4.2 Assessment of the Pacific halibut stock at the end of 2016

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Abstract

The stock assessment reports the status of the Pacific halibut (*Hippoglossus stenolepis*) resource in the Convention Area, including the Exclusive Economic Zones of the United States of America and Canada. Commercial fishery landings in 2016 were approximately 25.0 million pounds (~11,400 t, all weights in this document are reported as 'net' weights, head and guts removed; this is approximately 75% of the round weight), up from a low of 23.7 million pounds (~10,700 t) in 2014. Bycatch mortality was estimated to be 7.1 million pounds (~3,200 t), the lowest level in the estimated time series. The 2016 IPHC fishery-independent setline survey estimates of coastwide aggregate legal (O32; over 32 inches (81.3 cm) in length) WPUE were 6% higher than the value observed in 2015, representing the fifth year of stable catch rates. Age distributions in 2016 from both the survey and fishery remained similar to those observed in 2011-15, indicating a relatively stable stock, but not showing clear evidence of strong coastwide recent recruitment events. At the coastwide level, individual size-at-age continues to be very low relative to the rest of the time-series, although there has been little change over the last several years.

This stock assessment consists of an ensemble 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. As has been the case since 2012, this stock assessment is 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 2016 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. The SB at the beginning of 2017 is estimated to be 212 million pounds (~96,200 t), with an approximate 95% confidence interval ranging from 153 to 286 million pounds (~69,400-129,700 t). Recruitment estimates show the largest recent cohorts in 1999 and 2005, and there is little information on the relative strength of subsequent cohorts, which will be the most important for stock productivity over the next decade.

A comparison of the median current ensemble SB to reference levels specified by the current harvest policy suggests that the stock is currently at 41% of equilibrium unfished levels; however, the probability distribution indicates considerable uncertainty, with a 5/100 (5%) probability the stock is below the $SB_{30\%}$ level. Stock projections for a range of alternative management actions were conducted using the integrated results from the stock assessment ensemble, summaries of the 2016 fishery, and other sources of mortality, as well as the results of apportionment calculations and the target harvest rates from current IPHC harvest policy. The results for 2017 show somewhat more risk than those from last year's assessment: the stock is projected to increase gradually over 2018-20 in the absence of any removals, and for removals of up to around 40 million pounds (~18,100 t). For removals around 40 million pounds (~18,100 t), projections are slightly decreasing. The risk

of stock declines begins to increase rapidly for levels of harvest above 40 million pounds (~18,100 t) of total mortality, becoming more pronounced by 2020. The current IPHC Harvest Policy (the Blue Line) suggests that 37.9 million pounds, ~17,200 t, total removals, corresponds to a 56/100 (56%) chance of stock decline in 2018 and the *status quo* SPR line (41.6 million pounds, ~18,900 t) corresponds to a 68/100 (68%) chance of stock decline in 2018.

Introduction

The stock assessment reports the status of the Pacific halibut (*Hippoglossus stenolepis*) resource in the Convention Area, including the Exclusive Economic Zones of the United States of America and Canada. As in recent stock assessments, the resource is modeled 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 Pacific halibut fishery has been managed by the International Pacific Halibut Commission (IPHC) since 1923. Catch limits for each of eight regulatory areas are set each year by six Commissioners from the United States of America and Canada. The stock assessment provides a summary of recently collected data, model estimates of stock size and trend. Specific management information is summarized via a decision table reporting the estimated risks associated with alternative management actions and catch tables illustrating the level of harvest in each Regulatory Area indicated by the IPHC's current harvest policy (the Blue Line; see Stewart 2017a for the details of this calculation).

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). For 2016, the most important change was the transition to a model-based estimator for the IPHC fishery-independent setline survey (Stewart 2017b, Webster 2017). This method extracts more information from the survey catch rates through estimation of spatial and temporal correlations among stations, as well as using covariates such as depth to more accurately infer unsampled survey stations. In addition to improving the quality of the survey index, this transition added hook-competition and survey timing corrections into the index of Numbers-Per-Unit-Effort used in the stock assessment model for the first time. In aggregate, the historical time series of data available for this assessment represents a considerable resource for analysis. The range of relative data quality is also considerable, with the most complete information available only in recent years (Fig. 1). A detailed summary of input data used in this stock assessment can be found in Stewart (2017b).

All available information was finalized on 11 November 2016 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 2016. These include commercial fishery WPUE, commercial fishery age composition data, and 2016 removals for all fisheries still operating after 11 November 2016. Some of these data may therefore be revised in various documents as late-season landings and validation of data are incorporated; all preliminary series in the assessment will be fully updated in 2017.

Briefly, known Pacific halibut removals consist of target fishery landings and discards (wastage), bycatch in non-target fisheries, research (included with fishery landings), sport, and personal use. Over the period 1917-2016 removals have totaled 7.1 billion lbs (3.2 million t), ranging annually from 34 to 100 million lbs (16,000-45,000 t) with an annual average of 63 million lbs (~29,000 t). Annual removals were above average from 1985 through 2010 and have decreased annually from a peak in 2004 in response to management measures. Commercial fishery landings in 2016 were approximately 25.0 million pounds (~11,400 t), up from a low of 23.7 million pounds (~10,700 t) in 2014. Bycatch mortality was estimated to be 7.1 million pounds (~3,200 t), the lowest level in the estimated time series, beginning with the arrival of foreign fishing fleets in 1962. The total sport removals were estimated to be 7.4 million pounds (~3,300 t), down slightly from 2015. Removals from all sources in 2016 were estimated to be 41.9 million pounds (~19,000 t), down slightly from 42.1 million pounds in 2015 (~19,100 t).

Data are initially compiled by management area and then aggregated to the coastwide level and to four geographical regions: Area 2 (2A, 2B, and 2C), Area 3 (3A, 3B), Area 4 (4A, 4CDE) and Area 4B (Fig. 1). 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).

The 2016 IPHC fishery-independent setline survey detailed a coastwide aggregate legal (O32; over 32 inches (81.3 cm) in length) Weight-Per-Unit-Effort (WPUE) which was 6% higher than the value observed in 2015, representing the fifth year of stable catch rates. Most regulatory areas show a similar overall trend over recent years, with somewhat more positive trends observed in Area 2. Setline survey NPUE showed a much less pronounced decline from the late 1990s (only 10-15%), based on the revised survey series compared to previous analyses, and a similarly increasing trend over the last few years. Commercial fishery WPUE (based on extensive, but still incomplete logbook records available for this assessment) was unchanged at the coastwide level and showed increases in all areas except 2A, 4B, and 4C from 2015 to 2016.. The largest decline, 47%, was observed in Area 2A. Age distributions in 2016 from both the survey and fishery remained similar to those observed in 2011-15, indicating a relatively stable stock, but not showing clear evidence of strong coastwide recent recruitments. At the coastwide level, individual size-at-age continues to be very low relative to the rest of the time-series, although there has been little change over the last several years.

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 (Table 1). AAF models are commonly applied when biological differences among areas or sampling programs make coastwide summary of data sources 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 accommodate temporal and spatial trends in where and how data have been collected, and fishery catches have occurred, because each region need not have data for each year modelled.

The ensemble approach recognizes that there is no "perfect" assessment model, and that 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. The basic approach to each of the four assessment models used in 2014 (Stewart and Martell 2015b) remains unchanged for 2015. 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.

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 should be possible to refine this weighting 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 and 2016, however; these methods still require further development. In the interim, the results did not suggest weights differing substantially from the *status quo*, so 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

In in-depth review of the 2015 assessment models resulted in a number of improvements (Cox et al. 2016, Stewart and Martell 2016); however, those ensemble results remained similar to previous assessments. Comparison of this year's results with previous stock assessments indicates that the estimates of spawning biomass from the 2016 ensemble remain consistent with those from 2012-2015, which lie inside the predicted 50% interval of the ensemble in recent years (Fig. 2). Models prior to 2012, which had shown a problematic retrospective pattern, suggested terminal stock 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 from the 2015 ensemble (for 2016) were slightly higher than the current results, but statistically very similar given the degree of uncertainty (Table 2).

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 around 2010 (Fig. 3). The differences among the individual models contributing to the ensemble are most pronounced prior to the early 2000s (Fig. 4). However, current stock size estimates (at the beginning of 2017) also differ substantially among the four models (Fig. 5). 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 Areas 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 (Fig. 6). 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 (Fig. 7). Recruitments after 2010 do not yet have information available in the fishery or survey data, and therefore remain highly uncertain.

In addition to recruitment trends, observed decreases in size-at-age (Stewart 2017) have also been an important contributor to recent stock declines. In the last few years, the estimated female spawning biomass appears to have stabilized near 200 Mlb and begun to increase slowly (Table 3, Fig. 3). The SB at the beginning of 2017 is estimated to be 212 million pounds (~96,200 t), with an approximate 95% interval ranging from 153 to 286 million pounds (~69,400-129,700 t; Fig. 8). The median estimate of exploitable biomass consistent with the IPHC's current harvest policy is 181 million lbs (82,100 t) at the beginning of 2017. The median from the ensemble suggest that the stock is currently at 41% of equilibrium unfished biomass; however, the probability distribution indicates a very wide plausible interval ranging from 5/100 (5%) at the 30% level to 90/100 (90%) at almost 50% of equilibrium conditions (Fig. 9). All sources of estimated removals for 2016 correspond to a fishing intensity point estimate of $F_{47\%}$ (Table 3, Fig. 10). The 95% interval of this distribution is considerable ($F_{60\%}$-$F_{33\%}$), 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.

Long time-series models

The two long time-series models provided different perceptions of current vs. historical stock sizes (Fig. 11). The AAF model suggests that the stock is increasing gradually and at 37% of the equilibrium unfished stock size; however, the model estimates that current spawning biomass is at only 121% of the historically low levels estimated for the 1970s. The coastwide model also suggests that the stock is currently increasing and at 47% of the equilibrium unfished stock size; however, the current spawning biomass is estimated to be at 231% 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 Area 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 Areas 2 and 3 and Area 4 during the early part of the 1900s when there are no data available from Area 4 (Stewart and Martell 2016).

Both of the long time-series models estimate that average Pacific halibut recruitment is higher (38 and 70% for the coastwide and AAF models respectively) during favorable Pacific Decadal Oscillation (PDO) regimes, a widely used indicator of productivity in the north Pacific that is correlated with Pacific halibut recruitment (Clark and Hare 2002). 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. Average conditions from 2014 through October 2016 have been positive; however, many other environmental indicators, current and temperature patterns have been anomalous relative to historical periods.

Major sources of uncertainty

This stock assessment includes substantial 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 a substantial improvement over the use of a single assessment model, there are important sources of uncertainty that are not included.

Two primary uncertainties continue to hinder our current understanding of the Pacific halibut resource:

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. Ongoing efforts to test methods for direct marking of male and female fish at sea will continue in 2017 via voluntary marking in all regulatory areas along with collection of genetic samples for determining the accuracy and precision of the marking program;
2) The treatment of spatial dynamics and movement rates among Regulatory Areas, which are represented via the coastwide and AAF approaches, and have very strong 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 Area 4, are necessary for parameterizing a spatially explicit stock assessment. Current understanding of these rates has now been summarized, but remains uncertain.

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 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 estimation (observer sampling and representativeness), discard mortality rates, and any other unreported sources of removals in either directed or non-directed fisheries could create significant 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.

Since 2012, natural mortality has been an important source of uncertainty 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 AAF model (0.15) differs substantially from the value estimated in the coastwide model (0.21). 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.

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 2001 and ending with 10% less spawning output in 2016 (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 (Fig. 12). This result illustrates the importance of ongoing research into factors influencing reproductive biology and success for Pacific halibut.

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 and females in Area 2 and 3 (using the short AAF model); effectively testing the sensitivity to the assumption of sex-ratio of the commercial catch. An increase or decrease in relative selectivity was found to result in differing absolute levels of spawning biomass, but little effect on trend, given a constant assumption over time (Fig. 13). 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.

The third sensitivity added for this assessment explored the effect of assuming half or double the current Discard Mortality Rate (DMR) used in the commercial fishery time series, 16%. The assessment result was found to be largely insensitive to this input, despite a change in mortality that would result in 0.59 million lbs (~270 t, at 8%) less mortality or an increase of 1.18 million lbs (~535 t, at 32%) in just the terminal year (Fig. 14). The reason why the assessment results remain so similar, is that this change in mortality is only around 2% or less of the overall removals. Despite the lack of change in assessment results, a change in the underlying DMR could result in an important increase or decrease in fishery yield via the harvest policy calculations, and could be of much greater interest to long term management decisions

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 (Fig. 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 (Fig. 16), being inside the confidence intervals four of five years. This is not unexpected for short time-series where there is a greater proportion of the total information available contained in each year's data.

Forecasts and decision table

Stock projections were conducted using the integrated results from the stock assessment ensemble, summaries of the 2016 fishery, and other sources of mortality, as well as the results of apportionment calculations (Webster and Stewart 2017) and the target harvest rates from current IPHC harvest policy (Stewart 2017). The steps included:

1) apportioning the coastwide estimate of exploitable biomass according to the legal-sized (O32) survey catches in each regulatory area;
2) applying the area-specific target harvest rates to estimate the total CEY for each area, including all removals over 26 inches (66 cm) in length (O26) associated with a given level of harvest; and
3) calculating the total mortality and projecting the stock trends three years into the future assuming constant values for all sources of removals.

The decision table (Table 4) provides a comparison of the relative risk (in times out of 100), using stock and fishery metrics (columns), for a range of alternative harvest levels for 2017 (rows). The block of columns entitled "Stock Trend" provides for evaluation of the risks to short term trend in spawning biomass, without reference to a particular harvest policy. The remaining columns portray these risks relative to the spawning biomass reference points ("Stock Status") and fishery performance identified in the current harvest policy. The alternatives provided include:

- No mortality (useful to evaluate the stock trend due solely to population processes),
- No directed mortality (but accounting for bycatch and other removals not under direct IPHC control including recreational removals from some sources and personal use removals),
- The Blue Line (consistent with the current harvest policy and, historically, IPHC staff advice),
- The *status quo* SPR (Spawning Potential Ratio) removals (maintaining the same average fishing intensity as has been realized over the recent period of increasing stock size from 2014-16),
- Arbitrary values (at 10 million pounds (~4,500 t) increments) intended to foster the evaluation of the relative change in risk probability across a range of total mortality levels.

For each row of the decision table, the total mortality of all sizes and from all sources, the total coastwide fishery CEY and the associated level of fishing intensity (median value with the 95% interval 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 2017 can be directly evaluated in terms projected total mortality and risk.

The results for 2017 show somewhat more risk than those from last year's assessment: the stock is projected to increase gradually over 2018-20 in the absence of any removals, and for removals of up to around 40 million pounds (~18,100 t). For removals around 40 million pounds (~18,100 t), projections are slightly decreasing. The risk of stock declines begins to increase rapidly for levels of harvest above 40 million pounds (~18,100 t) of total mortality, becoming more pronounced by 2020 (Table 4; Fig. 17). The Blue Line (37.9 million pounds, ~17,200 t, total removals) corresponds to a 56/100 (56%) chance of stock decline in 2018 and a 77/100 (77%) chance in 2020. However, the risk of substantial stock decline (>5% decline) is much lower at only 3/100 (3%) in 2018 and a 53/100 (53%) in 2019. The *status quo* SPR line (41.6 million pounds, ~18,900 t) corresponds to a 68/100 (68%) chance of stock decline in 2018 and an 87/100 (87%) chance in 2020, again with much lower values of substantial decline.

For stock status, fishery trend and fishery status metrics based on the current harvest policy, there is a relatively small chance (<37/100; 37%) that the stock will decline below the threshold ($SB_{30\%}$) reference point in projections for all the levels of removals evaluated over three years. For removals in excess of the Blue Line, there is a greater than a 50/100 (50%) chance that the fishery CEY would be smaller in 2018-20 if the current harvest policy were applied in those years.

Future research

Future research will continue to focus on topics identified in previous assessments and extensions already underway:

1) Continued expansion and/or refinement of the ensemble of models used in the stock assessment. Specifically, an explicit spatial model will continue to be developed that may allow for improved incorporation of the uncertainty due to spatial processes such as

migration and recruitment distribution among regulatory areas. Longer term efforts will include explicit modelling of growth within potential assessment models.

2) Continued development of weighting approaches for models included in the ensemble, potentially including fit to the survey index of abundance, retrospective and predictive performance.
3) Continued development of methods for sampling the sex-ratio of the commercial catch. The results of the stock assessment are sensitive to the sex-ratio, and therefore this source of uncertainty is a high priority for future data collection.
4) Further investigation of the factors contributing to recruitment strength, recruitment distribution, and the information available from trawl surveys, particularly in the Bering Sea. There are several avenues of research that can be explored using a spatial model, but not with the currently available structures.
5) Explore methods for including uncertainty in wastage 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.
6) 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.
7) Continued integration of the assessment data and analyses with the development of the harvest policy and the Management Strategy Evaluation process.

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Table 1. Summary of the four models included in the 2016 stock assessment ensemble.

	Coastwide data aggregation	Areas-As-Fleets
Short time-series (1996+)	x	x
Long time series	x	x

Table 2. Comparison of 2016 median ensemble beginning-of-year biomass estimates (Mlb, with relative 95% confidence intervals) from the 2015 and current assessments.

Quantity	2015 Assessment	2016 Assessment
2016 Exploitable biomass	185	174
2016 Spawning biomass	219 (155-292)	207 (154-275)

Table 3. Median spawning biomass (millions lbs), fishing intensity (based on median Spawning Potential Ratio, where smaller values indicate higher fishing intensity) and exploitable biomass estimates from the 2016 assessment.

Year	Spawning biomass	Fishing intensity ($F_{XX\%}$)	Exploitable biomass
1996	473.7	48%	647.2
1997	510.9	43%	703.2
1998	504.3	41%	663.1
1999	489.3	39%	659.4
2000	462.1	39%	613.3
2001	427.4	36%	540.0
2002	387.0	32%	476.7
2003	343.1	29%	415.0
2004	305.8	27%	365.2
2005	271.8	25%	321.5
2006	244.2	25%	282.7
2007	223.9	25%	248.1
2008	209.9	25%	221.1
2009	192.4	26%	192.6
2010	185.6	27%	176.0
2011	183.7	32%	166.1
2012	186.5	37%	160.5
2013	194.4	39%	159.8
2014	200.6	45%	161.8
2015	204.6	46%	169.6
2016	207.5	47%	173.7
2017	212.2	NA	181.2

Table 4. Decision table of yield alternatives (rows) and risk metrics (columns). Values in the table represent the probability, in "times out of 100" of a particular risk.

				Stock Trend				Stock Status				Fishery Trend				Fishery Status
				Spawning biomass				Spawning biomass				Fishery CEY from the harvest policy				Harvest rate
				in 2018		in 2020		in 2018		in 2020		in 2018		in 2020		in 2017
2017 Alternative	Total removals (M lb)	Fishery CEY (M lb)	Fishing intensity	is less than 2017	is 5% less than 2017	is less than 2017	is 5% less than 2017	is less than 30%	is less than 20%	is less than 30%	is less than 20%	is less than 2017	is 10% less than 2017	is less than 2017	is 10% less than 2017	is above target
No removals	0.0	0.0	$F_{100\%}$	<1	<1	<1	<1	3	<1	1	<1	<1	<1	<1	<1	0
FCEY = 0	11.2	0.0	$F_{77\%}$ 61%-84%	1	<1	3	<1	3	<1	1	<1	<1	<1	<1	<1	<1
	20.0	8.6	$F_{66\%}$ 49%-75%	5	<1	20	4	4	<1	3	<1	<1	<1	<1	<1	<1
	30.0	18.4	$F_{55\%}$ 39%-67%	32	<1	53	31	5	<1	6	<1	6	3	8	4	8
Blue Line	37.9	26.1	$F_{48\%}$ 33%-62%	56	3	77	53	6	<1	12	<1	47	33	48	39	50
status quo SPR	41.6	29.7	$F_{46\%}$ 32%-60%	68	6	87	64	6	<1	15	<1	57	45	57	49	61
	50.0	37.9	$F_{40\%}$ 27%-55%	92	29	98	88	7	<1	25	1	94	83	95	86	95
	60.0	47.7	$F_{35\%}$ 23%-51%	>99	52	>99	99	9	<1	37	3	>99	>99	>99	>99	>99
				a	b	c	d	e	f	g	h	i	j	k	l	m

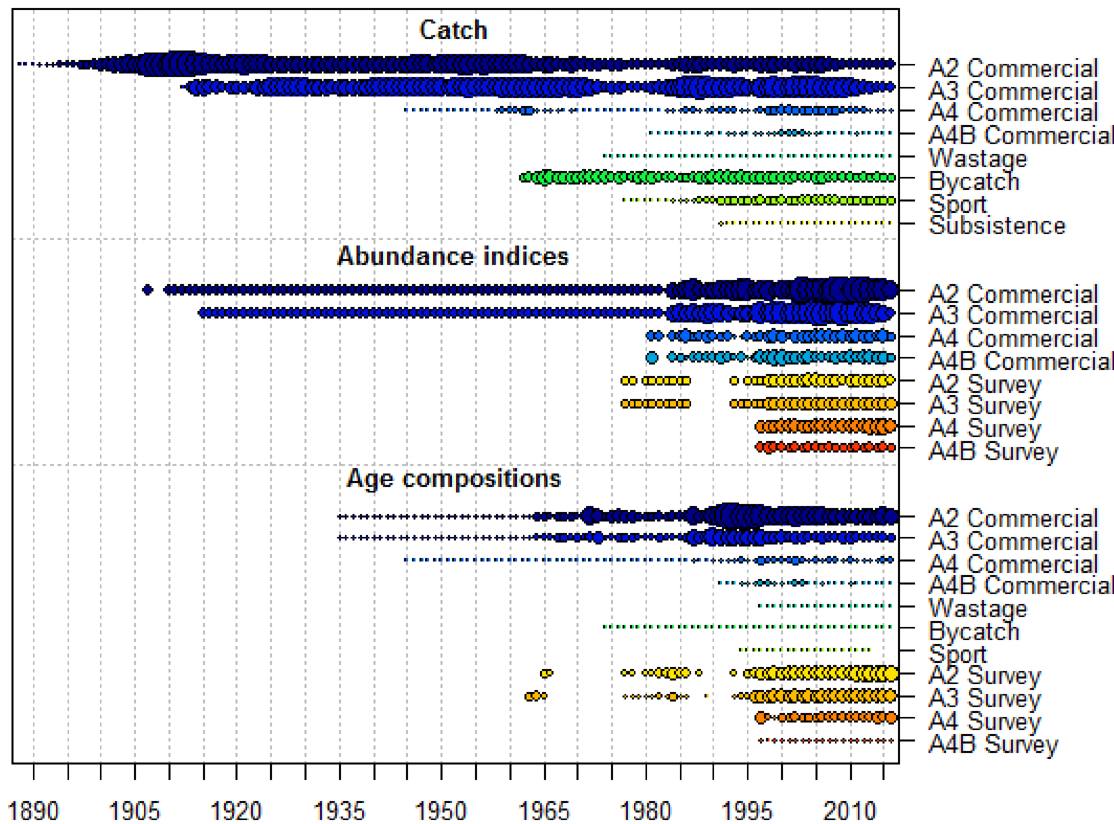

Figure 1. Overview of data sources. Circle areas are proportional to magnitude (catches) or the relative precision of the data (indices of abundance and age composition data).

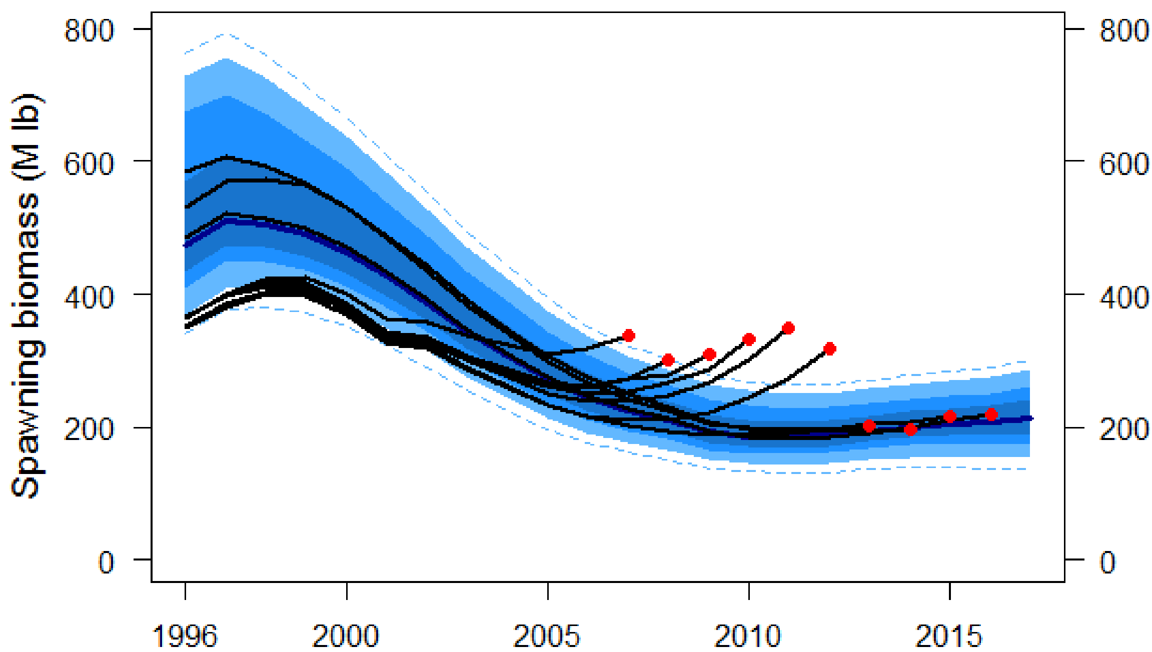

Figure 2. Retrospective comparison among recent stock assessments. The black lines denote point estimates from previous assessments conducted in 2006-2015. The shaded area represents the approximate probability distribution from the 2016 ensemble.

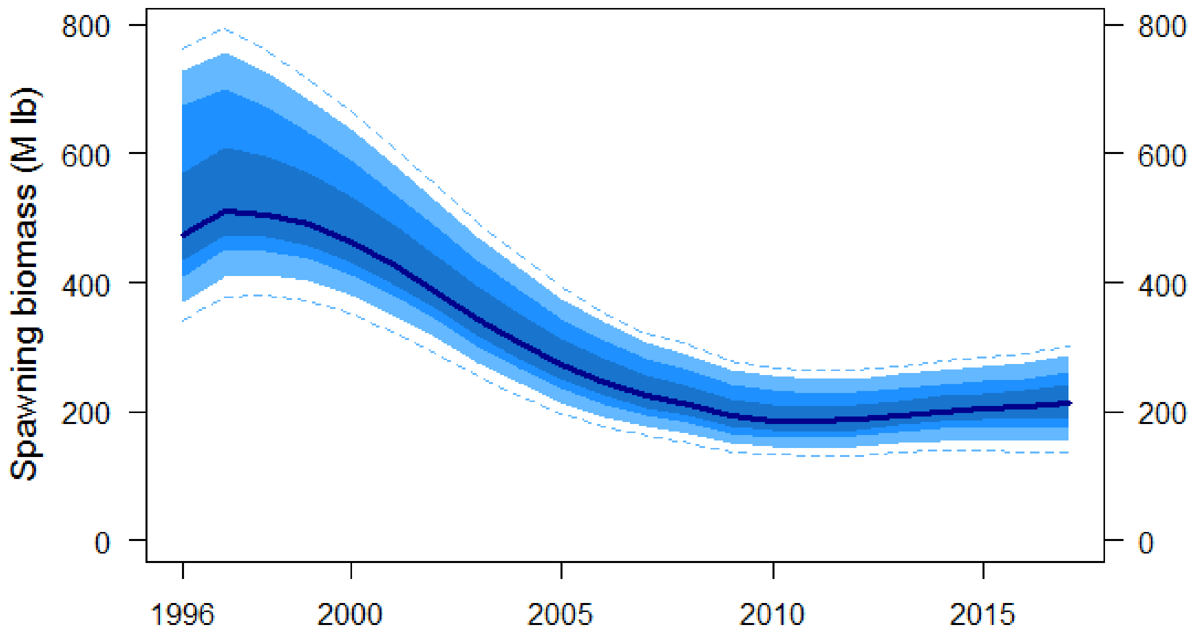

Figure 3. Trend in spawning biomass estimated in the 2016 stock assessment. The dark line indicates the median (or "50:50 line") with an equal probability of the estimate falling above or below that level; colored bands moving away from the median indicate the intervals containing 50/100, 75/100, and 95/100 estimates; outer dashed lines indicating the 99/100 interval.

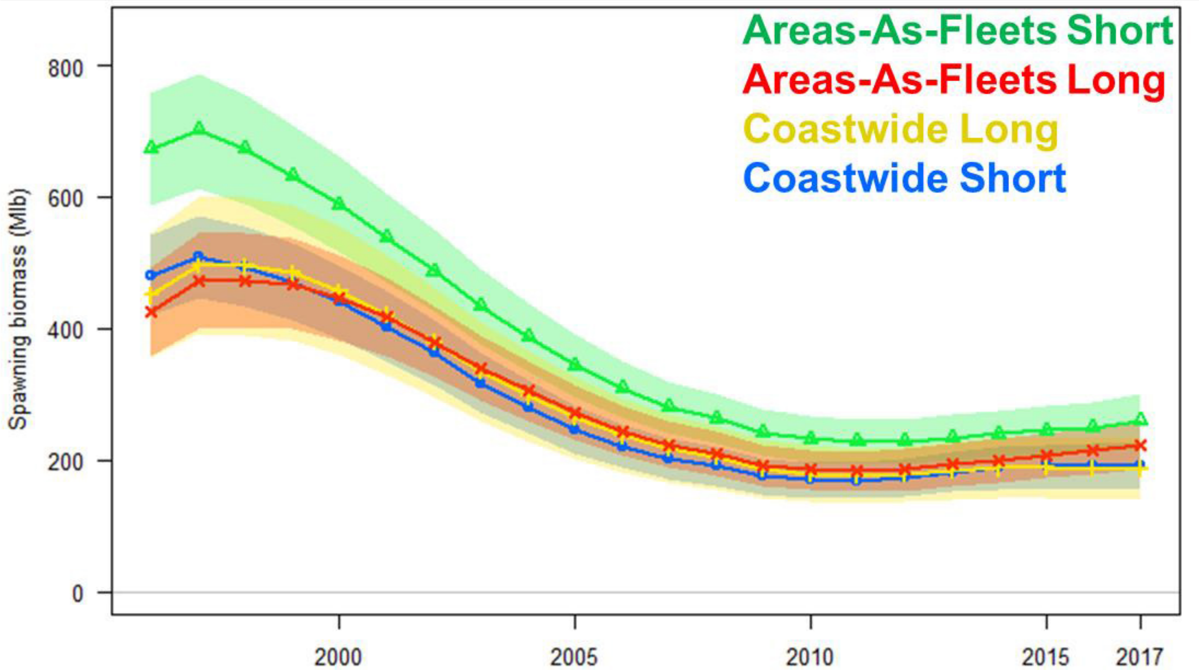

Figure 4. Comparison of models included in the 2016 stock assessment. Solid lines with points indicate point estimates, dashed lines and shading approximate 95% intervals reflecting within-model uncertainty.

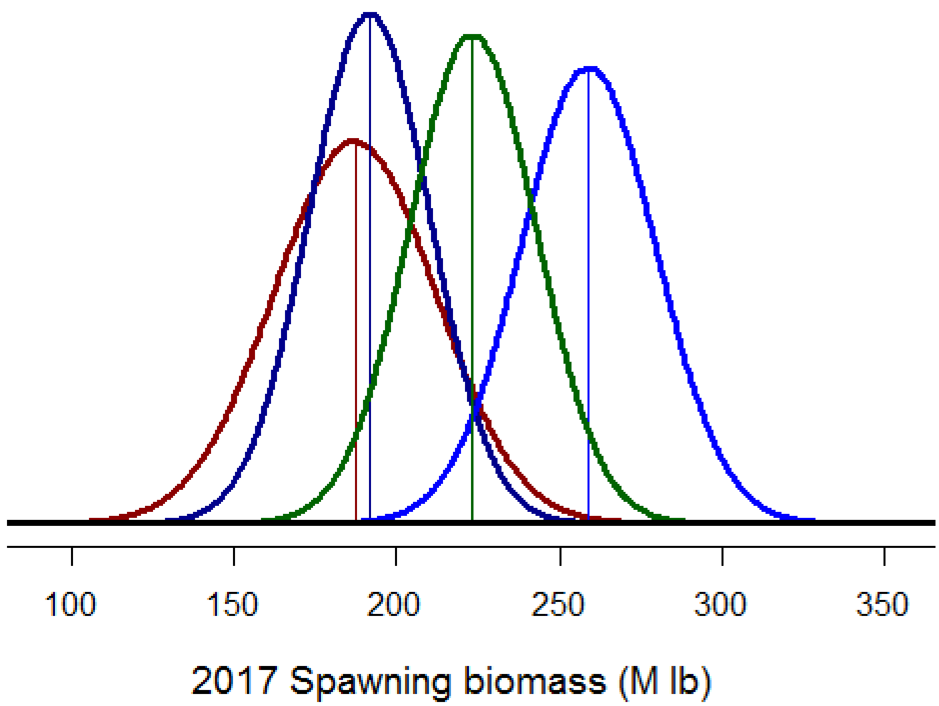

Figure 5. Distribution of individual model estimates for the 2017 spawning biomass. Vertical lines indicate the median values.

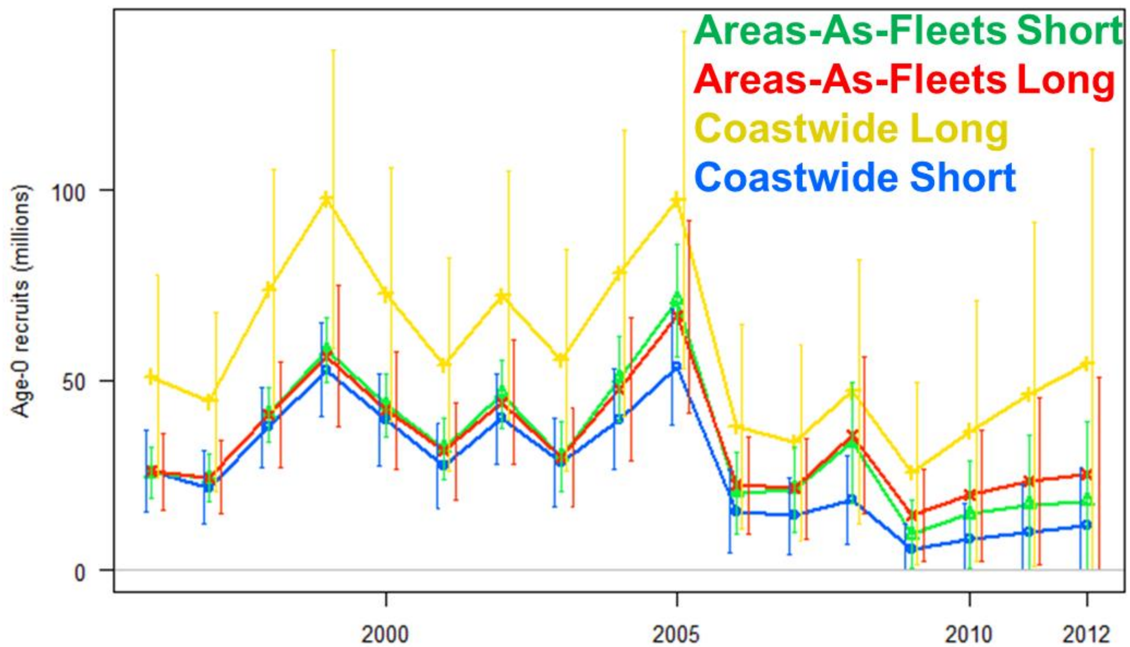

Figure 6. Recent recruitment strengths (by birth year) estimated by all four ensemble models. Note that estimates after 2010 are highly uncertain, as they are not yet well informed by direct observations.

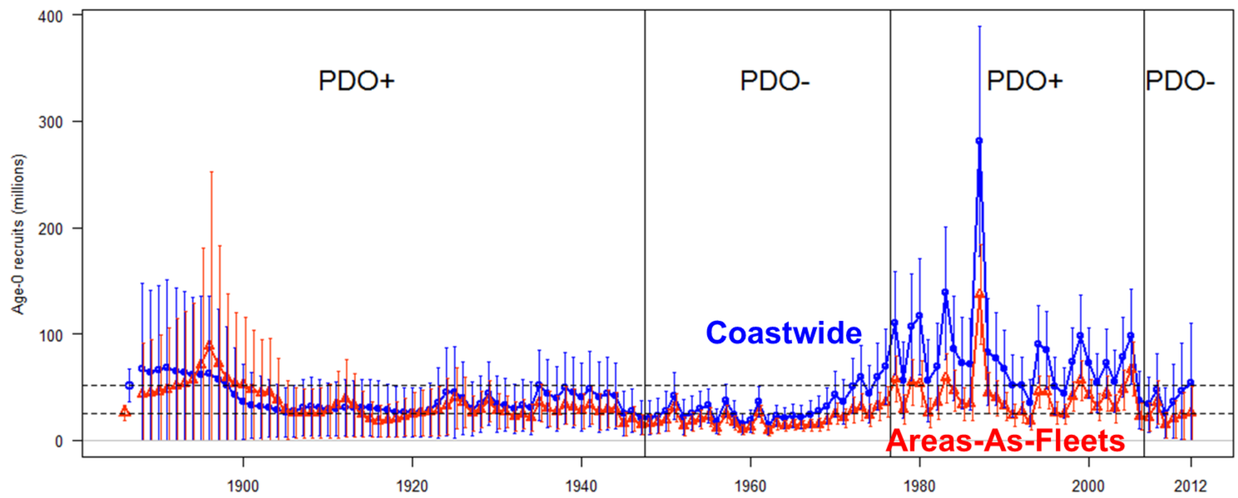

Figure 7. Trend in historical recruitment strengths (by birth year) estimated by the two long time-series models, including the effects of the Pacific Decadal Oscillation (PDO) regimes. Note that estimates after 2010 are highly uncertain, as they are not yet well informed by direct observations.

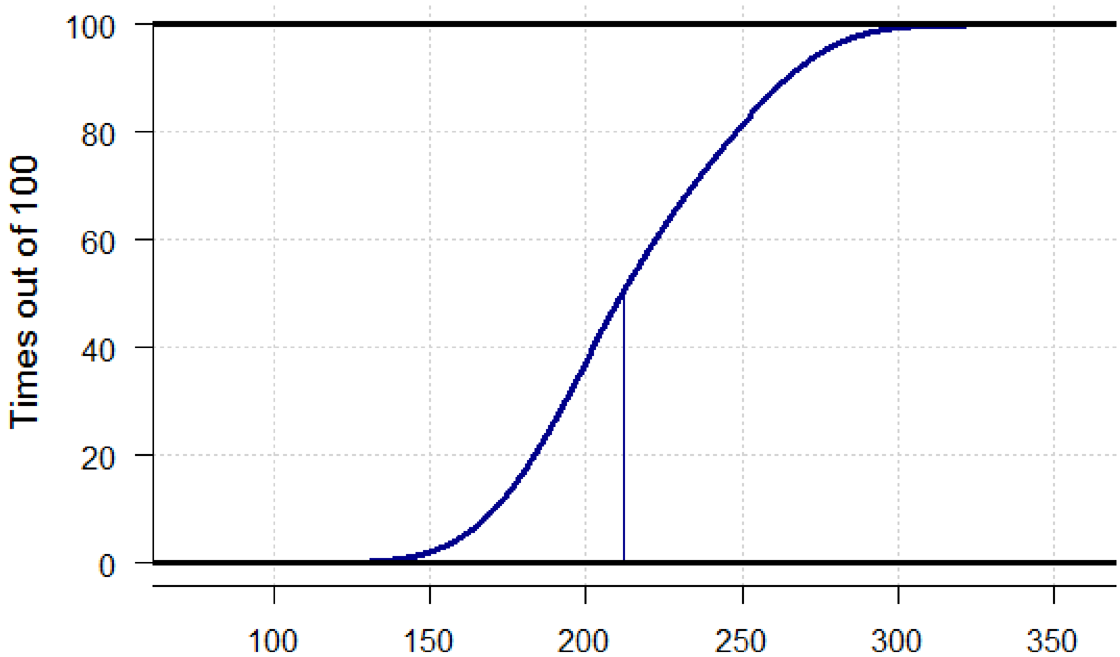

Figure 8. Cumulative distribution of 2017 ensemble spawning biomass estimate. Curve represents the estimated probability that the biomass is less than or equal to the value on the x-axis. Vertical line indicates the median value (212 million lbs, ~96,200 t).

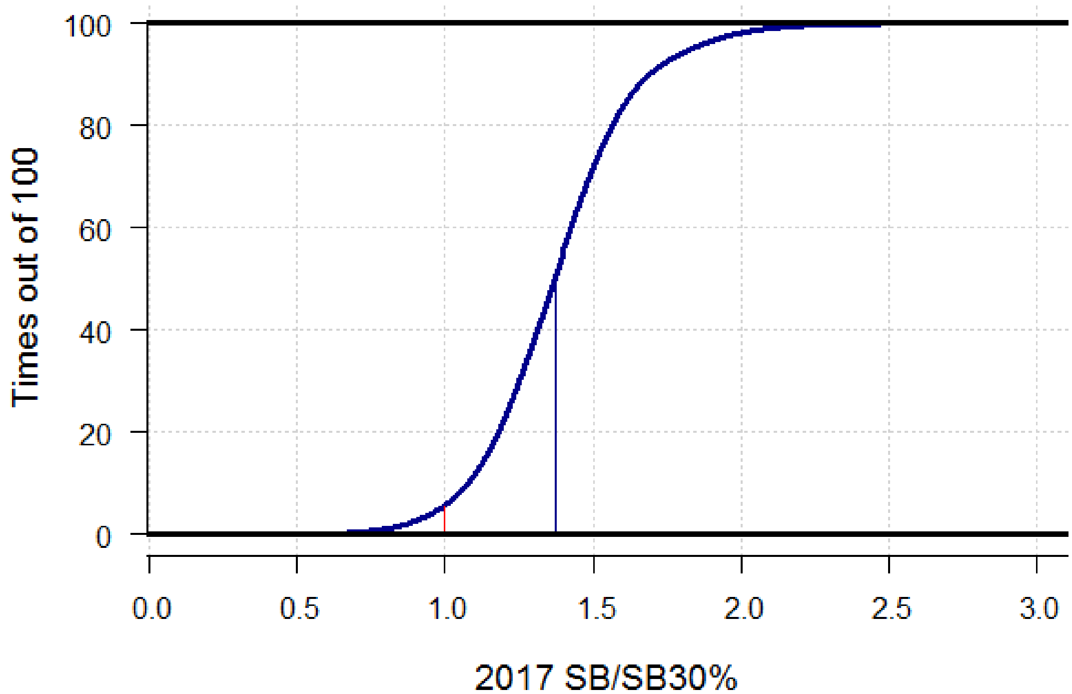

Figure 9. Cumulative distribution of 2016 ensemble spawning biomass estimates relative to the $SB_{30\%}$ reference point. Curve represents the estimated probability that the biomass is less than or equal to the value on the x-axis. Vertical lines indicate the median value (41%), and the value corresponding to the IPHC's harvest policy threshold.

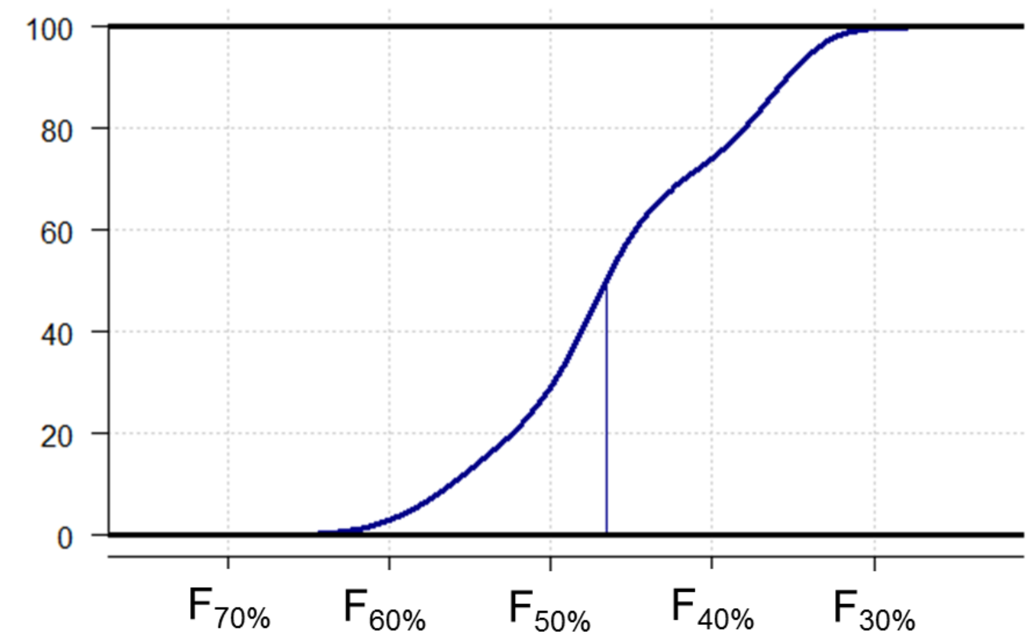

Figure 10. Cumulative distribution of the estimated relative fishing intensity (based on the Spawning Potential Ratio) estimated to have occurred in 2016. Curve represents the estimated probability that the fishing intensity is less than or equal to the value on the x-axis. Vertical line indicates the median value ($F_{47\%}$).

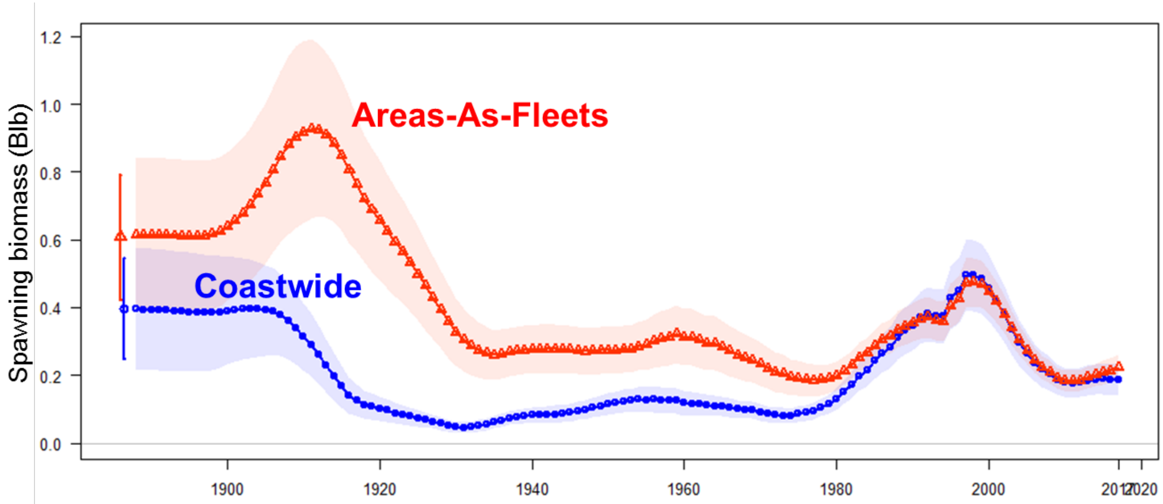

Figure 11. Spawning biomass estimates from the two long time-series models. Shaded region indicates the approximate 95% within-model confidence interval.

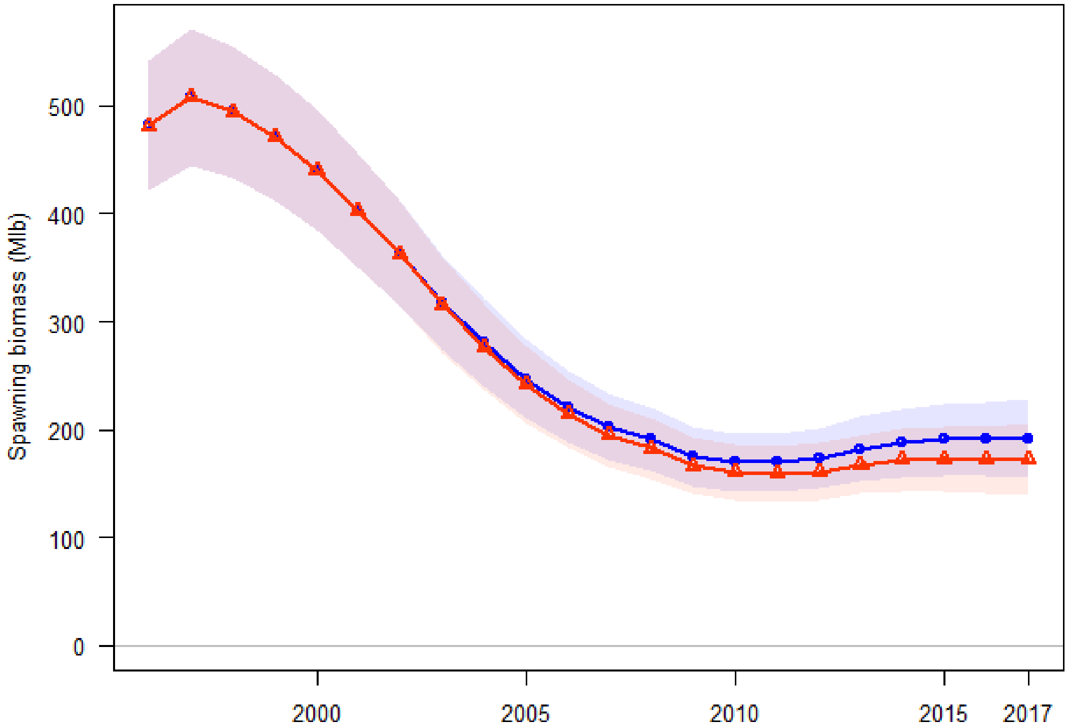

Figure 12. Spawning biomass estimates from a sensitivity analysis using the short coastwide model to evaluate the effect of a 10% decrease in spawning output over the last 15 years (lower series) with the results included in the ensemble (upper series). Shaded region indicates the approximate 95% within-model confidence interval.

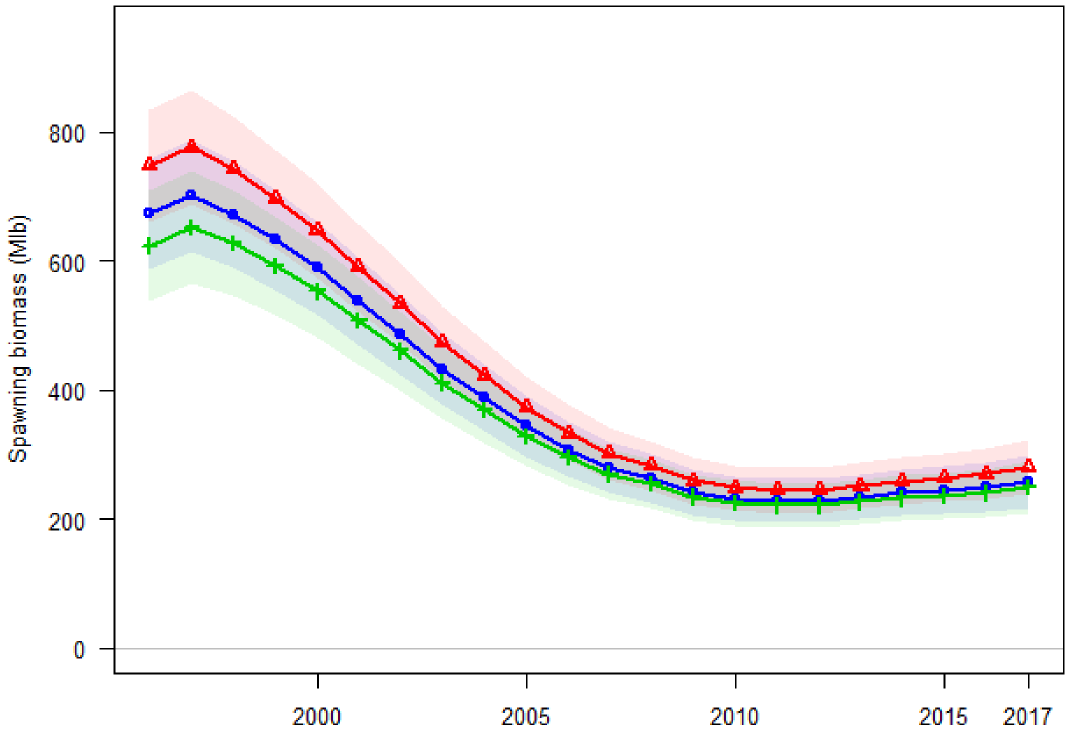

Figure 13. Spawning biomass estimates from a sensitivity analysis using the short AAF model to evaluate the effect of a 20% change (+/-) in the relative selectivity of the commercial fishery in Areas 2 and 3 (lower and upper series) with the results included in the ensemble (middle series). Shaded region indicates the approximate 95% within-model confidence interval.

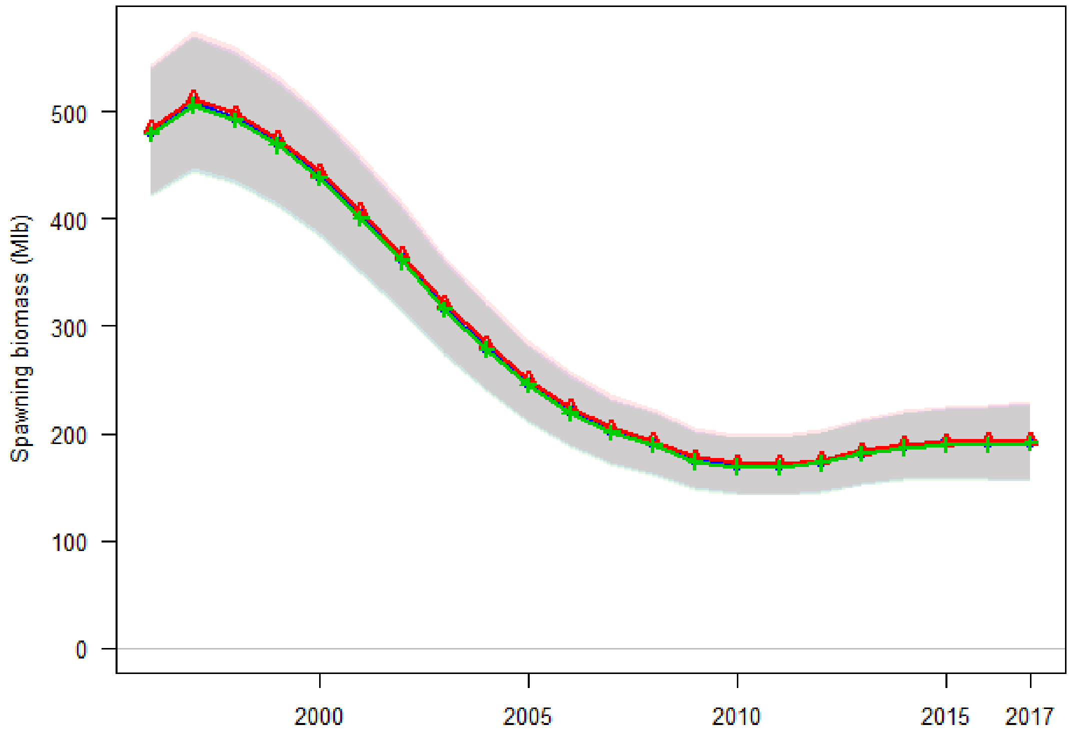

Figure 14. Spawning biomass estimates from a sensitivity analysis using the short coastwide model to evaluate the effect of changing the currently assumed DMR for the directed Pacific halibut fishery from 16% to either 8% or 32%. All three series are plotted; the shaded region indicates the approximate 95% within-model confidence interval.

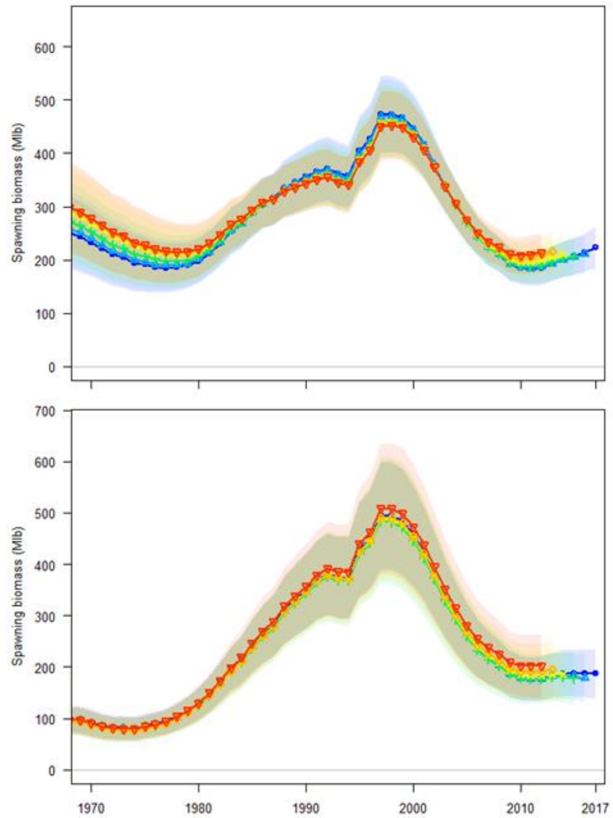

Figure 15. Results of the retrospective analysis on spawning biomass estimates using the Areas-as-fleets long (upper panel) and coastwide long (lower panel) time-series models and sequentially removing one year of data for five years. Dashed lines and shaded regions indicate within-model 95% uncertainty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

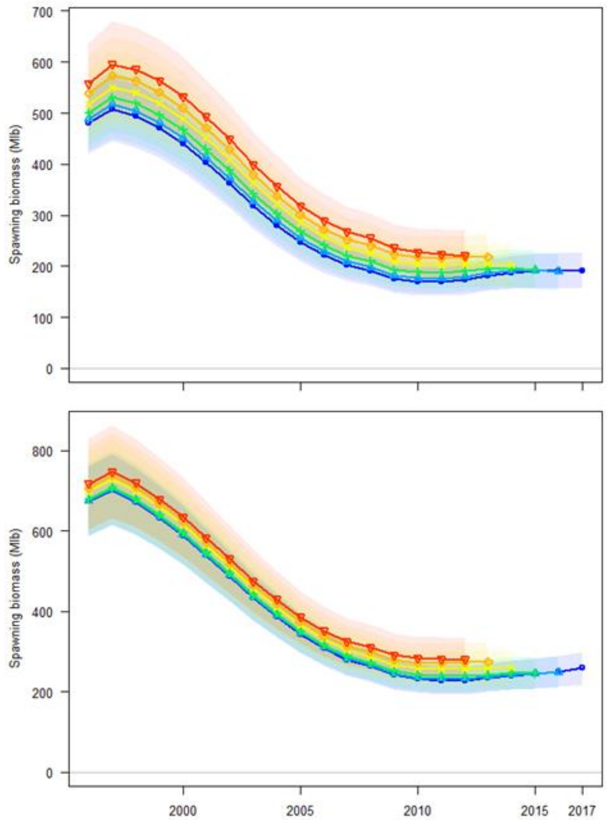

Figure 16. Results of the retrospective analysis on spawning biomass estimates using the coastwide short (upper panel) and Areas-As-Fleets short (lower panel) time-series models and sequentially removing one year of data for five years. Dashed lines and shaded regions indicate within-model 95% uncertainty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

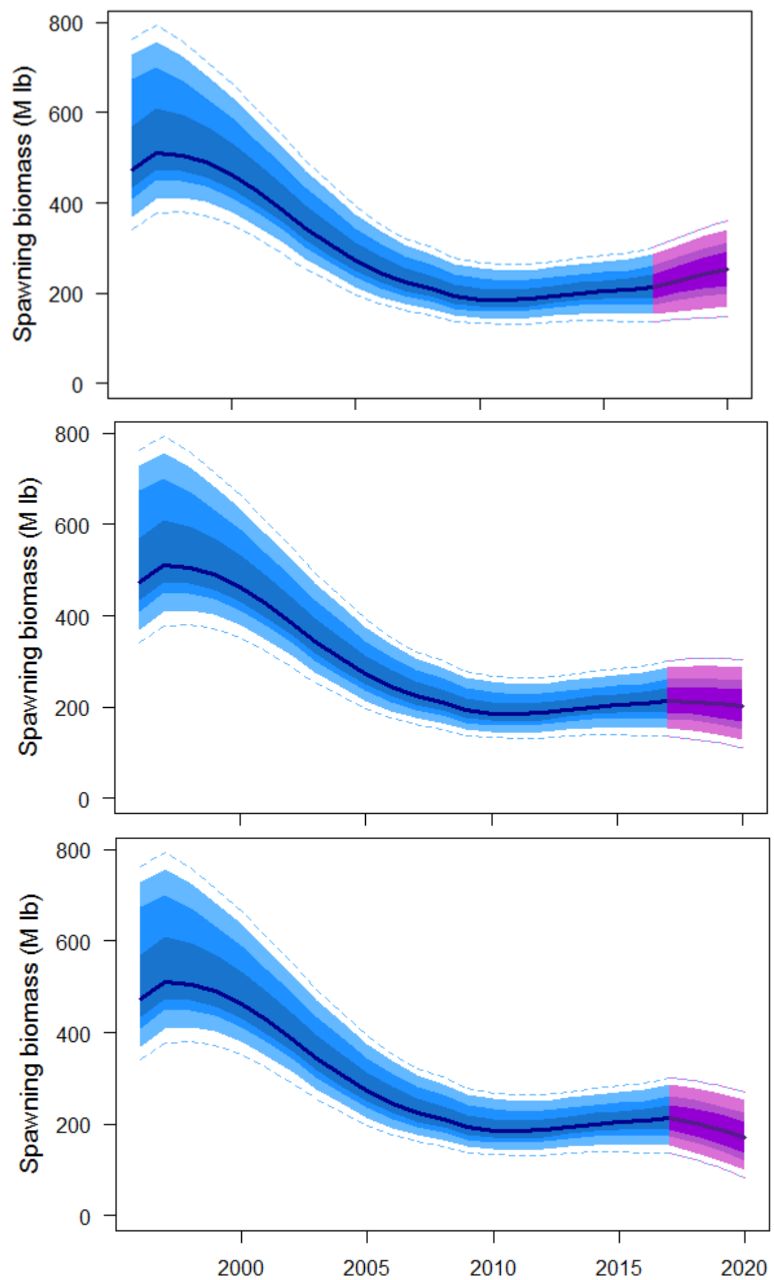

Figure 17. Three-year projections of stock trend under alternative levels of mortality: no removals (upper panel), Blue Line removals (middle panel) and 60 million lbs (~27,220 t) of total removals (lower panel).