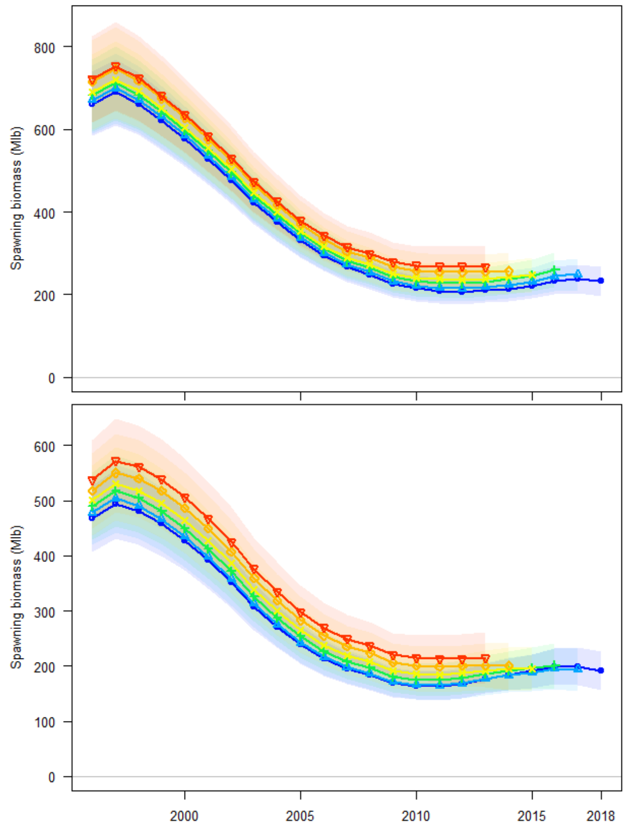

FIGURE 16. Results of the retrospective analysis on spawning biomass estimates using the coastwide short (upper panel) and Areas-As-Fleets short (lower panel) time-series models and sequentially removing one year of data for five years. Dashed lines and shaded regions indicate within-model 95% intervals.

FORECASTS AND DECISION TABLE

Stock projections were conducted using the integrated results from the stock assessment ensemble, estimates of removals from the 2017 directed fisheries and other sources of mortality. The harvest decision table (Table 3) provides a comparison of the relative risk (in times out of 100), using stock and fishery metrics (rows), against a range of alternative harvest levels for 2018 (columns). The orientation of this table has changed from previous analyses in order to make the comparison of additional metrics easier (the second year of projection is now explicitly included), and to increase consistency with the results produced from the Management Strategy Evaluation (Hicks & Stewart 2017). The block of rows entitled “Stock Trend” provides for evaluation of the risks to short-term trend in spawning biomass, independent of all harvest policy calculations. The remaining rows portray risks relative to the spawning biomass reference points (“Stock Status”) and fishery performance identified in the interim management procedure. The alternatives (columns) provided include several coarsely spaced levels of mortality intended to provide for evaluation of stock dynamics including:

- No mortality (useful to evaluate the stock trend due solely to population processes),

- A 10 million pound (~4,500 t) 2018 Total Constant Exploitation Yield (TCEY[3])
- A 50 million pound (~22,700 t) 2018 TCEY
- A 60 million pound (~27,200 t) 2018 TCEY
- The removals consistent with the reference SPR ($F_{46\%}$) level.

A finer grid of alternative TCEY values is provided around the column corresponding to the reference level of fishing intensity (SPR=46%; for 2018 a TCEY of 31 million pounds, ~14,060 t).

For each row of the decision table, the total mortality of all sizes and from all sources, the coastwide TCEY and the associated level of fishing intensity (median value with the 95% credible range below; measured via the Spawning Potential Ratio) are reported. Fishing intensity reflects the relative reduction in equilibrium (long-term) spawning biomass per recruit from all sources and sizes of removals, reported as $F_{x\%}$, (where x = the SPR) for comparison to other management processes in both nations where harvest rate targets and limits are commonly reported in these units. As in previous years, it is expected that additional alternatives will be produced during the IPHCs annual process such that all management alternatives considered for 2018 can be directly evaluated in terms projected total mortality and risk.

The stock is projected to decrease gradually over the period from 2018-20 for removals around the reference SPR level (Figure 11). The risk of stock declines begins to increase rapidly for TCEYs above 31 million pounds (~14,060 t), becoming more pronounced by 2020 (Table 3). The reference SPR corresponds to a 78/100 (78%) chance of stock decline through 2019, and a 46% chance of at least a 5% decline through 2021 at that constant level of TCEY. TCEYs corresponding to recent levels of fishing mortality correspond to probabilities of stock decline over the next one to three years greater than 95%. There is a relatively small chance (<21/100; 21%) that the stock will decline below the threshold reference point (SB30%) in projections for all the levels of TCEY up to 40 million pounds (~18,100 t) evaluated over three years; for TCEYs exceeding that level, the probability begins to increase rapidly.

[3] The TCEY corresponds approximately to the mortality comprised of Pacific halibut greater than 26 inches (66 cm) in length.

TABLE 3. Harvest decision table for 2018. Columns correspond to yield alternatives and rows to risk metrics. Values in the table represent the probability, in “times out of 100” (or percent chance) of a particular risk.

		2018 Alternative	No removals							*Reference: SPR=46%*								
		Total removals (M lb)	0.0	11.8	21.8	28.8	29.8	30.8	31.8	32.8	33.8	34.8	35.8	37.3	41.8	51.8	61.9	
		TCEY (M lb)	0.0	10.0	20.0	27.0	28.0	29.0	30.0	31.0	32.0	33.0	34.0	35.5	40.0	50.0	60.0	
		Fishing Intensity	$F_{100\%}$	$F_{73\%}$	$F_{58\%}$	$F_{50\%}$	$F_{49\%}$	$F_{48\%}$	$F_{47\%}$	$F_{46\%}$	$F_{45\%}$	$F_{44\%}$	$F_{43\%}$	$F_{42\%}$	$F_{39\%}$	$F_{32\%}$	$F_{27\%}$	
		Fishing Intensity Interval	–	61-84%	45-73%	37-67%	36-66%	36-65%	35-65%	34-64%	33-63%	32-63%	32-62%	31-61%	28-58%	23-53%	19-48%	
Stock Trend (spawning biomass)	In 2019	Is less than 2018	1	3	24	59	64	69	74	78	81	85	87	91	98	>99	>99	a
		Is 5% less than 2018	<1	<1	<1	2	2	3	4	5	7	9	11	14	29	69	96	b
	In 2020	Is less than 2018	<1	1	14	46	52	57	62	67	71	76	80	85	95	>99	>99	c
		Is 5% less than 2018	<1	<1	1	9	11	14	18	21	25	29	34	41	61	94	>99	d
	In 2021	Is less than 2018	<1	2	23	59	63	68	72	76	79	83	86	90	97	>99	>99	e
		Is 5% less than 2018	<1	<1	5	27	32	36	41	46	50	55	59	66	83	99	>99	f
Stock Status (Spawning biomass)	In 2019	Is less than 30%	3	4	5	6	6	7	7	7	7	7	7	8	9	11	15	g
		Is less than 20%	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	1	h
	In 2020	Is less than 30%	2	2	4	6	6	6	7	7	8	8	9	9	12	21	32	i
		Is less than 20%	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	1	1	j
	In 2021	Is less than 30%	1	1	4	7	8	8	9	10	11	12	13	15	21	37	54	k
		Is less than 20%	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	1	2	7	l
Fishery Trend (TCEY)	In 2019	Is less than 2018	<1	<1	7	33	38	43	49	55	60	64	68	71	78	89	97	m
		Is 10% less than 2018	<1	<1	3	23	26	30	34	38	43	48	53	59	72	82	92	n
	In 2020	Is less than 2018	<1	<1	10	38	43	49	54	59	63	67	70	73	79	91	98	o
		Is 10% less than 2018	<1	<1	6	27	31	36	40	45	50	54	59	64	74	84	95	p
	In 2021	Is less than 2018	<1	<1	14	44	50	55	59	63	67	69	72	74	81	93	>99	q
		Is 10% less than 2018	<1	<1	9	34	38	43	48	52	56	60	63	67	75	86	99	r
Fishery Status (Fishing intensity)	In 2018	Is above $F_{46\%}$	0	<1	4	29	33	38	43	50	54	60	64	69	77	87	95	s

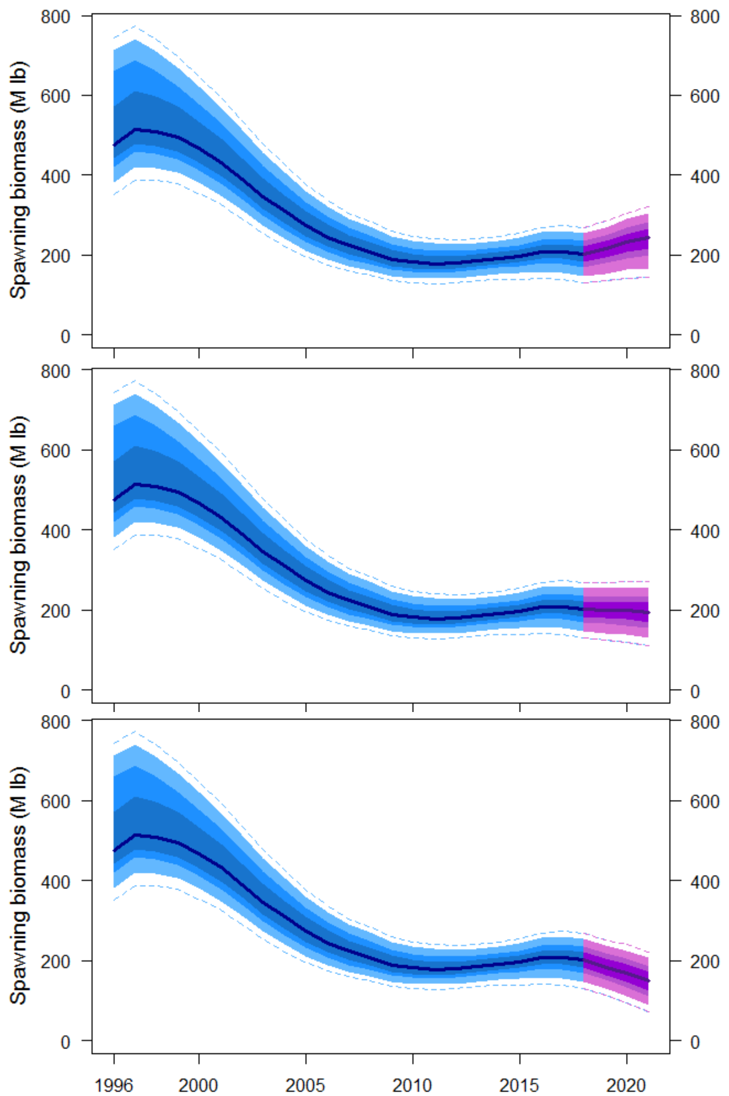

FIGURE 17. Three-year projections of stock trend under alternative levels of mortality: no removals (upper panel), Reference SPR=46% (32.8 million pounds, ~14,900 t; middle panel) and a TCEY of 60 million pounds (~27,200 t; lower panel).

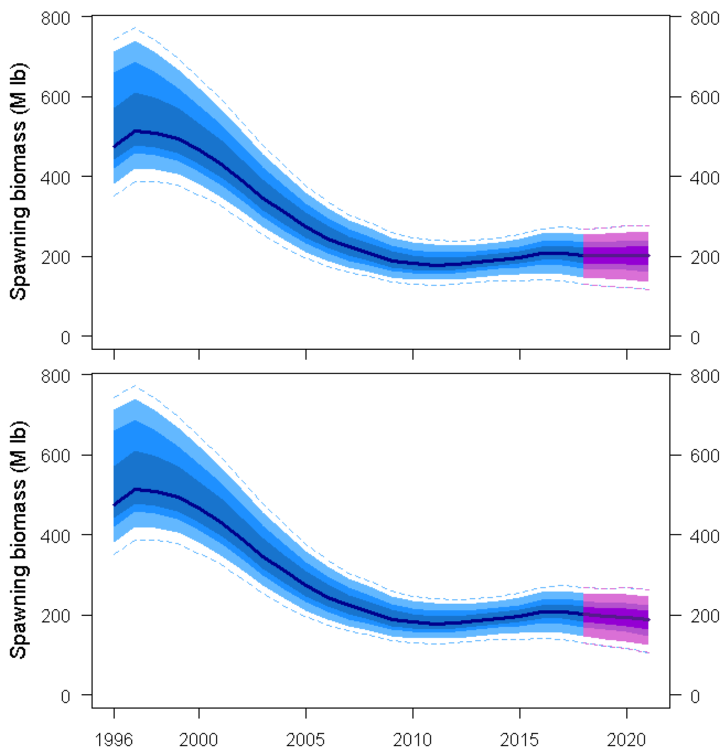

FIGURE 18. Three-year projections of stock trend under an SPR=50% (TCEY=27.0 million pounds, ~12,250 t; upper panel) and an SPR=42% (TCEY=35.5 million pounds, ~16,100 t; lower panel).

RESEARCH PRIORITIES

Research priorities for the stock assessment and related analyses can be delineated into two broad categories: gaps in biological understanding and technical development.

Biological understanding: During the last several years, the IPHC Secretariat has developed a comprehensive five-year research program (Planas 2017). The development of the research priorities has been closely tied to the needs of the stock assessment and harvest strategy policy analyses, such that each of the IPHC's ongoing projects (e.g., determining the sex-ratio of the commercial landings, updating estimates of the maturity schedule for Pacific halibut, better understanding of recruitment processes and stock structure, etc.) will provide data, and hopefully knowledge, about key biological and ecosystem processes that can then be incorporated directly into analyses supporting the management of Pacific halibut.

Technical development: The IPHC's stock assessment, Management Strategy Evaluation (MSE), and harvest strategy policy methods is ongoing, and responds to new developments in the data or analyses necessary each year. New approaches are tested, reported to the IPHC's SRB (generally in June), refined (and reviewed again in October, as needed), and ultimately incorporated in the development of the best scientific information available for the annual management process. Current technical research priorities include:

1) Maintaining consistency and coordination between MSE, and stock assessment data, modelling and methodology.

2) Continued refinement of the ensemble of models used in the stock assessment.

3) Continued development of weighting approaches for models included in the ensemble, potentially including fit to the survey index of abundance, retrospective, and predictive performance.
4) Exploration of methods for better including uncertainty in discard mortality and bycatch estimates in the assessment (now evaluated only via alternative catch tables or model sensitivity tests) in order to better include these sources uncertainty in the decision table.
5) Bayesian methods for fully integrating parameter uncertainty may provide improved uncertainty estimates within the models contributing to the assessment, and a more natural approach for combining the individual models in the ensemble.

ACKNOWLEDGEMENTS

We thank all of the IPHC Secretariat staff for their contributions to data collection, analysis and preparation for the stock assessment. We also thank the staff at the NMFS, DFO, ADFG, WDFW, ODFW, and CDFW for providing the annual information required for this assessment in a timely manner. The SRB and the Science Advisors provided critical review and helpful guidance during the 2017 process.

RECOMMENDATION/S

That the Commission:

a) **NOTE** paper IPHC-2018-AM094-10 which provides the results of the 2017 stock assessment for Pacific halibut.

REFERENCES

Hicks, A., and Stewart, I. 2017. IPHC Managment Strategy Evaluation (MSE): Update. IPHC-2017-IM093-10. 32 p.

Planas, J. 2017. IPHC 5-year biological and ecosystem science program: update IPHC-2017-IM093-11. 5 p.

Stewart, I. 2017. Pacific halibut stock assessment development for 2017. IPHC-2017-SRB10-07. 14 p.

Stewart, I.J., and Hicks, A.C. 2017. 4.2 Assessment of the Pacific halibut stock at the end of 2016. IPHC Report of Assessment and Research Activities 2016: 365-394.

Stewart, I.J., and Martell, S.J.D. 2016. Appendix: Development of the 2015 stock assessment. IPHC Report of Assessment and Research Activities 2015. p. A1-A146.