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# Assessment of the Pacific halibut（Hippoglossus stenolepis）stock at the end of 2022 

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## Purpose

To provide the Commission with a detailed report of the 2022 stock assessment analysis．

## ExECUTIVE Summary

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 2022．A summary of the data and assessment results，as well as management related information is provided both on the stock assessment webpage and in the meeting materials for the IPHC＇s 99 ${ }^{\text {th }}$ Annual Meeting（AM099；IPHC－2023－AM099－11）．The input data files for each model included in this stock assessment are available on the IPHC＇s stock assessment webpage．
A detailed overview of data sources is provided in a separate document（IPHC－2023－SA－02）； only a few key observations are described here．Fishing mortality from all sources in 2022 was estimated to be up 4\％from 2021．In addition to the estimated mortality，the assessment includes data from both fishery dependent and fishery independent sources，as well as auxiliary biological information．The 2022 modelled Fishery－Independent Setline Survey（FISS；see IPHC－2023－ AM099－08 and IPHC－2023－AM099－09）detailed a coastwide aggregate Numbers－Per－Unit－Effort （NPUE）which decreased by 8\％from 2021 to 2022．The modelled coastwide FISS Weight－Per－ Unit－Effort（WPUE）of legal（O32）Pacific halibut，the most comparable metric to observed commercial fishery catch rates，decreased by $18 \%$ from 2021 to 2022．Preliminary coastwide commercial fishery WPUE（based on all 2022 logbook records available for this assessment） decreased 15\％coastwide．Biological information（ages and lengths）from both the commercial fishery and FISS shows a shift from the previously dominant 2005 year－class to the 2012 cohort （10 years old in 2022），representing the largest abundance at any single age．At the coastwide level，individual size－at－age continues the increasing trend for younger ages up to about 14， depending on the IPHC Regulatory Area．
This stock assessment continues to be implemented using the generalized Stock Synthesis software（Methot and Wetzel 2013）．The analysis consists of an ensemble of four equally weighted models：two long time－series models，reconstructing historical dynamics back to the beginning of the modern fishery，and two short time－series models incorporating data only from 1992 to the present，a time－period for which estimates of all sources of mortality and survey indices are available for all regions．For each time－series length，there are two models：one fitting to coastwide aggregate data，and one fitting to data disaggregated into the four geographic regions．This combination of models includes uncertainty in the form of alternative hypotheses about several important axes of uncertainty，including：natural mortality rates（estimated in all models except the short coastwide time－series model），environmental effects on recruitment （estimated in the long time－series models），and other model parameters．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 2022 stock assessment represents a full analysis，following the previous full assessment conducted in 2019，updated in 2020 and again in 2021．Changes from the 2021 assessment were developed and reviewed by the IPHC＇s Scientific Review Board（SRB），in June（SRB020；

IPHC-2022-SRB020-07, IPHC-2022-SRB020-R) and September 2022 (SRB021; IPHC-2022-SRB021-08, IPHC-2022-SRB021-R). Improvements to the modelling and data for 2002 included: updating the software version, including an informative prior on natural mortality $(M)$ and assigning larger values to the youngest ages (0-2) based on meta-analysis of other flatfish species, improving the basis for data weighting via the use of bootstrapped effective sample sizes, estimating $M$ in the short time-series Areas-As-Fleets (AAF) model, and adding standard data sources from all fisheries and surveys.
Overall, spawning biomass estimates remain highly consistent with those of recent stock assessments. However, the higher estimated value of natural mortality in the AAF short model when included with the other four models (two of which already estimated natural mortality) strongly affected the ensemble stock assessment estimates of recent and historical fishing intensity. The 2022 stock assessment estimates a lower level of fishing intensity and higher relative stock status compared to previous assessments, as well as a 26\% increase in the yield corresponding to the reference level of fishing intensity ( $F_{43 \%}$ ) for 2023 compared to 2022.

The results of the 2022 stock assessment indicate that the Pacific halibut stock declined continuously from the late 1990s to around 2012. 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. The spawning biomass (SB) is estimated to have increased gradually to 2016, and then decreased to an estimated 192 million pounds ( $\sim 87,100 \mathrm{t}$ ) at the beginning of 2023, with an approximate $95 \%$ credible interval ranging from 122 to 272 million pounds ( $\sim 55,400-123,200 \mathrm{t}$ ). The recent spawning biomass estimates from the 2022 stock assessment are very consistent with previous analyses for the period from 2012 to the present. Pacific halibut recruitment estimates show the large cohorts in 1999 and 2005. Cohorts from 2006 through 2011 are estimated to be much smaller than those from 1999-2005, which has led to recent estimated declines in both the stock and fishery yield as these low recruitments have moved int the spawning biomass. Based on age data through 2022, individual models in this assessment produced estimates of the 2012 year-classes that were slightly lower than the magnitude of the 2005 year-class. The 2012 year-class is estimated to be $29 \%$ mature in 2022 and the maturation of this cohort has a strong effect on the short-term projections.
The IPHC's interim management procedure uses a relative spawning biomass of $30 \%$ as a fishery trigger, reducing the reference fishing intensity if relative spawning biomass decreases further toward a limit reference point at $20 \%$, where directed fishing is halted due to the critically low biomass condition. The relative spawning biomass at the beginning of 2023 was estimated to be 42\% (credible interval: 21-55\%), slightly higher than the estimate for 2022 (41\%). Both of these estimates are higher than those from the 2021 stock assessment (i.e., 2022 was estimated at $33 \%$ ), with the change caused by the higher estimate of natural mortality in the current analysis. The probability that the stock is below $S B_{30 \%}$ is estimated to be $25 \%$ at the beginning of 2023, with less than a $1 \%$ chance that the stock is below $S B_{20 \%}$. The IPHC's current interim management procedure specifies a target level of fishing intensity of a Spawning Potential Ratio (SPR) corresponding to an $F_{43 \%}$; this equates to the level of fishing that would reduce the lifetime spawning output per recruit to $43 \%$ of the unfished level given current biology, fishery characteristics and demographics. Based on the 2022 assessment, the 2022 fishing intensity is estimated to correspond to an $F_{51 \%}$ (credible interval: 32-64\%). Stock projections were conducted using the integrated results from the stock assessment ensemble, details of IPHC Regulatory Area-specific catch sharing plans and estimates of mortality from the 2022 directed fisheries and other sources of mortality. The projections for this assessment are more optimistic than those from recent assessments due to the maturing 2012 year-class and the increase in
the estimated overall productivity of the stock resulting from $3 / 4$ rather than $2 / 4$ models estimating natural mortality at much higher values than the historical fixed assumption of 0.15 . This translates to a lower probability of stock decline for 2022 than in recent assessments as well as a decrease in this probability through 2023-24. Further, the trend in spawning biomass is estimated to have stabilized as the 2012 year-class continues to mature. This translates to a lower probability of stock decline at higher yields for 2023 than in recent assessments as well as a decrease in this probability through 2024-26. There is greater than a $50 \%$ probability of stock decline in 2024 (53-86/100) for all yields greater than the status quo, including the entire range of SPR values from 40-46\%. The 2023 "3-year surplus" alternative, corresponds to a TCEY of 43.0 million pounds $19,504 \mathrm{t}$ ), and a projected SPR of $48 \%$ (credible interval 28-62\%). At the reference level (a projected SPR of 43\%), the probability of spawning biomass decline from 2023 to 2024 is $75 \%$, decreasing to $71 \%$ in three years. The one-year risk of the stock dropping below $S B_{30 \%}$ is $25 \%$ across all alternatives. Retrospective analyses for each of the four models, and a discussion of major sources of uncertainty are also included in this document.

## Introduction

The stock assessment reports the status of the Pacific halibut (Hippoglossus stenolepis) resource in the IPHC Convention Area. 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 the Salish Sea, but excludes known extremities in the western Bering Sea within the Russian Exclusive Economic Zone (Figure 1). The Pacific halibut fishery has been managed by the IPHC since 1923. Mortality limits for each of eight IPHC Regulatory Areas ${ }^{1}$ are set each year by the Commission. 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 a separate document (IPHC-2023-SA-02) on the IPHC's stock assessment webpage. 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. Mortality tables projecting detailed summaries for fisheries in each IPHC Regulatory Area (and reference levels indicated by the IPHC's interim management procedure) will be reported at the 99th Session of the IPHC Annual Meeting (AM099) in January 2023.

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FIGURE 1. IPHC Convention Area (insert) and IPHC Regulatory Areas.
The IPHC's stock assessment and review process has developed from the first ad hoc meeting held in 2012 (Stewart et al. 2013b) to the formal SRB process including periodic external independent peer review. The IPHC's SRB meets two times per year: in June to review stock assessment development, and in September to review progress in response to the June review and to finalize the model structure and methods to be used in conducting the year's stock assessment. Within this annual review process two types of stock assessments are produced: 1) updated assessments where new data are added but the methods and model structures remain largely unchanged, and 2) full stock assessments occurring every three years in which model structure and methods are revised to reflect new data, approaches and comments from SRB and independent review. The 2015 (Stewart and Martell 2016; Stewart et al. 2016), and the 2019 (Stewart and Hicks 2019; Stewart and Hicks 2020) stock assessments were full analyses. The 2022 stock assessment represents a full analysis, following updates in 2020 and again in 2021. Changes from the 2021 assessment were developed and reviewed by the IPHC's Scientific Review Board (SRB), in June (SRB020; IPHC-2022-SRB020-07, IPHC-2022-SRB020R) and September 2022 (SRB021; IPHC-2022-SRB021-08, IPHC-2022-SRB021-R). Changes to the modelling that were included in the stock assessment and new data for 2022 include:

1. Update the version of the stock synthesis software used for the analysis (3.30.19; Methot and Wetzel 2013).
2. Expand the treatment of natural mortality $(M)$ to include an informative prior based on longevity and assign increased values at the youngest ages based on meta-analysis of other flatfish species.
3. Improve the basis for data weighting via use of bootstrapped effective sample sizes as model inputs based on the FISS and fishery sampling programs, rather than the raw number of sets/trips used in previous assessments.
4. Estimate $M$ in the short time-series Areas-As-Fleets (AAF) model.
5. Include standard updates to mortality estimates from all fisheries, directed commercial fishery and FISS (fishery-independent setline survey) biological and trend information, and other sources including data collected in 2022.

## 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, 2015, and again in 2019 (Stewart and Hicks 2019). For 2022, the largest change to the underlying data was the development of a bootstrapping procedure to estimate the effective sample size of the age-composition data, given the actual sampling design and sample sizes in each year (Stewart and Hicks 2022). All available information for the 2022 stock assessment was finalized on 1 November 2022 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 2022 commercial fishery WPUE, 2022 commercial fishery age composition data, and 2022 mortality estimates for all fisheries still operating after 1 November. All preliminary data series in this analysis will be fully updated as part of the 2023 stock assessment.

Data for stock assessment use are initially compiled by IPHC Regulatory Area, and then aggregated to four Biological Regions: Region 2 (Areas 2A, 2B, and 2C), Region 3 (Areas 3A, $3 B$ ), Region 4 (4A, 4CDE) and Region 4B and then coastwide. In addition to the aggregate mortality (including all sizes of Pacific halibut), the assessment includes data from both fishery dependent and fishery independent sources as well as auxiliary biological information, with the most spatially complete data available since the late-1990s. Primary sources of information for this assessment include modelled indices of abundance (IPHC-2023-AM099-09); based on the FISS (in numbers and weight) and other surveys), commercial fishery Catch-Per-Unit-Effort (weight), and biological summaries from both sources (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 decades (Figure 2). A detailed summary of input data used in this stock assessment can be found in IPHC-2023-SA-02 on the IPHC's stock assessment webpage.


FIGURE 2. Overview of data sources. Circle areas are proportional to magnitude (mortality/catches) or the relative precision of the data (larger circles indicate greater precision for indices of abundance and age composition data).

Briefly, known Pacific halibut mortality consists of directed/targeted commercial fishery landings and discard mortality (including research), recreational fisheries, subsistence, and non-directed discard mortality ('bycatch') in fisheries targeting other species and where Pacific halibut retention is prohibited. Over the period 1888-2022 mortality has totaled 7.3 billion pounds ( $\sim 3.3$ million metric tons, $t$ ). Since 1923, the fishery has ranged annually from 34 to 100 million pounds $(16,000-45,000 \mathrm{t})$ with an annual average of 63 million pounds ( $\sim 29,000 \mathrm{t}$ ). Annual mortality was above this long-term average from 1985 through 2010 and has averaged 38.1 million pounds ( $\sim 17,300 \mathrm{t}$ ) from 2018-22. Coastwide commercial Pacific halibut fishery landings (including research landings) in 2022 were approximately 26.2 million pounds ( $\sim 11,900 \mathrm{t}$ ), up $6 \%$ from 2021. Discard mortality in the directed commercial fishery increased $58 \%$ in 2022 to 1.5 million pounds ( $\sim 680 \mathrm{t}$ ). Discard mortality in non-directed fisheries was estimated to be 4.5 million
pounds in $2022(\sim 2,000 \mathrm{t})^{2}$, up $17 \%$ from 2021 and similar to estimates for 2020. The total recreational mortality (including estimates of discard mortality) was estimated to be 6.6 million pounds ( $\sim 3,000 \mathrm{t}$ ) down $14 \%$ from 2021. Mortality from all sources increased by $4 \%$ to an estimated 39.7 million pounds ( $\sim 18,000 \mathrm{t}$ ) in 2022.
The 2022 modelled FISS results detailed a coastwide aggregate NPUE (numbers per unit effort) which decreased by 8\% from 2021 to 2022, reversing the increase observed in 2021 and approaching the lowest values observed in the estimated time-series. Biological Region 3 decreased by $12 \%$, while Biological Region 2 increased by 1\%. Biological Regions 4 and 4B showed declines ( 2 and 6\%) and are at the lowest values in the estimated time-series. The 2022 modelled coastwide WPUE of legal (O32) Pacific halibut, the most comparable metric to observed commercial fishery catch rates, decreased by $11 \%$ from 2021 to 2022. This larger decline relative to that for NPUE indicates that recruitment of younger fish is contributing more to current stock productivity than somatic growth of fish already over the legal minimum size limit. Individual IPHC Regulatory Areas varied from a 10\% increase (Regulatory Area 2A) to a 37\% decrease (Regulatory Area 3A) in O32 WPUE. Preliminary commercial fishery WPUE estimates from 2022 logbooks decreased by 15\% at the coastwide level. The bias correction to account for additional logbooks compiled after the fishing season resulted in an estimated decline of $18 \%$ coastwide. Trends varied among IPHC Regulatory Areas and gears; Areaspecific trends were mixed, and generally similar to those from the FISS.
Biological information (ages and lengths) from the commercial fishery landings shows a switch from the 2005 year-class to the 2012 year-class as the largest coastwide contributor (in number) to the fish encountered. The FISS observed the 2012 cohort (10 years old) at the largest proportion in the total catch of any age class for the second year in a row. These observations of the 2012 cohort continue to show their increasing importance to the stock and to future fisheries. Individual size-at-age appears to be increasing for younger ages (<14) in most IPHC Regulatory Areas and coastwide. Although size-at-age changes slowly, if the current pattern persists into older ages, it could have large implications for overall yield. Direct estimates of the sex-ratio at age for the directed commercial fishery continue to show an average of $80 \%$ female (by number) in the landings.
The recent year (2022) showed a reverse in the trend of an increasing population distribution (measured via the modelled FISS catch in weight of all sizes Pacific halibut) toward Biological Region 3, with a decline in stock distribution in Region 3 to nearly the lowest in the estimated time-series. The proportion of the population in Biological Regions 2, 4, and 4B increased in 2022. Survey data are insufficient to estimate stock distribution prior to 1993. It is therefore unknown how historical distributions or the average distribution in the absence of fishing mortality may compare with recent observations.

## 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 2014a). 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

[^1](Stewart and Martell 2014a). Although recent modelling efforts have created some new alternatives, no single model satisfactorily approximates all aspects of the available data and scientific understanding. For 2022, an ensemble of four stock assessment models was again used to explore the range of plausible current stock estimates. The ensemble approach recognizes that there is no "true" 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; Stewart and Hicks 2018). 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; therefore providing a stronger basis for risk assessment.

This stock assessment continues to be implemented using stock synthesis, the generalized stock assessment software (Methot and Wetzel 2013). The analysis consists of an ensemble of four equally weighted models: two long time-series models, reconstructing historical dynamics back to the beginning of the modern fishery, and two short time-series models incorporating data only from 1992 to the present, a time-period for which estimates of all sources of mortality and survey indices are available for all regions. For each time-series length, there are two models: one fitting to coastwide aggregate data, and one fitting to data disaggregated into the four geographic regions (Areas-As-Fleets; AAF). 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 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.

This combination of models included a broad suite of structural and parameter uncertainty, including natural mortality rates (estimated in three of the four models and fixed in one model), 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 Hare 2006; Clark et al. 1999; Stewart and Hicks 2020; 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 four models in the ensemble was equally weighted, and within-model uncertainty from each model was propagated through to the ensemble results via the maximum likelihood estimates and an asymptotic approximation to their variance. Point estimates in this stock assessment correspond to median values from the ensemble: with the simple probabilistic interpretation that there is an equal probability above or below the reported value.

The 2019 stock assessment was a full analysis, including a complete re-evaluation of all data sources and modelling choices, particularly those needed to accommodate the newly available sex-ratio at age data from the commercial fishery. The 2020 and 2021 stock assessments represented updates, adding data sources where available, but retaining the same basic model structure for each of the four component models. The 2022 assessment was another full assessment; all changes from the 2021 assessment were developed and reviewed by the IPHC's Scientific Review Board (SRB), in June (SRB020; IPHC-2022-SRB020-07, IPHC-2022-SRB020-R) and September 2022 (SRB021; IPHC-2022-SRB021-08, IPHC-2022-SRB021-R).

The most important change in the 2022 assessment was the estimation of natural mortality $(M)$ in the short AAF model. Natural mortality has been a primary source of uncertainty in the Pacific halibut stock assessment (and in most fisheries analyses) for decades. Prior to 1998, the Pacific halibut stock assessment used a value of 0.20 . This was changed to a value of 0.15 in 1998, based on concerns that the consequences of an inaccurate estimate were less serious if the value was underestimated (Clark 1999; Clark and Parma 1999). The value of 0.15 was used for female Pacific halibut for all analyses until 2012. In the 2012 assessment, alternate values of natural mortality were used to include a broader range of uncertainty in the harvest decision table (Stewart et al. 2013a). In the 2013 assessment, a model (similar to the current coastwide long time-series model) was included that estimated a higher level of natural mortality directly from the data (Stewart and Martell 2014b). For the 2014 stock assessment, four models were used, two of which estimated natural mortality (both at higher values) and two relied on the fixed value of 0.15 (Stewart and Martell 2015b). This approach of four models, two estimating natural mortality and two using the fixed value of 0.15 continued through the 2021 assessment. With the additional years of data available and the directed commercial fishery sex-ratio time series reaching 4 years in length, for the 2022 stock assessment there was sufficient information to estimate natural mortality directly in the AAF short model, leading to estimation in 3 of the 4 models contributing to the ensemble.

All four models included an age-independent prior on $M$ for Pacific halibut that was developed based on the meta-analysis of Hamel (2014; and subsequently updated, Hamel pers. comm.), using the prediction interval based on the maximum observed age for a wide range of species. This prior is applied based on a maximum observed age for Pacific halibut of 55 years. In addition, elevated $M$ of young fish (ages 0-2) based on meta-analysis of the rates used in assessments for other flatfish species and the corresponding asymptotic size as well as the results of multi-species models estimating size-specific predation mortality (IPHC-2021-SRB020-08).

The biggest change to the treatment of raw data used in the stock assessment models was to determine maximum input sample sizes for age composition data based on a bootstrap procedure of the actual observations from each source and year (Stewart and Hamel 2014). This provides a better starting point for iterative reweighting of the data during modeling than does the raw number of sets/trips used in previous assessments. This change was included in the detailed bridging analysis provided during the June scientific review (IPHC-2021-SRB020-08).

## COMPARISON WITH PREVIOUS ASSESSMENTS

As in recent analyses, the transition from the 2021 stock assessment to the final 2022 models was performed in a stepwise manner, adding structural changes and then data incrementally to identify which pieces of new information had the largest effect on the results. This 'bridging' analysis included the update to the stock synthesis software version used for 2022 (3.30.19), the updating of 2021 data where needed and the addition of standard data sources for 2022
including FISS and commercial fishery indices, biological sampling and mortality estimates from all sectors. There was little effect on the historical time-series of spawning biomass or recruitment for three of the four models included in the stock assessment (Figures 3-5) but the estimation of $M$ in the short AAF model resulted in an increase in the spawning biomass (Figure 6). The estimated strength of the 2012 year-class either decreased slightly or remained at a similar value relative to other year classes with the addition of new data. However, the absolute size of all year class estimates increased due to the higher natural mortality assumed for younger ages.


FIGURE 3. Bridging analysis showing the change from the 2021 to final 2022 stock assessment model estimates of spawning biomass (upper panel) and recruitment (lower panel) for the short coastwide model.


FIGURE 4. Bridging analysis showing the change from the 2021 to final 2022 stock assessment model estimates of spawning biomass (upper panel) and recruitment (lower panel) for the long coastwide model.


FIGURE 5. Bridging analysis showing the change from the 2021 to final 2022 stock assessment model estimates of spawning biomass (upper panel) and recruitment (lower panel) for the long AAF model.


FIGURE 6. Bridging analysis showing the change from the 2021 to final 2022 stock assessment model estimates of spawning biomass (upper panel) and recruitment (lower panel) for the short AAF model.

Estimates for female Pacific halibut natural mortality from the three models where this parameter is estimated span values of 0.184 (AAF long), 0.213 (AAF short) and 0.215 (coastwide long); the coastwide short model retains the fixed value of 0.15 . Comparison of this year's ensemble results with previous stock assessments indicates that the estimates of spawning biomass from the 2022 ensemble remain very consistent with those from the 2012-21 assessments. Each of the previous terminal assessment values lie inside the predicted $50 \%$ interval of the current ensemble (Figure 7). The uncertainty is much greater prior to approximately 2005 reflecting the
differences among the four individual models, particularly the beginning of the time-series' in the two short models. The increase in spawning biomass due the change to estimating natural mortality in the short AAF model, relative to the 2021 assessment, is counterbalanced by the slightly lower estimates of spawning biomass in the two long models. However, with equal weighting of the four models the median productivity estimates (e.g., yield at a given level of fishing intensity) are considerably higher than the 2021 and earlier assessment models (Figure 8) and reflected in the projections reported below.


FIGURE 7. Retrospective comparison of female spawning biomass among recent IPHC stock assessments. Black lines indicate estimates from assessments conducted in 2012-2021 with the terminal estimate shown as a red point. The shaded distribution denotes the 2022 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; and 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.


FIGURE 8. Retrospective comparison of fishing intensity (measured as $F_{x x \%}$, where $x x \%$ indicates the Spawning Potential Ratio (SPR) or the reduction in the lifetime reproductive output due to fishing) among recent IPHC stock assessments. Thin black lines indicate estimates of fishing intensity from assessments conducted in 2014-2021 with the projection for the mortality limit adopted based on that assessment shown as a red point. The shaded distribution denotes the 2022 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; and 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. The grey line indicates the reference level of fishing intensity used by the Commission in each year it has been specified ( $F_{46 \%}$ during 2016-2020 and $F_{43 \%}$ during 2021-2022).

## BIOMASS, RECRUITMENT, AND REFERENCE POINT RESULTS

## Ensemble

The results of the 2022 stock assessment indicate that the Pacific halibut stock declined continuously from the late 1990s to around 2012 (Figure 7, Table 1). 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. The spawning biomass (SB) is estimated to have increased gradually to 2016, and then decreased to an estimated 191 million pounds ( $\sim 86,600 \mathrm{t}$ ) at the beginning of 2022, followed by a slight increase to 192 million pounds ( $\sim 87,100$ t) at the beginning of 2023. The approximate $95 \%$ credible interval for 2023 ranges from 122 to 272 million pounds ( $\sim 55,300-123,400 \mathrm{t}$; Figure 9). The differences among the individual models contributing to the ensemble are most pronounced prior to the early 2000s (Figure 10); however, current stock size estimates (at the beginning of 2023) also differ substantially among the four models (Figure 11). The differences in both scale and recent trend reflect the structural
assumptions, e.g., higher natural mortality estimated in three models and dome-shaped selectivity for Biological Regions 2 and 3 in the AAF models.

TABLE 1. Estimated recent median spawning biomass (SB; millions lbs) and fishing intensity (smaller values indicate higher fishing intensity) with approximate $95 \%$ credibility intervals, and age-0 recruitment (millions) and age-8+ biomass (millions lbs) from the individual models ( $\mathrm{CW}=$ coastwide, $\mathrm{AAF}=$ Areas-As-Fleets) comprising the ensemble.

| Year | SB | $\begin{gathered} \text { SB } \\ \text { interval } \end{gathered}$ | Fishing intensity$\left(F_{x x \%}\right)$ | Fishing intensity interval | Recruitment |  |  |  | Age-8+ biomass |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  |  |  | $\begin{gathered} \text { CW } \\ \text { Long } \end{gathered}$ | CW Short | AAF Long | AAF Short | $\begin{gathered} \text { CW } \\ \text { Long } \end{gathered}$ | CW Short | AAF Long | AAF Short |
| 1992 | 583 | 393-1,209 | 49\% | 29-68\% | 161.0 | 48.2 | 105.6 | 152.5 | 1,640 | 1,146 | 2,270 | 3,190 |
| 1993 | 569 | 385-1,122 | 49\% | 29-67\% | 108.1 | 22.8 | 62.3 | 75.1 | 1,537 | 1,088 | 2,097 | 2,924 |
| 1994 | 561 | 375-1,065 | 50\% | 30-67\% | 276.4 | 82.5 | 174.5 | 240.0 | 1,466 | 1,025 | 1,977 | 2,714 |
| 1995 | 635 | 416-1,139 | 58\% | 37-73\% | 258.0 | 72.5 | 158.7 | 210.7 | 2,044 | 1,355 | 2,451 | 3,340 |
| 1996 | 659 | 432-1,128 | 58\% | 36-71\% | 153.9 | 47.6 | 95.9 | 131.1 | 2,011 | 1,349 | 2,429 | 3,257 |
| 1997 | 717 | 471-1,166 | 52\% | 32-66\% | 137.7 | 36.8 | 86.7 | 115.5 | 2,072 | 1,409 | 2,491 | 3,291 |
| 1998 | 707 | 468-1092 | 51\% | 31-64\% | 221.4 | 69.0 | 147.8 | 198.0 | 1,976 | 1,364 | 2,355 | 3,075 |
| 1999 | 685 | 451-1022 | 49\% | 30-62\% | 288.8 | 92.2 | 189.7 | 267.4 | 1,822 | 1,271 | 2,165 | 2,795 |
| 2000 | 642 | 425-931 | 48\% | 29-61\% | 213.8 | 73.6 | 148.1 | 206.6 | 1,654 | 1,171 | 1,977 | 2,528 |
| 2001 | 587 | 386-832 | 46\% | 27-58\% | 155.4 | 45.2 | 115.5 | 162.0 | 1,459 | 1,036 | 1,754 | 2,210 |
| 2002 | 524 | 346-732 | 42\% | 25-54\% | 207.9 | 73.4 | 145.0 | 210.3 | 1,398 | 987 | 1,654 | 2,071 |
| 2003 | 461 | 304-634 | 38\% | 23-49\% | 163.2 | 52.5 | 100.5 | 141.2 | 1,334 | 928 | 1,549 | 1,923 |
| 2004 | 407 | 268-553 | 34\% | 21-46\% | 219.2 | 69.5 | 156.8 | 230.2 | 1,217 | 851 | 1,411 | 1,742 |
| 2005 | 356 | 235-477 | 32\% | 21-44\% | 298.3 | 105.6 | 212.1 | 307.6 | 1,095 | 760 | 1,272 | 1,562 |
| 2006 | 315 | 209-417 | 32\% | 21-43\% | 122.9 | 37.6 | 80.5 | 118.0 | 1,037 | 715 | 1,198 | 1,470 |
| 2007 | 283 | 190-372 | 30\% | 20-42\% | 105.0 | 23.3 | 73.6 | 101.5 | 1,033 | 707 | 1,177 | 1,455 |
| 2008 | 257 | 176-339 | 29\% | 20-41\% | 121.1 | 46.9 | 80.0 | 120.4 | 982 | 681 | 1,128 | 1,399 |
| 2009 | 230 | 159-304 | 30\% | 21-42\% | 50.3 | 1.4 | 31.3 | 39.9 | 888 | 615 | 1,039 | 1,291 |
| 2010 | 216 | 153-288 | 30\% | 20-42\% | 72.3 | 26.7 | 45.5 | 71.2 | 849 | 598 | 997 | 1,250 |
| 2011 | 208 | 151-280 | 35\% | 24-48\% | 129.6 | 26.2 | 81.3 | 124.4 | 802 | 571 | 938 | 1,177 |
| 2012 | 206 | 152-279 | 39\% | 27-52\% | 249.7 | 78.7 | 169.8 | 249.8 | 798 | 571 | 933 | 1,182 |
| 2013 | 211 | 160-286 | 41\% | 28-54\% | 103.5 | 2.1 | 80.5 | 109.7 | 849 | 620 | 984 | 1,256 |
| 2014 | 215 | 165-293 | 46\% | 31-59\% | 185.1 | 51.2 | 120.7 | 166.3 | 806 | 600 | 940 | 1,198 |
| 2015 | 221 | 171-301 | 46\% | 32-59\% | 143.9 | 28.4 | 92.3 | 99.9 | 761 | 569 | 899 | 1,137 |
| 2016 | 228 | 179-311 | 47\% | 32-60\% | 181.6 | 47.1 | 110.3 | 128.3 | 739 | 572 | 874 | 1,107 |
| 2017 | 227 | 178-309 | 47\% | 31-60\% | 178.6 | 39.6 | 108.2 | 126.6 | 675 | 519 | 812 | 1,019 |
| 2018 | 216 | 169-296 | 49\% | 33-62\% | NA | NA | NA | NA | 626 | 491 | 756 | 951 |
| 2019 | 208 | 160-286 | 48\% | 32-61\% | NA | NA | NA | NA | 628 | 468 | 742 | 943 |
| 2020 | 199 | 150-275 | 54\% | 38-66\% | NA | NA | NA | NA | 721 | 518 | 818 | 1,057 |
| 2021 | 192 | 139-267 | 51\% | 34-64\% | NA | NA | NA | NA | 705 | 460 | 809 | 1,038 |
| 2022 | 191 | 130-269 | 51\% | 32-64\% | NA | NA | NA | NA | 756 | 476 | 843 | 1,075 |
| 2023 | 192 | 122-272 | NA | NA | NA | NA | NA | NA | 760 | 457 | 840 | 1,033 |

Differences are also apparent in the absolute scale of recent recruitment estimates; however, relative recruitments from all four models show larger year-classes in 1999 and 2005 than in all subsequent years, with 2012 being estimated slightly lower than the magnitude of the 2005 yearclass (Figure 12, Table 1). All of these recent recruitments are much lower than the 1987 cohort,
and in the two long time-series models they are at or below those in the late 1970s and early 1980s (Figure 13). Cohorts from 2006 through 2011 are estimated to be much smaller than those from 1999-2005 which has resulted in declines in both the stock and fishery yield as these low recruitments became increasingly important to the age range over which much of the harvest and spawning takes place. Based on the most recent trend and age data, this assessment estimated the 2012 cohort to be critically important to the projected spawning biomass over the next 2-4 years. Twenty-nine percent (29\%) of this cohort is estimated to be mature in 2022 and increasing to $69 \%$ by 2025 , assuming the historical average maturity schedule currently used in the assessment. Short-term trends in fishery yield may increase as the fisheries continue to transition from older fish to the younger 2012 year-class, as was observed in the 2021 and 2022 fisheries. All models are estimating a slightly increasing, then stable 8+ biomass from a low in 2018 or 2019 but the ensemble shows a decline then stable spawning biomass through the beginning of 2023 (Table 1). Recruitment estimates after 2014 remain highly uncertain, and those after 2017 are poorly informed by any direct information from the fishery and survey data.


FIGURE 9. Cumulative distribution of the estimated spawning biomass at the beginning of 2023. 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 (192 million pounds; $\sim 87,100 \mathrm{t}$ ).


FIGURE 10. Estimated spawning biomass trends (1992-2023) based on the four individual models included in the 2022 stock assessment ensemble. Series indicate the maximum likelihood estimates; shaded intervals indicate approximate $95 \%$ credible intervals.


FIGURE 11. Distribution of individual model estimates for the 2023 spawning biomass. Vertical lines indicate the median values.


FIGURE 12. Estimated trends in age-0 recruitment (upper panel) and relative recruitment (standardized to the mean for each model over this time-period; lower panel) 1992-2017, based on the four individual models included in the 2022 stock assessment ensemble. Series indicate the maximum likelihood estimates; vertical lines indicate approximate $95 \%$ credible intervals.


FIGURE 13. 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.

## Ecosystem conditions

Average Pacific halibut recruitment is estimated to be higher (47 and 44\% 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 averages from 2014 through 2019 were positive, with 2020 through 2022 showing negative average conditions (data were only available through September for 2022). Although strongly correlated with historical recruitments, it is unclear whether the effects of climate change and other recent anomalous conditions in both the Bering Sea and Gulf of Alaska are comparable to those observed in previous decades.

## Reference points

The IPHC's interim management procedure uses a relative spawning biomass of $30 \%$ as a trigger, below which the reference fishing intensity is reduced. At a spawning biomass limit of $20 \%$, directed fishing is halted due to the critically low biomass condition. Beginning with the 2019 stock assessment, this calculation has been based on recent biological conditions rather than a long-term static average. By using current weight-at-age and estimated recruitments that are influencing the current stock only, the 'dynamic' calculation measures the effect of fishing on the spawning biomass. The relative spawning biomass decreased continuously over the period 1992-2012 to near 30\% (Figure 14). Since 2016, the relative spawning biomass has increased slightly to $42 \%$ at the beginning of 2023 (credible interval: 21-55\%). This result reflects the greater effects of recruitment and size-at-age, rather than fishing in the last few years, and both of these estimates are higher than those from the 2021 stock assessment (i.e., 2022 was estimated at $33 \%$ ), with the change caused by the higher estimate of natural mortality in the current analysis. That the spawning biomass has been decreasing in recent years and the relative spawning biomass has been increasing is not inconsistent: the biomass projected to occur in the absence of fishing (the denominator of the relative biomass calculation) has also been decreasing, and at a higher rate than the actual estimated spawning biomass (Figure 15).

The probability that the stock is below the $S B_{30 \%}$ level is estimated to be $25 \%$ at the beginning of 2023, with less than a $1 \%$ chance that the stock is below SB $_{20 \%}$ (Figure 16).


FIGURE 14. Estimated time-series of relative spawning biomass (compared to the unfished condition in each year) based on the median (dark blue line) and approximate $95 \%$ credibility interval (blue shaded area). IPHC management procedure reference points ( $S B_{30 \%}$ and $S B_{20 \%}$ ) are shown as dashed and solid lines respectively, with the region of biological concern ( $<S B_{20 \%}$ ) shaded in red.


FIGURE 15. Estimated time-series' of spawning biomass (blue line) and spawning biomass in the absence of fishing (black line).


FIGURE 16. Cumulative distribution of ensemble 2023 spawning biomass estimates relative to the $S B_{30 \%}$ reference point. Curve represents the estimated probability that the biomass is less than or equal to the value on the x-axis. Vertical lines denote the values corresponding to the fishing intensity threshold in the IPHC's harvest policy (red; SB30\%), and the median (blue; SB42\%).
The IPHC's current interim management procedure specifies a reference level of fishing intensity of $F_{43 \%}$, based on the Spawning Potential Ratio (SPR). This reference equates to the level of fishing that would reduce the lifetime spawning output per recruit to $43 \%$ of the unfished level given current biology, fishery characteristics and demographics. For the most recent three years fishing intensity is estimated to have been below reference levels and projections based on adopted mortality limits at the time. Prior to 2020, estimates of terminal year fishing intensity in each stock assessment were generally similar to those from the 2022 assessment (Figure 8). Based on the 2022 assessment, the 2022 fishing intensity is estimated to correspond to an $F_{51 \%}$ (credible interval: 32-64\%), much less than projected in the 2021 assessment, slightly higher than 2020 (when many fisheries did not achieve projected performance), and lower than other years since the late 1990s (Table 1; Figures 17 and 18). Comparing the relative spawning biomass and fishing intensity over the recent historical period provides for an evaluation of trends conditioned on the currently defined reference points via a 'phase' plot. The phase plot for Pacific halibut shows that the relative spawning biomass decreased as fishing intensity increased through 2010, then increased as the fishing intensity decreased through 2016, and has been relatively stable since then (Figure 18).


FIGURE 17. Cumulative distribution of the estimated fishing intensity (based on the Spawning Potential Ratio) estimated to have occurred in 2022. Curve represents the estimated probability that the fishing intensity is less than or equal to the value on the x-axis. Vertical lines indicate the reference ( $F_{43 \%}$; red) and the median value ( $F_{51 \%}$; blue).

## Long time-series models

The two long time-series models provided different perceptions of current vs. historical stock sizes, particularly for the lowest points in the series occurring in the 1930s and 1970s (Figure 19). The AAF model estimates that recent stock sizes are below those estimated for the 1970s, and the coastwide model above. 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 four of the models represent only simple approximations. Recent differences are likely attributable to the separation of signals from each Biological Region (particularly Region 2, with the longest time-series of data), and allowance for different properties in each region's fishery and survey in the AAF models. Historical differences appear to be due to the differing assumptions regarding connectivity between Regions 2-3 and Regions 4-4B during the early part of the 1900s when there are no data available from Regions 4-4B (Stewart and Martell 2016).


FIGURE 18. Phase plot showing the time-series of estimated spawning biomass (1993-2023) and fishing intensity (1992-2022) relative to current reference points. Dashed lines indicate the $F_{43 \%}$ (horizontal) reference fishing intensity and linear reduction below the SB30\% (vertical) trigger, the red area indicates levels below the $S B_{20 \%}$ limit. Each year is denoted by a solid point (credible intervals by horizontal and vertical whiskers), with the relative fishing intensity in 2022 and spawning biomass at the beginning of 2023 shown as the largest point (purple). Percentages along the $y$-axis indicate the probability of being above and below $F_{43 \%}$ in 2022; percentages on the $x$-axis the probabilities of being below $S B_{20 \%}$, between $S B_{20 \%}$ and $S B_{30 \%}$ and above $S B_{30 \%}$ at the beginning of 2023.


FIGURE 19. Spawning biomass estimates from the two long time-series models. Shaded region indicates the approximate $95 \%$ within-model credible interval. The black (upper) series is the Areas-As-Fleets model and the blue (lower) series is the coastwide model.

## 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.

The 2022 assessment includes five years (2017-21) of sex-ratio information from the directed commercial fishery landings. However, uncertainty in historical ratios, and the degree of variability likely present in those and future fisheries remains unknown. Additional years of data are likely to further inform selectivity parameters and cumulatively reduce uncertainty in stock size moving into the future. The treatment of spatial dynamics (and implicitly movement rates) among Biological Regions, which are represented via the coastwide and AAF approaches, has large implications for the current stock trend, as evidenced by the different results among the four models comprising the stock assessment ensemble. Further, movement rates for adult and younger Pacific halibut (roughly ages 2-6, which were not well-represented in the PIT-tagging study), particularly to and from Biological Region 4 (and especially to and from the Eastern Bering Sea), are important and uncertain components in understanding and delineating between the distribution of recruitment among biological Regions, and other factors influencing stock distribution and productivity. This assessment also does not include mortality, trends or explicit demographic linkages with Russian waters, although such linkages may be increasingly important as warming waters in the Bering Sea allow for potentially important exchange across the international border. Ongoing research to better understand the stock structure within the Convention Area as well as connectivity to Western North Pacific waters is ongoing. These investigations are particularly important for understanding the dynamics in IPHC Regulatory Area 4B, which is potentially the most demographically isolated of the eight IPHC Regulatory Areas.

Additional important contributors to assessment uncertainty (and potential bias) include factors influencing recruitment, size-at-age, and some estimated components of fishery mortality. The link between Pacific halibut recruitment strengths and environmental conditions remains poorly understood, and although correlation with the Pacific Decadal Oscillation is currently useful, it may not remain so in the future. Therefore, recruitment variability remains a substantial source of uncertainty in current stock estimates due to the lack of mechanistic understanding and the lag between birth year and direct observation in the fishery (8+ years) and survey data (6+ years). Reduced size-at-age relative to levels observed in the 1970s has been the most important driver of recent decade's stock productivity, but its cause also remains unknown. Like most stock assessments, fishing mortality estimates are assumed to be accurate. Therefore, uncertainty due to discard mortality estimation (observer sampling and representativeness), discard mortality rates, and any other unreported sources of mortality in either directed or nondirected fisheries (e.g. whale depredation) could create bias in this assessment.

Maturation schedules are currently under renewed investigation by the IPHC. Historical values are based on visual field assessments, and the simple assumption that fecundity is proportional to spawning biomass and that Pacific halibut do not experience appreciable skip-spawning (physiologically mature fish which do not actually spawn due to environmental or other conditions). To the degree that maturity, fecundity or skip spawning may be temporally variable, the current approach could result in bias in the stock assessment trends and reference points.

New information will be incorporated as it becomes available; however, it may take years to better understand the spatial and temporal variability inherent in these biological processes.

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 use both fixed (0.15/year for female Pacific halibut) and estimated values. The female value estimated in the long AAF model (0.184) is similar to the values estimated in the short AAF model (0.213) and the long coastwide model ( 0.215 ). These estimates are highly correlated to the relative commercial fishery selectivity of males and females, which is currently estimated based on five years of available data. Estimates of these processes contribute to the difference in scale and productivity for the two models which are not easily reconciled at present. Although this uncertainty is directly incorporated into the ensemble results, uncertainty in female natural mortality in the coastwide short model is not and remains an avenue for future investigation.

This stock assessment contains a broad representation of uncertainty in stock levels when compared to analyses for many other species. This is due to the inclusion of both within-model (parameter or estimation uncertainty) and among-model (structural) uncertainty. Due to the many remaining uncertainties in Pacific halibut biology and population dynamics, a high degree of uncertainty in both stock scale and trend will continue to be an integral part of an annual management process, which can result in variable mortality limits from year to year. Potential solutions to reduce the inter-annual variability in mortality limits include management procedures that utilize multi-year management approaches, which are being tested with the MSE framework.

## Convergence, Sensitivity and retrospective analyses

Basic convergence checks applied to all models included successful calculation of the Hessian matrix, checks for reasonable uncertainty in and correlations among estimated model parameters and tracking of results through sequential model or data changes to ensure plausible results. Further, during model development the two AAF models showed more challenging likelihood surfaces with occasional local minima. Therefore, final model runs were further evaluated via running models from a wide range starting values ('jittering', using at least 100 different starting points), and ensuring that no model discovered a better likelihood than was used to produce the final assessment results.

During the preliminary development of the 2022 stock assessment a wide range of bridging and sensitivity analyses were conducted (IPHC-2022-SRB020-07). 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 have included: the sex ratio of the directed commercial fishery landings, the treatment of historical selectivity in the long time-series models, and natural mortality. Likelihood profiles were used to investigate the sources of information on natural mortality and the general level of agreement among data sets. In addition, the preliminary development of the 2022 assessment included extensive evaluation of the treatment of the PDO as a covariate with average recruitment. Briefly, the way in which the PDO was linked to recruitment did not have a large effect of estimates of stock trend, nor was a method identified that better explained the historical variation (IPHC-2022-SRB020-07). Research priorities closely linked with stock assessment uncertainties have been explored through specific sensitivity analyses conducted in 2020 and 2021. In addition to those factors described above, these analyses have included the effects of unobserved whale depredation, and trends in spawning output (due to skip spawning or changes in maturity schedules) and the
results have supported the prioritization of maturity, fecundity and skip spawning as current and near-term research foci.
To illustrate the effects of recent data, separate from all other model changes and data updates, retrospective analyses were performed for each of the individual models contributing to the assessment. This exercise consists of sequentially removing the terminal year's data and rerunning the assessment model. This is commonly done for five or more years; however, the current models, restructured for the 2019 stock assessment around estimation of commercial fishery selectivity separately for males and females, rely on sex-ratios-at-age which are only available from 2017-2021. Therefore, the retrospective for this year's assessment does not go beyond five 'peels', each cumulatively removing one year of data (2022, 2021-2022, 2020-2022, 2019-2022, and 2018-2022). Estimates for relative male and female selectivity parameters become less certain with reduced data and required at least one year of data for reliable estimation and preferably more. As data accumulate since this change in model structure the retrospective analyses will be more informative of recent data effects rather than being affected by lack of information to inform selectivity differences.
The retrospective analysis revealed that spawning biomass time series for each of the four stock assessment models changed very little as the terminal year's data were removed; with the highest variance in the results observed for the AAF short and long models where the estimates of spawning biomass increasing or decreasing with the removal of four and five years of data (Figures 20-23; upper panels). As noted above, these models were very sensitive to the estimated values for natural mortality, which were correlated with relative male and female selectivity in the directed commercial fishery; removing four and five recent years of data left a paucity of sex ratio information to estimate differences in male and female selectivity. This result highlights the ongoing need for additional observations of the sex-ratio of commercial fishery landings, although as more data are collected it may be possible to reduce the frequency at which sex ratio data are included. The second clear result from the retrospective analysis was the effect of 2018 to 2021 data on the magnitude of the estimated 2012 year-class. This cohort is informed by each year of additional data and the estimated magnitude increased strongly across the model runs (Figures 20-23; lower panels). The addition of the 2022 data resulted in only a small decrease in the estimate of the 2012 year-class.


FIGURE 20. Spawning biomass (top panel) and recruitment (bottom panel) estimates from a retrospective analysis sequentially removing terminal years of data from the coastwide short model. Shaded regions and vertical whiskers indicate approximate $95 \%$ within-model credible intervals.


FIGURE 21. Spawning biomass (top panel) and recruitment (bottom panel) estimates from a retrospective analysis sequentially removing terminal years of data from the AAF short model. Shaded regions and vertical whiskers indicate approximate $95 \%$ within-model credible intervals.


FIGURE 22. Recent spawning biomass (top panel) and recruitment (bottom panel) estimates from a retrospective analysis sequentially removing terminal years of data from the coastwide long model (time series has been truncated to allow for easier inspection of terminal values). Shaded regions and vertical whiskers indicate approximate $95 \%$ within-model credible intervals.


FIGURE 23. Recent spawning biomass (top panel) and recruitment (bottom panel) estimates from a retrospective analysis sequentially removing terminal years of data from the AAF long model (time series has been truncated to allow for easier inspection of terminal values). Shaded regions and vertical whiskers indicate approximate $95 \%$ within-model credible intervals.

## Forecasts and decision table

Stock projections were conducted using the integrated results from the stock assessment ensemble in tandem with summaries of the 2022 directed and non-directed fisheries. The harvest decision table (Table 2) 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 2023 (columns). 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 relative to the approach identified in the interim management procedure. The alternatives (columns) include several levels of mortality intended for evaluation of stock and management procedure dynamics including:

- No fishing mortality (useful to evaluate the stock trend due solely to population processes)
- A 30 million pound ( $\sim 13,600$ t) 2023 TCEY
- Reductions of $10 \%, 15 \%$, and $18 \%$ from the 41.2 million pound coastwide TCEY set for 2022, which are 37.1, 35.0, and 33.8 million pounds ( $16,800,15,900$, and $15,300 \mathrm{t}$ ), respectively.
- The mortality consistent with repeating the coastwide TCEY set for 2022 (41.2 million pounds, $\sim 18,700 \mathrm{t}$; "status quo").
- The mortality at which there is a $50 \%$ chance that the spawning biomass will be smaller in three years than in 2022 ("3-year surplus")
- The mortality consistent with the current "Reference" SPR $\left(F_{43 \%}\right)$ level.
- A 60 million pound ( $\sim 27,200$ t) 2022 TCEY

A grid of alternative TCEY values corresponding to SPR values from $40 \%$ to $46 \%$ is also provided to allow for finer detail across the range of estimated SPR values identified by the MSE process as performing well with regard to stock and fishery objectives. For each column of the decision table, the total fishing mortality (including all sizes and sources), the coastwide TCEY and the associated level of fishing intensity projected for 2023 (median value with the 95\% credible interval below) are reported.

The projections of spawning biomass for this assessment are more optimistic than those from recent assessments due to the increasing projected maturity of the 2012 year-class. This translates to a lower probability of stock decline for 2022 than in recent assessments as well as a decrease in this probability through 2023-24 for similar mortality levels. The reference coastwide TCEY for 2023 is $26 \%$ higher than the reference coastwide TCEY for 2022 due to the increase in estimated productivity with a third model estimating natural mortality greater than the previously fixed value of 0.15 . There is greater than a $50 \%$ probability of stock decline in 2024 (53-86/100) for all yields greater than the status quo, including the entire range of SPR values from $40-46 \%$, which includes the $F_{43 \%}$ reference level. There is a 49 out of 100 chance that the spawning biomass will decline in 2024 with the status quo TCEY of 41.2 million pounds ( $\sim 18,700$ t). The 2023 " 3 -year surplus" alternative corresponds to a TCEY of 43.0 million pounds ( $\sim 19,500$ t), and a projected SPR of 48\% (credible interval 28-62\%; Table 2, Figure 24). At the reference level (a projected SPR of 43\%), the probability of spawning biomass decline from 2023 to 2024 is $75 \%$, decreasing to $71 \%$ in three years, as the 2012 cohort matures. The one-year risk of the stock dropping below $\mathrm{SB}_{30 \%}$ is $25 \%$ across all alternatives.

## Research Priorities

Research priorities for the stock assessment and related analyses have been consolidated with those for the IPHC's MSE and the Biological Research program (IPHC-2022-AM098-11).

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TABLE 2. Harvest decision table for 2023. 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.



FIGURE 24. Three-year projections of stock trend under alternative levels of mortality: no fishing mortality (upper panel), the status quo TCEY set in 2022 of 41.2 million pounds, ( $\sim 18,700 \mathrm{t}$; second panel), the 3 -year surplus (a TCEY of 43.0 million pounds, $\sim 19,500 \mathrm{t}$; third panel), and the TCEY projected for the IPHC's interim management procedure ( 52.0 million pounds, 23,600 t; lower panel).

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[^0]:    ${ }^{1}$ The IPHC recognizes sub-Areas 4C, 4D, 4E and the Closed Area for use in domestic catch agreements but manages the combined Area 4CDE.

[^1]:    2 The IPHC receives preliminary estimates of the current year's non-directed discard mortality from the National Marine Fisheries Service Alaska Regional Office, Northwest Fisheries Science Center, and Fisheries and Oceans Canada in late October.

