INTERNATIONAL PACIFIC
HALIBUT COMMISSION

IPHC–2022–SRB020–00
Last Update: 2 June 2022

20th Session of the IPHC Scientific Review Board (SRB020) – *Compendium of meeting documents*

14 – 16 June 2022, Seattle, WA, USA

Commissioners

Canada	United States of America
Paul Ryall	Glenn Merrill
Neil Davis	Robert Alverson
Peter DeGreef	Richard Yamada

Executive Director

David T. Wilson, Ph.D.

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IPHC-2022-SRB020-01

Last updated: 16 March 2022

PROVISIONAL: AGENDA & SCHEDULE FOR THE 20th SESSION OF THE IPHC SCIENTIFIC REVIEW BOARD (SRB020)

Date: 14-16 June 2022
Location: Seattle, WA, USA, & Electronic Meeting
Venue: IPHC HQ & Adobe Connect
Time: 12:30-17:00 (14th), 09:00-17:00 (15-16th) PDT
Chairperson: Dr Sean Cox (Simon Fraser University)
Vice-Chairperson: Nil

1. OPENING OF THE SESSION

2. ADOPTION OF THE AGENDA AND ARRANGEMENTS FOR THE SESSION

- *IPHC-2022-SRB020-01: Agenda & Schedule for the 20th Session of the Scientific Review Board (SRB020)*
- *IPHC-2022-SRB020-02: List of Documents for the 20th Session of the Scientific Review Board (SRB020)*

3. IPHC PROCESS

3.1. SRB annual workflow (D. Wilson)
3.2. Update on the actions arising from the 19th Session of the SRB (SRB019) (D. Wilson)
  - *IPHC-2022-SRB020-03: Update on the actions arising from the 19th Session of the SRB (SRB019) (IPHC Secretariat)*

3.3. Outcomes of the 98th Session of the IPHC Annual Meeting (AM098) (D. Wilson)
  - *IPHC-2022-SRB020-04: Outcomes of the 98th Session of the IPHC Annual Meeting (AM098) (D. Wilson)*

3.4. Observer updates (e.g. Science Advisors)

4. IPHC FISHERY-INDEPENDENT SETLINE SURVEY (FISS)

4.1. 2023 FISS design evaluation (R. Webster)
4.2. Updates to space-time modelling (R. Webster)

5. MANAGEMENT STRATEGY EVALUATION: UPDATE

6. PACIFIC HALIBUT STOCK ASSESSMENT: 2022

7. BIOLOGICAL AND ECOSYSTEM SCIENCES – PROJECT UPDATES

8. INTERNATIONAL PACIFIC HALIBUT COMMISSION 5-YEAR PROGRAM OF INTEGRATED RESEARCH AND MONITORING (2022-26)

9. PACIFIC HALIBUT FISHERY ECONOMICS – PROJECT REPORT

10. REVIEW OF THE DRAFT AND ADOPTION OF THE REPORT OF THE 20TH SESSION OF THE IPHC SCIENTIFIC REVIEW BOARD (SRB020)

SCHEDULE FOR THE 20th SESSION OF THE IPHC SCIENTIFIC REVIEW BOARD (SRB020)

Tuesday, 14 June 2022

Time	Agenda item	Lead
12:00-12:30	*Lunch – Meet and greet *Adobe Connect - Participants encouraged to call in and test connection	
12:30-12:35	1. OPENING OF THE SESSION 2. ADOPTION OF THE AGENDA AND ARRANGEMENTS FOR THE SESSION	S. Cox & D. Wilson
12:35-13:00	3. IPHC PROCESS 3.1 SRB annual workflow (D. Wilson) 3.2 Update on the actions arising from the 19th Session of the SRB (SRB019) 3.3 Outcomes of the 98th Session of the IPHC Annual Meeting (AM098) 3.4 Observer updates (e.g. Science Advisors)	D. Wilson
13:00-14:30	4. IPHC FISHERY-INDEPENDENT SETLINE SURVEY (FISS) 4.1 2023 FISS design evaluation 4.2 Updates to space-time modelling	R. Webster
14:30-16:00	5. MANAGEMENT STRATEGY EVALUATION: UPDATE	A. Hicks
16:00-17:00	SRB drafting session	SRB members

Wednesday, 15 June 2022

Time	Agenda item	Lead
09:00-09:30	Review of Day 1 and discussion of SRB Recommendations from Day 1	Chairperson
09:30-12:30	6. PACIFIC HALIBUT STOCK ASSESSMENT: 2022	I. Stewart
12:30-13:30	Lunch	
13:30-16:00	(6. cont.) PACIFIC HALIBUT STOCK ASSESSMENT: 2022	I. Stewart

16:00-17:00	SRB drafting session	SRB members
Thursday, 16 June 2022		
Time	**Agenda item**	**Lead**
09:00-09:30	Review of Day 2 and discussion of SRB Recommendations from Day 2	Chairperson
09:30-10:15	7. BIOLOGICAL AND ECOSYSTEM SCIENCES – PROJECT UPDATES	J. Planas
10:15-11:45	8. INTERNATIONAL PACIFIC HALIBUT COMMISSION 5-YEAR PROGRAM OF INTEGRATED RESEARCH AND MONITORING (2022-26)	D. Wilson
11:45-12:30	9. PACIFIC HALIBUT FISHERY ECONOMICS – PROJECT REPORT	B. Hutniczak
12:30-13:30	Lunch	
13:30-14:30	SRB drafting session	SRB members
14:30-17:00	10. REVIEW OF THE DRAFT AND ADOPTION OF THE REPORT OF THE 20th SESSION OF THE IPHC SCIENTIFIC REVIEW BOARD (SRB020)	S. Cox

INTERNATIONAL PACIFIC HALIBUT COMMISSION

IPHC-2022-SRB020-02

Last updated: 2 June 2022

PROVISIONAL: LIST OF DOCUMENTS FOR THE 20th SESSION OF THE IPHC SCIENTIFIC REVIEW BOARD (SRB020)

Document	Title	Availability
IPHC-2022-SRB020-01	Agenda & Schedule for the 20th Session of the Scientific Review Board (SRB020)	✓ 16 Mar 2022
IPHC-2022-SRB020-02	List of Documents for the 20th Session of the Scientific Review Board (SRB020)	✓ 16 Mar 2022 ✓ 13 May 2022 ✓ 2 June 2022
IPHC-2022-SRB020-03	Update on the actions arising from the 19th Session of the SRB (SRB019) (IPHC Secretariat)	✓ 11 May 2022
IPHC-2022-SRB020-04	Outcomes of the 98th Session of the IPHC Annual Meeting (AM098) (D. Wilson)	✓ 6 May 2022
IPHC-2022-SRB020-05	2023-25 FISS design evaluation (R. Webster)	✓ 13 May 2022
IPHC-2022-SRB020-06 Rev_1	IPHC Secretariat MSE Program of Work (2022–2023) and an update on progress (A. Hicks & I. Stewart)	✓ 12 May 2022 ✓ 1 June 2022
IPHC-2022-SRB020-07	Development of the 2022 Pacific halibut (*Hippoglossus stenolepis*) stock assessment (I. Stewart & A. Hicks)	✓ 11 May 2022
IPHC-2022-SRB020-08	Report on current and future biological and ecosystem science research activities (J. Planas)	✓ 11 May 2022
IPHC-2022-SRB020-09	Pacific Halibut Multiregional Economic Impact Assessment (PHMEIA): Project Report (B. Hutniczak)	✓ 6 May 2022
IPHC-2022-SRB020-10	International Pacific Halibut Commission 5-Year program of integrated research and monitoring (2022-26) (D. Wilson, J. Planas, I. Stewart, A. Hicks, R. Webster, B. Hutniczak, & J. Jannot)	✓ 13 May 2022
Information papers		
Nil to-date	Nil to-date	-

UPDATE ON THE ACTIONS ARISING FROM THE 19TH SESSION OF THE IPHC SCIENTIFIC REVIEW BOARD (SRB019)

PREPARED BY: IPHC SECRETARIAT (11 MAY 2022)

PURPOSE

To provide the Scientific Review Board (SRB) with an opportunity to consider the progress made during the intersessional period, on the recommendations/requests arising from the SRB019.

BACKGROUND

At the SRB019, the members recommended/requested a series of actions to be taken by the IPHC Secretariat, as detailed in the SRB019 meeting report (IPHC-2021-SRB019-R) available from the IPHC website, and as provided in Appendix A.

DISCUSSION

During the 19th Session of the SRB (SRB019), efforts will be made to ensure that any recommendations/requests for action are carefully constructed so that each contains the following elements:

1) a specific action to be undertaken (deliverable);
2) clear responsibility for the action to be undertaken (such as the IPHC Staff or SRB officers);
3) a desired time frame for delivery of the action (such as by the next session of the SRB or by some other specified date).

RECOMMENDATION/S

That the SRB:

1) **NOTE** paper IPHC-2022-SRB020-03, which provided the SRB with an opportunity to consider the progress made during the inter-sessional period, in relation to the consolidated list of recommendations/requests arising from the previous SRB meeting (SRB019).
2) **AGREE** to consider and revise the actions as necessary, and to combine them with any new actions arising from SRB020.

APPENDICES

Appendix A: Update on actions arising from the 19th Session of the IPHC Scientific Review Board (SRB019)

APPENDIX A
Update on actions arising from the 19th Session of the IPHC Scientific Review Board (SRB019)

RECOMMENDATIONS

Action No.	Description	Update
SRB019–Rec.01 (para. 13)	***2022-24 IPHC Fishery-independent setline survey (FISS) design evaluation*** The SRB **RECOMMENDED** that the Commission note the SRB018 endorsement of the proposed 2022 design and provisional endorsement of the proposed 2023-24 designs, as provided at Appendix IV, recognizing that the designs for 2023-24 will be reviewed again at subsequent SRB meetings.	**Completed:** Noted by the Commission at AM098
SRB019–Rec.02 (para. 14)	**NOTING** the presentation of three alternative 2022 sampling designs (Figs. 1, 2, and 3) that optimize the SRB018-endorsed proposed 2022 design for cost, thereby meeting the goals of long-term revenue neutrality (Secondary Objective), without compromising the scientific goals of the FISS (Primary Objective), the SRB **RECOMMENDED** that the Secretariat prioritize 2022 sampling designs that include IPHC Regulatory Area 4CDE despite the relatively low contribution of this area to overall biomass and variance. This region is an important area to monitor for future range shifts and biological samples collected here are likely to be important for understanding the biology of Pacific halibut at their leading range edge.	**Completed:** Such designs continue to be prioritized by the Secretariat, but we note that the recommended design may not be fully implemented each year due to limited interest from potential charter vessels.
SRB019–Rec.03 (para. 18)	***Modelling of IPHC length-weight data*** The SRB **RECOMMENDED** that the IPHC provide a revised length-net weight relationship for each IPHC Regulatory Area based on modelling of combined FISS and commercial sample data to be used for the calculation of all non-IPHC mortality estimates where individual weights cannot be collected, for 2021 and until further notice.	**Completed:** Revised length-weight relationships have been estimated for all areas. These are presented on the IPHC website, and were publicized through email contacts to domestic agency and tribal staff.

Action No.	Description	Update
SRB019–Rec.04 (para. 30)	***Pacific halibut stock assessment: 2021 - Modelling updates*** **NOTING** that the surplus production analysis revealed a recent pattern of harvest exceeding surplus production despite current biomass being below the target biomass, the SRB **RECOMMENDED** that the IPHC Secretariat continue to report on surplus production in addition to trends and scale of surplus production and fishing intensity as part of the annual assessment.	**Completed**: This information was included in the 2021 stock assessment and presentation to the Commission.
SRB019–Rec.05 (para. 34)	***Management Strategy Evaluation: Update*** The SRB **RECOMMENDED** the investigation of empirical procedures to inform mortality limits in non-assessment years of a multi-year assessment MP.	**In progress**: Empirical procedures will be implemented as a component of the management procedures for multi-year assessments. This will provide a stepping-stone to a complete empirical procedure.
SRB019–Rec.06 (para. 35)	**NOTING** the inclusion of uncertainty stemming from implementation ***uncertainty***, the SRB **RECOMMENDED** that the IPHC Secretariat develop, for presentation at SRB020, alternative scenarios that represent implementation ***bias***, i.e. the potential for quota reductions called for by the management procedure to be less likely implemented than quota increases.	**In progress**: Implementation error and bias has been developed and the details are currently being coded into the closed-loop simulation framework.
SRB019–Rec.07 (para. 38)	***IPHC Secretariat MSE Program of Work (2021-23)*** The SRB **RECOMMENDED** that the initial management procedure be evaluated on the basis of the current operating model.	**Completed**: Results from the initial MSE simulations were presented to the Commission at AM098. A new OM incorporating multiple models has been developed for the investigation of size limits and multi-year assessments.

Action No.	Description	Update
SRB019–Rec.08 (para. 39)	The SRB **RECOMMENDED** that the IPHC Secretariat develop alternative OMs from various hypotheses related to population processes or environmental covariates for implementation in the MSE framework, noting paragraph 38, and that tasks leading to the adoption of a well-defined MP should be prioritized.	**In progress**: A new OM with multiple models representing various hypotheses for movement and natural mortality has been developed.
SRB019–Rec.09 (para. 43)	***IPHC 5-Year biological and ecosystem science research plan (2017-21)*** The SRB **RECOMMENDED** that the Secretariat consider the value of other opportunistically collected samples that would facilitate further downstream analyses in a cost effective manner.	**In progress**: The IPHC Secretariat is maximizing opportunities for sample collection from fish encountered in experimental field trials as well as in the IPHC FISS.
SRB019–Rec.10 (para. 56)	***Research integration*** The SRB **RECOMMENDED** that the IPHC Secretariat identify those research areas with uncertainty and indicate research questions that would require the SRB to provide input and/or decision in future documentation and presentations provided to the SRB.	**In progress**: The Secretariat is working towards delineating research questions that address key areas of uncertainty for Stock Assessment and Management Strategy Evaluation.

REQUESTS

Action No.	Description	Update
SRB019–Req.01 (para. 8)	***Update on the actions arising from the 18th Session of the SRB (SRB018)*** The SRB **RECALLED** three actions for delivery at SRB020 as follows: a) SRB018–Req.1 (para. 13) IPHC Fishery-independent setline survey (FISS): 2022-24 FISS design evaluation. The SRB **REQUESTED** plots by survey area of WPUE vs. depth from both FISS and commercial fisheries to help understand if there is part of	**In progress:** Work addressing (a) and (b) will be presented at SRB020.

Action No.	Description	Update
	the Pacific halibut stock in deeper waters not covered by the FISS. b) SRB018–Req.2 (para. 14) The SRB **REQUESTED** that the IPHC Secretariat conduct a preliminary comparison, to be presented at SRB020, between male, female, and sex-aggregated analysis of the FISS data using the spatial-temporal model. c) SRB018–Req.14 (para. 52) The SRB **NOTED** that, without a clearer understanding of the Commissions purpose for future use of this work, it is difficult to provide guidance on prioritising model development (e.g. improve spatial resolution, incorporate dynamic / predictive processes, adding more detail on subsistence and recreational fisheries, including uncertainty in the assessment). The SRB therefore **REQUESTED** specific guidance and clarification from the Commission on the objectives and intended use of this study.	
SRB019–Req.02 (para. 19)	***Modelling of IPHC length-weight data*** **NOTING** the emerging difference between length-weight regressions based on historical vs. recent data, the SRB **REQUESTED** further investigation of the underlying processes (whether in the observation process - e.g. timing of sample collection - or biological changes - e.g. changes in somatic growth) driving these differences. While the suggested solution provides a numerical solution it also annually requires significant sampling and analysis efforts which could potentially be reduced through a better understanding of the processes involved.	**In progress**: Work is underway examining these data more closely in the context of Pacific halibut condition and understanding factors that may affect changes in condition. We note that weighing of fish at sea is now a routine part of the sampling process with the principle goal of ensuring accurate recording of Pacific halibut weights on the FISS.
SRB019–Req.03 (para. 22)	***Review of IPHC hook competition standardization*** **NOTING** the presentation of methods used for hook competition standardization, the SRB **REQUESTED** continued analysis of this phenomenon and incorporation of these corrections in the FISS data analysis, including potential use of hook timer studies if the technology permits.	**In progress**: Field research using standard and modified circle hook designs and hook-timers is planned for summer 2022.

Action No.	Description	Update
SRB019–Req.04 (para. 24)	***Accounting for the effects of whale depredation on the FISS*** **NOTING** the presentation of methods used for accounting for whale depredation, and the limited impact of the correction at this point, the SRB **REQUESTED** that the IPHC Secretariat continue to monitor the influence of whale depredation on the FISS and the stock assessment. If the whale depredation correction becomes more important in the future, it will become important to conduct a broader investigation of ways that this phenomenon could be described and accounted for, if at all, in the FISS. Also, the impact / treatment of the associated compositions should be better explained within the stock assessment.. While the SRB generally supports the idea to use all possible data there is a question as to whether the simple time covariate approach risks introducing bias through changes in density of Pacific halibut and / or whales and through ignoring possible depredation selectivity by size and sex.	**In progress**: Collection of whale interactions information is an ongoing part of the FISS, and Secretariat staff will continue to monitor any changes in rates of whale interactions.
SRB019–Req.05 (para. 31)	***Pacific halibut stock assessment: 2021 - Modelling updates*** The SRB **REQUESTED** that the IPHC Secretariat consider the following topics for inclusion in the 2022 full stock assessment and presentation for SRB evaluation at SRB020 in June 2022: a) Sensitivity analysis of the assessment to processes being investigated by the Biological and Ecosystem Research Program, e.g. spatiotemporal differences in maturity schedules, discard mortality, and length-weight relationships; b) Continued exploration of data weighting; c) Evaluation of treatment of commercial sex ratio; d) Use of the Pacific Decadal Oscillation (PDO) and other environmental covariates to predict recruitment; e) Estimation of whale depredation mortality for potential explicit inclusion in the assessment model; and	**Completed** Sensitivity analyses covering maturity and unobserved mortality were included in the 2021 stock assessment. Directly measured weights have been incrementally included in all analyses beginning in 2015, with full adoption of the revised relationship completed in 2021. Items (b) – (f) are all included in the preliminary stock assessment; see IPHC-2022-SRB020-07.

Action No.	Description	Update
	f) Other factors discussed since the last stock assessment.	
SRB019–Req.06 (para. 46)	***Biological and ecosystem science research*** ***Reproduction*** The SRB **NOTED** that the IPHC Secretariat is finalising a proposed sampling design for the collection of ovaries in the 2023 FISS, for providing precise estimates of fecundity and **REQUESTED** for SRB020 in June 2022, more detail on the considerations taken to ensure the sampling maximises the opportunity to address the objectives.	**In progress**: The IPHC Secretariat is working towards selecting appropriate methods for fecundity estimations and towards devising a sampling strategy for 2023.
SRB019–Req.07 (para. 50)	***Growth and Physiological Condition*** The SRB **REQUESTED** that the IPHC Secretariat pause further pursuit of this research until it can articulate specifically how this approach will inform the stock assessment or MSE and why this approach is preferable to investigation of age-length-weight information which is available at a much broader geographic and temporal scale.	**Completed**: The IPHC Secretariat is complying with this request.
SRB019–Req.08 (para. 59)	***Pacific halibut fishery economics update*** The SRB **NOTED** that substantial uncertainties surround our understanding of recreational fishing effort dynamics (e.g. the expected change in effort with changes in season length or size limits and the availability of alternative target species such as Pacific salmon) and **REQUESTED** that the IPHC Secretariat assess and present at SRB020, the feasibility and value of various stated preference (e.g. a discrete choice experiment) and revealed preference (e.g. time series analysis of fishing effort patterns with respect to regulatory changes) approaches to understanding recreational effort dynamics.	**Project closed:** The socioeconomic study was concluded at the 98th Session of the IPHC Annual Meeting (AM098) (IPHC–2022–AM098–R, par. 70).
SRB019–Req.09 (para. 60)	The SRB **REQUESTED** that the IPHC Secretariat assess and present at SRB020, the potential of using data from the Guided Angler Fish Program (USA) and Pacific Region Experimental Recreational Halibut Program (Canada) as inputs to the economic analysis of Pacific halibut, particularly the trade-offs between the commercial and the recreational sector.	**Project closed:** The socioeconomic study was concluded at the 98th Session of the IPHC Annual Meeting (AM098) (IPHC–2022–AM098–R, par. 70).

Action No.	Description	Update
SRB019–Req.10 (para. 61)	The SRB **REQUESTED** further information (e.g. inverse demand curves), to be presented at SRB020, on the regional supply-price relationships for commercial landings, as well as localized importance of the Pacific halibut fishery to communities.	**Project closed:** The socioeconomic study was concluded at the 98th Session of the IPHC Annual Meeting (AM098) (IPHC–2022–AM098–R, par. 70).
SRB019–Req.11 (para. 63)	***International Pacific Halibut Commission 5-year program of integrated science and research (2021-26)*** The SRB **REQUESTED** that the IPHC Secretariat consider the following changes (in no particular order) to this document by SRB2020: a) Add an Executive Summary; b) Change the title, the overall statement of purpose section, and Fig. 4 to better reflect the goals and intent of the research program; c) Enhance stock assessment section to reflect research in this area including some of the priorities from the external review etc.; d) Include the intent to use the MSE to provide research direction and prioritisation (feedback) to the biological research program; e) Keep monitoring section separate as is, but demonstrate the linkage to the research through resource sharing etc.; f) Add a performance metric related to the provisioning of high-quality management advice that meets the Commission's needs; g) Include specific subsections on implications for integration with other core areas and relevance to management; h) Draft the section on climate change.	**In progress**: See paper IPHC-2022-SRB020-10

OUTCOMES OF THE 98TH SESSION OF THE IPHC ANNUAL MEETING (AM098)

PREPARED BY: IPHC SECRETARIAT (D. WILSON, 6 MAY 2022)

PURPOSE

To provide the SRB with the outcomes of the 98th Session of the IPHC Annual Meeting (AM098) relevant to the mandate of the SRB.

BACKGROUND

The agenda of the Commission's Annual Meeting (AM098) included several agenda items relevant to the SRB:

5. ***STOCK STATUS OF PACIFIC HALIBUT (2021) & HARVEST DECISION TABLE (2022)***
   - *5.1 IPHC Fishery-Independent Setline Survey (FISS) design and implementation in 2021 (K. Ualesi, D. Wilson, C. Jones & R. Rillera)*
   - *5.2 Space-time modelling of survey data (R. Webster)*
   - *5.3 2022-24 FISS designs (R. Webster)*
   - *5.4 Stock Assessment: Data overview and stock assessment (2021), and harvest decision table (2022) (I. Stewart, A. Hicks, R. Webster, D. Wilson, & B. Hutniczak)*
   - *5.5 Pacific halibut mortality projections using the IPHC mortality projection tool (2022) (I. Stewart)*

6. ***IPHC SCIENCE AND RESEARCH***
   - *6.1 IPHC 5-year Biological and Ecosystem Science Research Plan (2017-21): update (J. Planas)*

7. ***MANAGEMENT STRATEGY EVALUATION***
   - *7.1 IPHC Management Strategy Evaluation: update (A. Hicks)*

8. ***PACIFIC HALIBUT FISHERY ECONOMICS – PROJECT REPORT***
   - *8.1 Pacific Halibut Multiregional Economic Impact Assessment (PHMEIA) (B. Hutniczak)*

DISCUSSION

During the course of the 98th Session of the IPHC Annual Meeting (AM098) the Commission made a number of specific recommendations and requests for action regarding the stock assessment, MSE process, and 5-year research program. Relevant sections from the report of the meeting are provided in Appendix A for the SRB's consideration.

RECOMMENDATION

That the SRB:

1) **NOTE** paper IPHC-2022-SRB020-04 which details the outcomes of the 98th Session of the IPHC Annual Meeting (AM098) relevant to the mandate of the SRB.

APPENDICES

Appendix A: Excerpts from the 98th Session of the IPHC Annual Meeting (AM098) Report (IPHC-2022-AM098-R).

APPENDIX A

Excerpt from the 98th Session of the IPHC Annual Meeting (AM098) Report (IPHC-2022-AM098-R)

RECOMMENDATIONS

Management Strategy Evaluation

AM098–Rec.01 (para. 69) The Commission **RECOMMENDED** that an MSE agenda item be added to the upcoming special session to discuss and provide direction on elements of the MSE workplan, including distribution procedures to incorporate in the management procedures being simulated in 2022 and evaluated at the 99th Session of the IPHC Annual Meeting (AM099).

12th Special Session of the Commission (SS012)

AM098–Rec.02 (para. 116) The Commission **RECOMMENDED** that the 12th Special Session of the Commission be held electronically in late February or early March 2022 and include the following agenda items: 1) FY2023 budget review and adoption; 2) Management Strategy Evaluation; 3) IPHC Fishery Regulations: Daily bag limit in IPHC Regulatory Area 2B (Sect. 28) (IPHC-2022-AM098-PropB4). *[see below for outcomes]*

Length-Weight

AM098–Rec.03 (para. 121) The Commission **RECOMMENDED** the adoption of the updated length-weight relationship as detailed in paper IPHC-2022-AM098-INF07, and its dissemination to the appropriate domestic management agencies.

REQUESTS

Management Strategy Evaluation

AM098–Req.02 (para. 61) The Commission **RECALLED** SS011-Rec.01 and **REQUESTED** that the current size limit (32 inches), a 26 inch size limit, and no size limit be investigated. to understand the long-term effects of a change in the size limit.

AM098–Req.03 (para. 63) The Commission **REQUESTED** that the IPHC Secretariat work with the SRB and others as necessary to identify potential costs and benefits of not conducting an annual stock assessment. This will include a prioritized list of work items that could be accomplished in its place.

AM098–Req.04 (para. 64) The Commission **REQUESTED** that multi-year management procedures include the following concepts:

a) The stock assessment occurs biennially (and possibly triennial if time in 2022 allows) and no changes would occur to the FISS (i.e. remains annual);
b) The TCEY within IPHC Regulatory Areas for non-assessment years:
    i. remains the same as defined in the previous assessment year, or
    ii. changes within IPHC Regulatory Areas using simple empirical rules, to be developed by the IPHC Secretariat, that incorporate FISS data.

AM098–Req.05 (para. 66) The Commission **NOTED** that a distribution procedure is necessary to evaluate the size limit and multi-year assessment management procedures, and **REQUESTED** that a range of distribution procedures be used to highlight potential differences in the performance of size limits and multi-year assessments.

AM098–Req.06 (para. 68) The Commission **REQUESTED** that work continue on methods to evaluate MSE outcomes, including providing new alternative methods to quickly evaluate large sets of management procedures, which may involve ranking them in various ways.

Pacific halibut fishery economics – Project Report

AM098–Req.07 (para. 73) The Commission **AGREED** that it wished to see the Commission improve its knowledge of key inputs into the Pacific halibut stock assessment and Management Strategy Evaluation (MSE) processes, thereby providing the best possible advice for management decision making processes. Accordingly the Commission **REQUESTED** that no additional economic analyses be undertaken and that the Commission instead dedicate its efforts and funds to core areas of responsibility.

RECOMMENDATIONS FROM THE 12TH SPECIAL SESSION OF THE IPHC (SS012)

(25 February 2022)

RECOMMENDATIONS

Management Strategy Evaluation

SS012-Rec.01 (para. 10) The Commission **RECOMMENDED** the following five distribution procedures to be used in the management strategy evaluation of size limits and multi-year assessments, noting that these distribution procedures are for analytical purposes only and are not endorsed by both parties, thus would be reviewed in the future if the Commission wishes to evaluate them for implementation.

a) Baseline based on recent year O32 FISS results, relative harvest rates of 1.0 for IPHC Regulatory Areas 2-3A, relative harvest rates of 0.75 for IPHC Regulatory Areas 3B-4, and no application of the current interim agreements for 2A and 2B;

b) Baseline based on recent year O32 FISS results, relative harvest rates of 1.0 for IPHC Regulatory Areas 2-3A, relative harvest rates of 0.75 for IPHC Regulatory Areas 3B-4, and current interim agreements for 2A and 2B;

c) Baseline based on recent year O32 FISS results with 1.65 Mlbs to 2A and 20% of the coastwide TCEY to 2B;

d) Baseline based on recent year O32 FISS results, relative harvest rates of 1.0 for IPHC Regulatory Areas 2-3, 4A, and 4CDE, a relative harvest rate of 0.75 for IPHC Regulatory Area 4B, and no agreements for 2A and 2B;

e) Baseline based on recent year O32 FISS results, relative harvest rates of 1.0 for IPHC Regulatory Areas 2-3, 4A, and 4CDE, a relative harvest rate of 0.75 for IPHC Regulatory Area 4B, and current interim agreements for IPHC Regulatory Areas 2A and 2B.

INTERNATIONAL PACIFIC
HALIBUT COMMISSION

IPHC-2022-SRB020-05

2023-25 FISS design evaluation

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PURPOSE

To present the proposed designs for the IPHC's Fishery-Independent Setline Survey (FISS) for the 2023-25 period, and an evaluation of those designs, for review by the Scientific Review Board.

BACKGROUND

The IPHC's Fishery-Independent Setline Survey (FISS) provides data used to compute indices of Pacific halibut density for use in monitoring stock trends, estimating stock distribution, and as an important input in the stock assessment. Stock distribution estimates are based on the annual mean weight per unit effort (WPUE) for each IPHC Regulatory Area, computed as the average of WPUE of all Pacific halibut and for O32 (greater than or equal to 32" or 81.3cm in length) Pacific halibut estimated at each station in an area. Mean numbers per unit effort (NPUE) is used to index the trend in Pacific halibut density for use in the stock assessment models.

FISS history 1993-2019

The IPHC has undertaken FISS activity since the 1960s. However, methods were not standardized to a degree (e.g., the bait and gear used) that allows for simple combined analyses until 1993. From 1993 to 1997, the annual design was a modification of a design developed and implemented in the 1960s, and involved fishing triangular clusters of stations, with clusters located on a grid (IPHC 2012). Coverage was limited in most years and was generally restricted to IPHC Regulatory Areas 2B through 3B. The modern FISS design, based on a grid with 10 nmi (18.5 km) spacing, was introduced in 1998, and over the subsequent two years was expanded to include annual coverage in parts of all IPHC Regulatory Areas within the depth ranges of 20-275 fathoms (37-503 m) in the Gulf of Alaska and Aleutian Islands, and 75-275 fathoms (137-503 m) in the Bering Sea (IPHC 2012). Annually-fished stations were added around islands in the Bering Sea in 2006, and in the same year, a less dense grid of paired stations was fished in shallower waters of the southeastern Bering Sea, providing data for a calibration with data from the annual National Marine Fishery Service (NMFS) bottom trawl survey (Webster et al. 2020).

Through examination of commercial logbook data and information from other sources, it became clear by 2010 that the historical FISS design had gaps in coverage of Pacific halibut habitat that had the potential to lead to bias in estimates derived from its data. These gaps included deep and shallow waters outside the FISS depth range (0-20 fathoms and 275-400 fathoms), and unsurveyed stations on the 10 nmi grid within the 20-275 fathom depth range within each IPHC Regulatory Area. This led the IPHC Secretariat to propose expanding the FISS to provide coverage of the unsurveyed habitat with United States and Canadian waters. In 2011 a pilot expansion was undertaken in IPHC Regulatory Area 2A, with stations on the 10 nmi grid added to deep (275-400 fathoms) and shallow (10-20 fathoms) waters, the Salish Sea, and other, smaller gaps in coverage. (The 10 fathom limit in shallow waters was due to logistical difficulties in standardized fishing of longline gear in shallower waters.) A second expansion in IPHC Regulatory Area 2A was completed in 2013, with a pilot California survey between latitudes of 40-42°N.

The full expansion program began in 2014 and continued through 2019, resulting in the sampling of the entire FISS design of 1890 stations in the shortest time logistically possible. The FISS expansion program allowed us to build a consistent and complete picture of Pacific halibut density throughout its range in Convention waters. Sampling the full FISS design has reduced bias as noted above, and, in conjunction with space-time modelling of survey data (see below), has improved precision and fully quantified the uncertainty associated with estimates based on partial annual sampling of the species range. It has also provided us with a complete set of observations over the full FISS design (Figure 1) from which an optimal subset of stations can be selected when devising annual FISS designs. This station selection process began in 2019 for the 2020 FISS and continues with the current review of design proposals for 2023-25. Note that in the Bering Sea, the full FISS design does not provide complete spatial coverage, and FISS data are augmented with calibrated data from National Marine Fisheries Service (NMFS) and Alaska Department of Fish and Game (ADFG) trawl surveys (stations can vary by year – 2019 designs are shown in Figure 1). Both supplementary surveys have been conducted approximately annually in recent years.

Space-time modelling

In 2016, a space-time modelling approach was introduced to estimate time series of weight and numbers-per-unit-effort (WPUE and NPUE), and to estimate the stock distribution of Pacific halibut among IPHC Regulatory Areas. This represented an improvement over the largely empirical approach used previously, as it made use of additional information within the survey data regarding the degree of spatial and temporal of Pacific halibut density, along with information from covariates such as depth (see Webster 2016, 2017). It also allowed a more complete of accounting of uncertainty; for example, prior to the use of space-time modelling, uncertainty due to unsurveyed regions in each year was ignored in the estimation. Prior to the application of the space-time modelling, these unsampled regions were either filled in using independently estimated scalar calibrations (if fished at least once), or catch-rates at unsampled stations were assumed to be equal to the mean for the entire Regulatory Area. The IPHC’s Scientific Review Board (SRB) has provided supportive reviews of the space-time modelling approach (e.g., IPHC-2018-SRB013-R), and the methods have been published in a peer-review journal (Webster et al. 2020). Similar geostatistical models are now routinely used to standardise fishery-independent trawl surveys for groundfish on the West Coast of the U.S. and in Alaskan waters (e.g., Thorson et al. 2015 and Thorson 2019). The IPHC space-time models are fitted through the R-INLA package in R.

FISS design objectives

The primary purpose of the annual FISS is to sample Pacific halibut to provide data for the stock assessment (abundance indices, biological data) and estimates of stock distribution for use in the IPHC’s management procedure. The priority of the current rationalised FISS is therefore to maintain or enhance data quality (precision and bias) by establishing baseline sampling requirements in terms of station count, station distribution and skates per station. Potential considerations that could add to or modify the design are logistics and cost (secondary design layer), and FISS removals (impact on the stock), data collection assistance for other agencies, and IPHC policies (tertiary design layer). These priorities are outlined in Table 1.

Table 1. Prioritization of FISS objectives and corresponding design layers.

Priority	**Objective**	**Design Layer**
Primary	Sample Pacific halibut for stock assessment and stock distribution estimation	Minimum sampling requirements in terms of: • Station distribution • Station count • Skates per station
Secondary	Long term revenue neutrality	Logistics and cost: operational feasibility and cost/revenue neutrality
Tertiary	Minimize removals, and assist others where feasible on a cost-recovery basis.	Removals: minimize impact on the stock while meeting primary priority Assist: assist others to collect data on a cost-recovery basis IPHC policies: ad-hoc decisions of the Commission regarding the FISS design

Design review and finalisation process

Since completion of the FISS expansions, a review process has been developed for annual FISS designs created according to the above objectives:

- The Secretariat presents design proposals based only on primary objectives (Table 1) to the SRB for three subsequent years at the June meeting (recognizing that data from the current summer FISS will not be available for analysis prior to the September SRB meeting);
- These design proposals, revised (if necessary) based on June SRB input, are then reviewed by Commissioners at the September work meeting;
- At their September meeting, the SRB reviews revisions to the design proposals made to account for secondary and tertiary objectives

Following the review process, designs may be further modified to account for any updates based on secondary and tertiary objectives before being finalised during the Interim and Annual meetings and the period prior to implementation:

- Presentation of FISS designs for ‘endorsement’ by the Commission occurs at the November Interim Meeting;
- Ad hoc modifications to the design for the current year (due to unforeseen issues arising) are possible at the Annual Meeting;
- The endorsed design for current year is then modified (if necessary) to account for any additional tertiary objectives prior to summer implementation (February-April).

Consultation with industry and stakeholders occurs throughout the FISS planning process, at the Research Advisory Board meeting (29 November in 2021) and particularly in finalizing design details as part of the FISS charter bid process, when stations can be added and other adjustments made to provide for improved logistical efficiency. We also note the opportunities for stakeholder input during public meetings (Interim and Annual Meetings).

Note that while the review process examines designs for the next three years, revisions to designs for the second and third years are expected during subsequent review periods as additional data are collected. Having design proposals available for three years instead of the next year only assists the IPHC with medium-term planning of the FISS, and allows reviewers (SRB, IPHC Commissioners) and stakeholders to see more clearly the planning process for sampling the entire FISS footprint over multiple years. Extending the proposed designs beyond three years was not considered worthwhile, as we expect further evaluation undertaken following collection of data during the one to three-year period to influence design choices for subsequent years.

PROPOSED DESIGNS FOR 2023-25

The designs proposed for 2023-25 (Figures 2 to 4) use efficient subarea sampling in IPHC Regulatory Areas 2A, 4A and 4B, and incorporate a randomized subsampling of FISS stations in IPHC Regulatory Areas 2B, 2C, 3A and 3B (except for the near-zero catch rate inside waters around Vancouver Island), with a sampling rate chosen to keep the sample size close to 1000 stations in an average year, a logistically feasible footprint for the annual FISS. In 2021, designs for 2023-24 were also approved subject to later revision (IPHC-2022-AM098-R). The designs developed in 2021 have largely been carried over into the current 2023-24 proposal, with exceptions noted below.

- IPHC Regulatory Area 2A: Sample the highest-density waters of IPHC Regulatory 2A in northern Washington and central/southern Oregon each year of the 2023-25 period, and in 2023 only, add the moderate density waters of southern Washington/northern Oregon and northern California **(revision from previous 2023 design proposal)**.
- IPHC Regulatory Area 4A: Sample the higher-density western subarea of IPHC Regulatory Area 4A in all three years, the medium-density northern shelf edge subarea in 2023 only, and the historically lower-density southeastern subarea in 2025 only.
- IPHC Regulatory Area 4B: Sample the high-density eastern subarea in all three years, and the western subarea in 2023 only **(revision from previous 2023 design proposal)**.

Stations in the moderate-density waters of IPHC Regulatory 2A proposed for 2023 sampling have not been sampled since 2017 (California) or 2019 (WA/OR). This is a revision from previous proposals, which did not include these stations prior to 2025 (Webster 2021). Evaluation of potential designs in IPHC Regulatory Area 2A showed that unless these waters were sampled in 2023, we project that precision targets would not be met, with an expected 2023 coefficient of variation for mean O32 WPUE of 20% (target range is <15%). We have also received anecdotal reports of increasing recreational catch rates in northern California, providing additional motivation for bringing forward sampling in those waters.

A review of commercial catch data shows moderate catch rates in recent years in southeast IPHC Regulatory 4A. With these stations last sampled in 2019, sampling in 2025 will provide an updated understanding of Pacific halibut density in this subarea and inform future decisions on sampling frequency in IPHC Regulatory Area 4A. Note that several stations on the IPHC Regulatory Area 4A shelf edge overlap the NMFS bottom trawl survey (in purple in Figure 2, and are not proposed for FISS sampling in the foreseeable future.

In the most recent surveys of IPHC Regulatory Area 4B, the eastern subarea had by far the highest catch rates and is the priority for frequent sampling. The western and central subareas were approved for sampling in 2022, but only the central subarea is to be sampled due to a lack of charter vessel bids for the western subarea. Thus, the western subarea has been added to the 2023 proposal to reduce the risk of bias.

Following this three-year period, the only remaining waters unsampled since FISS rationalization began in 2020 will be:

- Zero-to-low density waters in IPHC Regulatory Area 2A comprising deep (>275 ftm) and shallow (<20 ftm) stations and northern California south of 40°N (sampled comprehensively in 2017), and low-density waters of the Salish Sea (previously sampled in 2018).
- Near-zero density waters in the Salish Sea in IPHC Regulatory Area 2B (sampled in 2018 only).

We anticipate proposing these stations for sampling in 2026-28, 9-10 years after previous FISS sampling, so that the entire 1890-station FISS grid will have been fished from 2020-28.

The design proposals again include full sampling of the standard FISS grid in IPHC Regulatory Area 4CDE. The Pacific halibut distribution in this area continues to be of particular interest, as it is a highly dynamic region with an apparently northward-shifting distribution of Pacific halibut, and increasing uncertainty regarding connectivity with populations adjacent to and within Russian waters. Ongoing oceanographic (e.g., sea ice and bottom temperatures) and ecosystem (e.g., prey species abundance and distribution) changes in this Regulatory Area highlight the potential for changes in the biology and abundance of Pacific halibut in the Bering Sea. Despite prioritizing comprehensive sampling of this Regulatory Area in 2020-22, in each year logistical challenges have precluded achieving the full design. Therefore, it is retained throughout the current three-year plan, to be re-evaluated when and if sampling is successful.

While the proposed designs continue to rely on randomised subsampling of stations within the core IPHC Regulatory Areas (2B, 2C, 3A and 3B) and logistically efficient subarea designs elsewhere, other designs have been considered and remain as options (Webster 2021, Appendix A).

FISS DESIGN EVALUATION

Precision targets

In order to maintain the quality of the estimates used for the assessment, and for estimating stock distribution, the IPHC Secretariat has set a target range of less than 15% for the coefficient of variation (CV) of mean O32 and all sizes WPUE for all IPHC Regulatory Areas. We also established precision targets of IPHC Biological Regions and a coastwide target (IPHC-2020-AM096-07), but achievement of the Regulatory Area targets is expected to ensure that targets for the larger units will also be met.

Reducing the potential for bias

In IPHC Regulatory Areas in which stations are not subsampled randomly (IPHC Regulatory Areas 2A, 4A and 4B), sampling a subset of the full data frame in any area or region brings with it the potential for bias. This is due to trends in the unsurveyed portion of a management unit (Regulatory Area or Biological Region) potentially differing from those in the surveyed portion. Therefore, we also examine how frequently part of an area or region (subarea) should be surveyed in order to reduce the likelihood of appreciable bias. For this, we use a threshold of a 10% absolute change in biomass percentage: based on historical trends (1993-2021): how quickly can a subarea's percent of the biomass of a Regulatory Area change by at least 10%

(e.g., from 15 to 25% of the area's biomass)? By sampling each subarea frequently enough to reduce the chance of its percentage changing by more than 10% between successive surveys of the subarea, we minimize the potential for appreciable bias in the Regulatory Area's index.

We examined the effect of subsampling the FISS stations for a management unit on precision as follows:

- Where a randomised design is not used, identify logistically efficient subareas within each management unit and select priorities for future sampling.
- Generate simulated data for all FISS stations based on the output from the most recent space-time modelling.
- Fit space-time models to the observed data series augmented with 1 to 3 additional years of simulated data, where the design over those three years reflects the sampling priorities identified above.
- Project precision estimates and quantify bias potential for comparison against threshold.

Table 2 shows projected CVs following completion of the proposed 2022-25 FISS designs. With these designs, we are projected to maintain CVs within the target range. Estimates from the terminal year are most informative for management decisions, but they also typically have the largest CVs (all else being equal; these are then reduced in subsequent years as observations are available in both adjacent years, due to the temporal correlation). The final column in Table 2 shows the CV projections immediately following the 2023 FISS, which are also within the target range.

Table 2. Projected CVs (%) for 2022-25 for O32 WPUE estimated after completion of the proposed 2023-25 FISS designs, and (final column) after completion of the proposed 2023 FISS design only.

Reg. Area	2022	2023	2024	2025	2023 (Estimated in 2023)
2A	13	12	13	15	14
4A	10	9	10	10	12
4B	12	9	10	12	9

For maintaining low bias, we looked at estimates of historical changes in the proportion of biomass in each subarea, and used that to guide the sampling frequency in future designs. Thus, subareas that have historically had rapid changes in biomass proportion need to be sampled most frequently, and those that are relatively stable can be sampled less frequently. For example, if a subarea's % of its Regulatory Area's biomass changed by no more than 8% over 1-2 years but by up to 12% over three years, we should sample it at least every three years based on the 10% criterion discussed above. These criteria are updated as new data are collected and thus they respond to updates in our understanding of the rates of change occurring in each subarea.

Based on estimates from the historical times series (1993-2021) of O32 WPUE, the proposed designs for 2023-25 would be expected to maintain low bias by ensuring that it is unlikely that biomass proportions for all subareas change by more than 10% since they were previously sampled (Table 3). We note that the lack of sampling in the western subarea of IPHC Regulatory 4B in 2022 means that maximum change from the historical time series for this subarea was 13%, exceeding the 10% threshold. Sampling this historically-variable subarea in 2023 again reduces values to within 10%.

Table 3. Maximum expected changes (%) in biomass proportion since previous sampling of subareas that are unsampled in a given year, based on the estimated 1993-2021 time series.

Reg. Area	2022	2023	2024	2025
2A	9	9	9	9
4A	10	7	6	8
4B	13	5	8	10

Post-sampling evaluation for 2021

The evaluation of precision of proposed designs above is based on using simulated sample data generated under the fitted space-time model as data for future years. If observed data are more (or less) variable than those generated under the model, actual estimates of precision may differ from those projected from models making use of the generated data. Table 4 compares the estimates of the CV for mean O32 WPUE for the approved 2021 design based on using simulated data for 2021 and estimated from fitting the models including observed 2021 data. Only the three areas using subarea designs are included, as these are the only areas for which the design options under consideration have a strong influence on precision.

Table 4. Comparison of projected (in 2020) and estimated CVs (%) for O32 WPUE for 2021 by IPHC Regulatory Area.

Regulatory Area	2021 projected CV (%)	2021 estimated CV (%)
2A	15	18
4A	11	15
4B	14	18

Projected CVs in all three areas were lower than those estimated once the observed 2021 data were incorporated into the modelling, although the reasons differ among areas. The 2021 FISS in IPHC Regulatory Areas 4A and 4B did not complete all planned stations due to logistical issues, with 10 out of 59 stations unfished in the former area and 36 out of 73 unfished in the latter. In both areas, the unfished stations covered some of the most productive habitat in recent years. The difference between projected and estimated CVs in IPHC Regulatory Area 2A appears due to an increase in the underlying variability of Pacific halibut density, which is the main factor leading us to recommend increasing the number of targeted stations in this area in

2023 relative to the provisional 2023 proposal made in 2021 (Webster 2021). (Projected CVs were not calculated for other IPHC Regulatory Areas as they are not at present used to evaluate design proposals. Estimated CVs for O32 WPUE for the core IPHC Regulatory Areas of 2B, 2C, 3A and 3B ranged from 4-8% in 2021, with a CV of 10% in IPHC Regulatory 4CDE. With high numbers of proposed stations in each area, CVs will remain well within the target range under proposed designs.)

CONSIDERATION OF COST

Ideally, the FISS design would be based only on scientific needs. However, some Regulatory Areas are consistently more expensive to sample than others, so for these the efficient subarea designs were developed. The purpose of factoring in cost was to provide a statistically efficient and logistically feasible design for consideration by the Commission. During the Interim and Annual Meetings and subsequent discussions, cost, logistics and tertiary considerations (Table 1) are also factored in developing the final design for implementation in the current year. It is anticipated that under most circumstances, cost considerations can be addressed by adding stations to the minimum design proposed in this report. In particular, the FISS is funded by sales of captured fish and is intended to have long-term revenue neutrality, meaning that any design must also be evaluated in terms of the following factors:

- Expected catch of Pacific halibut
- Expected Pacific halibut sale price
- Charter vessel costs, including relative costs per skate and per station
- Bait costs
- IPHC Secretariat administrative costs

Balancing these factors may result in modifications to the design such as increasing sampling effort in high-density regions and decreasing effort in low density regions. At present, with stocks near historic lows and extremely low prices for fish sales, the current funding model may require that some low-density habitat be omitted from the design entirely (as occurred in 2020). This will have implications for data quality, particularly if such reductions in effort relative to proposed designs continue over multiple years. Note that this did not occur in the 2021 and 2022 designs, as it was sufficient to include additional stations in core IPHC Regulatory Areas to generate a revenue-neutral coastwide design.

SRB REQUESTS

At SRB018 (IPHC-2021-SRB018-R), the SRB made the following requests:

SRB018–Req.1 (para. 13) The SRB **REQUESTED** plots by survey area of WPUE vs. depth from both FISS and commercial fisheries to help understand if there is part of the Pacific halibut stock in deeper waters not covered by the FISS.

SRB018–Req.2 (para. 14) The SRB **REQUESTED** that the IPHC Secretariat conduct a preliminary comparison, to be presented at SRB020, between male, female, and sex-aggregated analysis of the FISS data using the spatial-temporal model.

We examined data from commercial sets in our database from the last ten years (2012-21) for the May-September period in which the FISS is undertaken. Very few sets (36) are recorded with mean depths greater than the 732 m (400 ftm) depth limit of the FISS. Several are within IPHC Regulatory Areas 2C and 3A, at locations that are encompassed by the existing FISS grid (i.e., there is no gap in FISS coverage due to locally deep waters). The largest cluster of sets (15) occurs in western IPHC Regulatory Area 4A. We note that the proportion of commercial catch recorded in waters deeper than 732 m is 0% or near 0% in all areas and years except for IPHC Regulatory Area 4A in 2013 (1.3% of catch in that year).

Figure 5 plots mean commercial CPUE for 2012-21 by 50 fathom depth bins and area. Points based on data from fewer than three vessels are omitted for reasons of confidentiality. Sets with depth over 732 m (400 fathoms) are aggregated into a 400+ fathom bin, plotted at 425 fathoms on the figure.

Mean all sizes WPUE from observed FISS data for 2012-21 is shown in Figure 6. Again, means are computed for 50-fathom depth bins. In all areas except IPHC Regulatory Area 2C, WPUE drops to zero at or shallower than the final depth bin. The IPHC Regulatory Area 2C mean for the 350-400 fathom bin is based on just two observations, both from the same station off southeast Baranov Island, with no potential unsampled stations on the FISS 10 nmi grid in deeper water nearby.

The commercial data show some evidence for Pacific halibut presence in deeper waters than those covered by the FISS in IPHC Regulatory Areas 2C, 3A and 4A. As noted above, mapping of these commercial sets shows that in IPHC Regulatory Areas 2C and 3A these waters are encompassed by existing FISS stations: in the case of IPHC Regulatory Area 3A, almost all sets are in a localized area of deeper waters in Prince William Sound surrounded by FISS stations, while a couple of others are on the Gulf of Alaska shelf edge, also close to existing FISS stations. It is only the IPHC Regulatory Area 4A data that suggest the possibility of habitat missed by the FISS, with the potential for adding up to two deeper stations off the north coast of Umnak Island. (Note that to preserve confidentiality of commercial data, plots of individual set locations are not included here.) However, we note the following:

- Commercial fishers may be targeting known but isolated locations of Pacific halibut in patchy habitat that may easily be missed by an expanded 10 nmi FISS grid
- They may also be targeting the easiest to access locations – any consideration of a further FISS expansion should include sampling waters deeper than 732 m throughout an expanded grid to avoid the potential for bias
- At least some of the commercial sets cross the 732 m contour, and it is possible the catch was taken at depths shallower than 732 m
- The number of additional stations in deeper waters is likely to be extremely small, as these depths comprise a very narrow band on the shelf edge, and thus the impact on overall mean WPUE is likely to be minimal
- The magnitude of any gain in coverage and potential reduction in bias will need to be balanced by the high cost and logistical difficulty of fishing in deeper waters in IPHC Regulatory Area 4A

Regarding the second request, we note there are some limitations with the sex information from the FISS. For fish under the commercial size limit of 81.3 cm (32”), only a subsample is selected for biological sampling, and for larger areas, the sampled fish represent only a very small proportion of all under 81.3 cm fish. We therefore limit our analysis to O32 fish, which results in less information on the male population, which due to their much slower growth are more greatly represented among the U32 fish. Furthermore, sex information is missing from about 5% of the O32 Pacific halibut overall, including over 100 sets with no sex data in the early years of the time series (1993-96). In the years 2003-04, there are very high rates of fish with unknown sex, up to almost 40% depending on area compared to <2% in a typical year.

In our preliminary analysis, we modelled data from IPHC Regulatory Area 3A. With the caveats above in mind, Figure 7 compares trends in O32 WPUE by sex with the overall trend previous estimated, for IPHC Regulatory Area 3A, as estimated through three separate spatio-temporal models. Trends in both sexes are similar, noting the gaps in sex-specific information identified above. However, examination of maps of the Gaussian spatial random field (the spatially correlated model residuals), show differences in the distributions of female and male fish. Figure 8 shows that while female O32 fish are distributed across the Regulatory Area, males are more highly concentrated in the west. Maps for other years will be made available as part of the accompanying presentation.

RECOMMENDATIONS

That the SRB:

1) **NOTE** paper IPHC-2022-SRB020-05 that provides background on and a discussion of the IPHC fishery-independent setline survey design proposals for the 2023-25 period;
2) **ENDORSE** the 2023 FISS design as presented in Figure 2, and
3) Provisionally **ENDORSE** the 2024-25 designs (Figures 3 and 4), recognizing that these will be reviewed again at subsequent SRB meetings.

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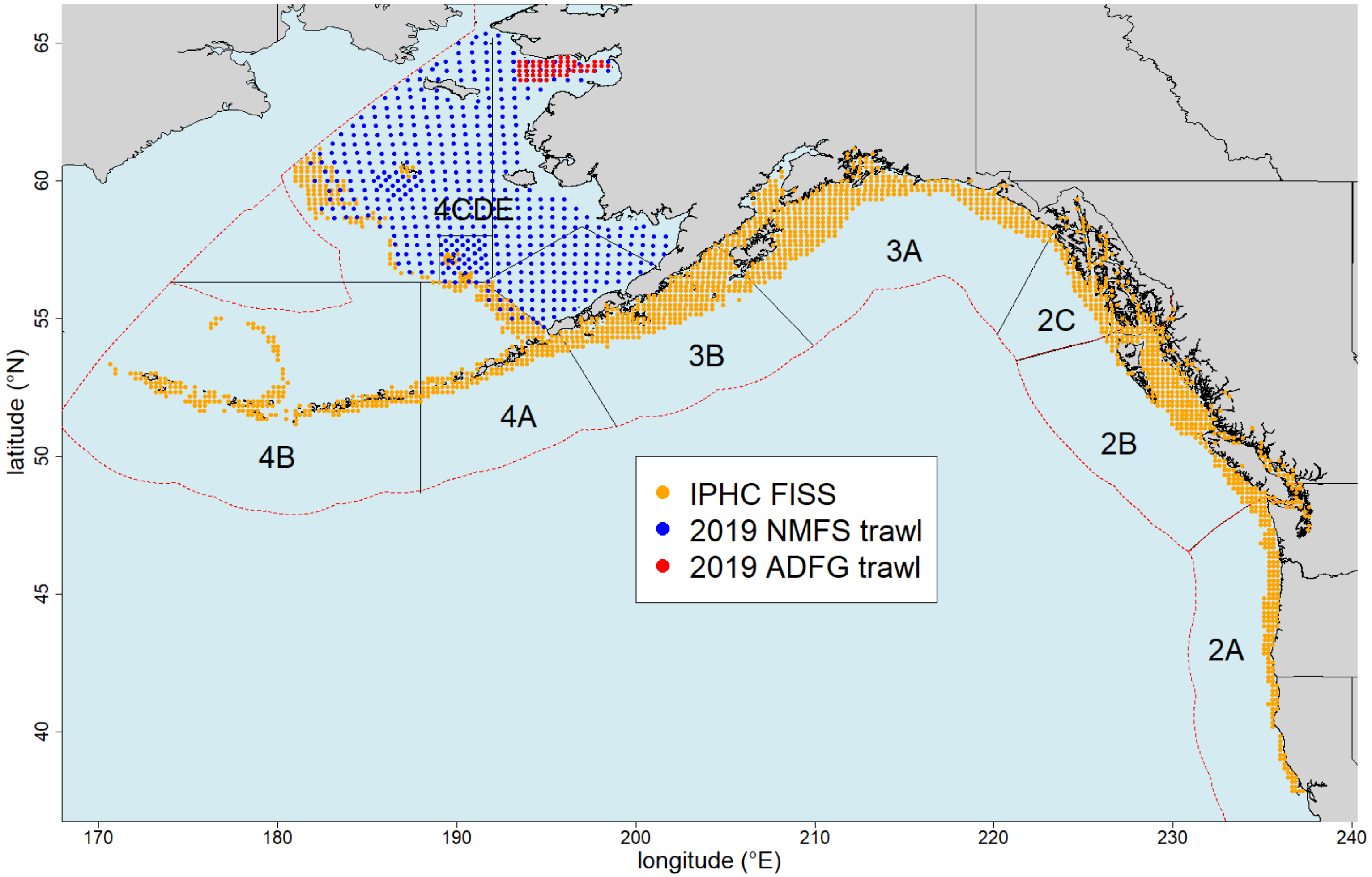

Figure 1. Map of the full 1890 station FISS design, with orange circles representing stations available for inclusion in annual sampling designs, and other colours representing trawl stations from 2019 NMFS and ADFG surveys used to provide complementary data for Bering Sea modelling.

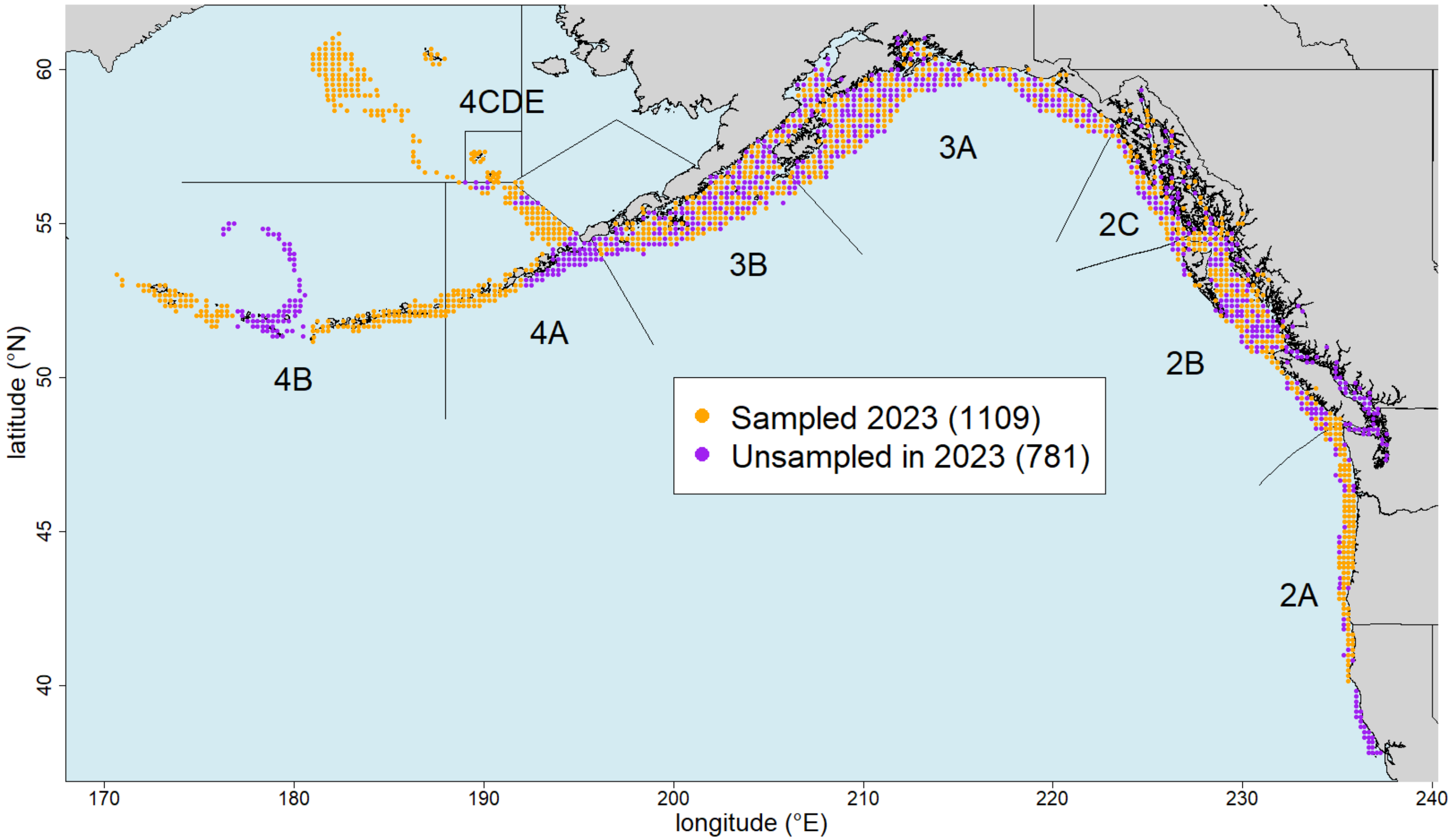

Figure 2. Proposed minimum FISS design in 2023 (orange circles) based on randomized sampling in 2B-3B, and a subarea design elsewhere. Purple circles are optional for meeting data quality criteria.

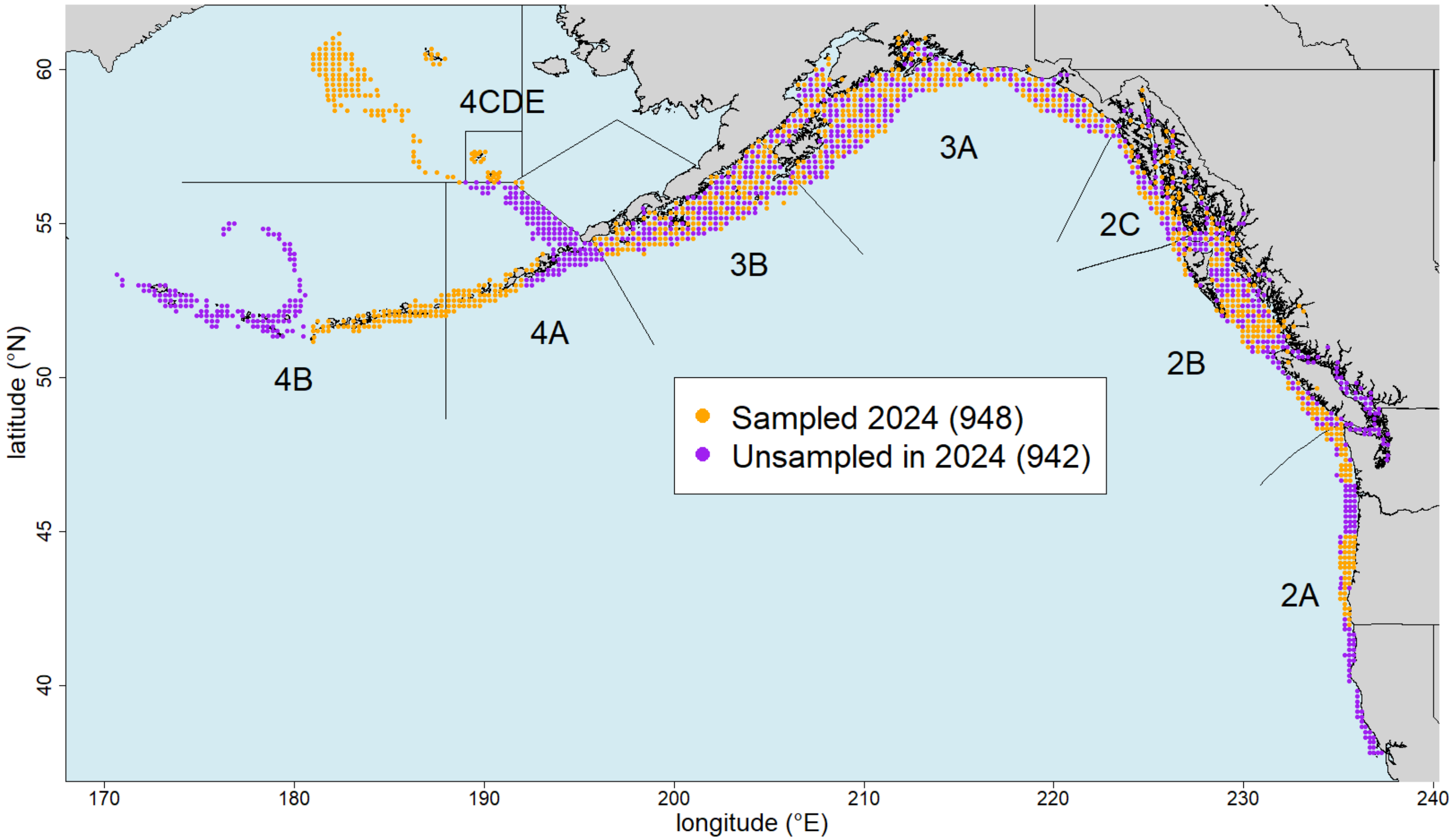

Figure 3. Proposed minimum FISS design in 2024 (orange circles) based on randomized sampling in 2B-3B, and a subarea design elsewhere. Purple circles are optional for meeting data quality criteria.

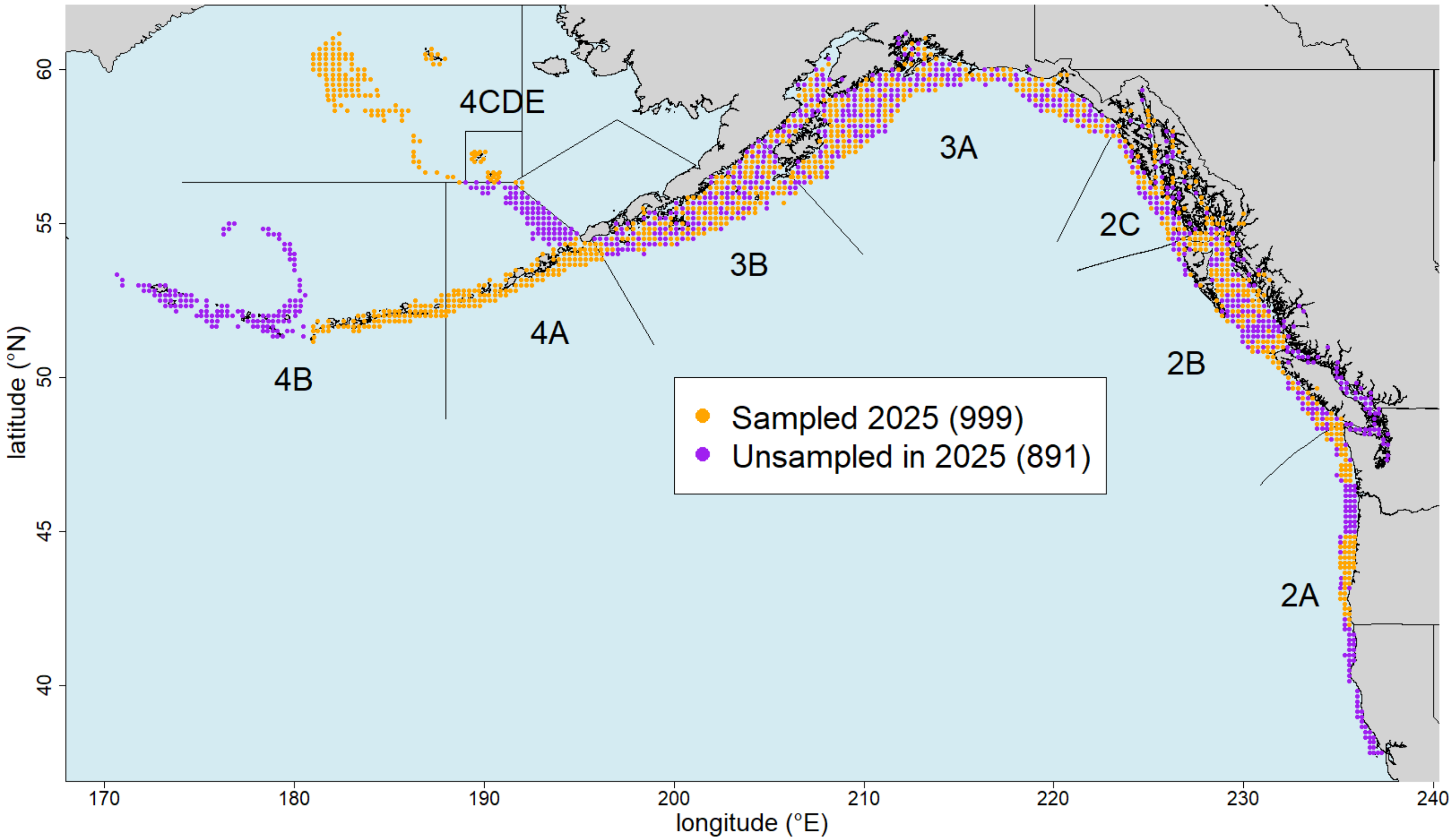

Figure 4. Proposed minimum FISS design in 2025 (orange circles) based on randomized sampling in 2B-3B, and a subarea design elsewhere. Purple circles are optional for meeting data quality criteria.

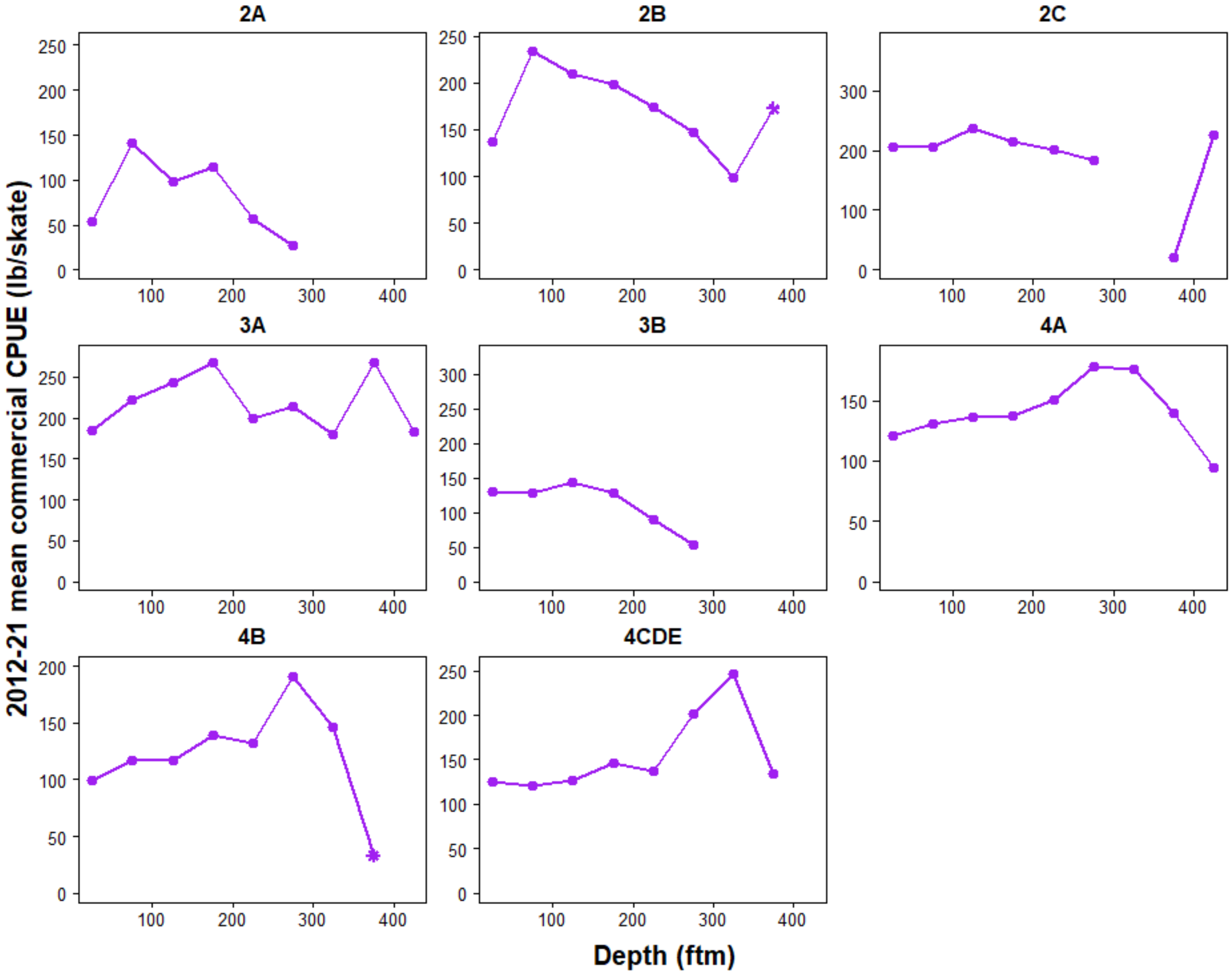

Figure 5. Mean commercial CPUE by IPHC Regulatory Area for 2012-21 calculated from logbook data binned into 50 fathom depth bins. Means based on fewer than five sets are indicated with star symbols, while those based on data from fewer than three vessels are omitted.

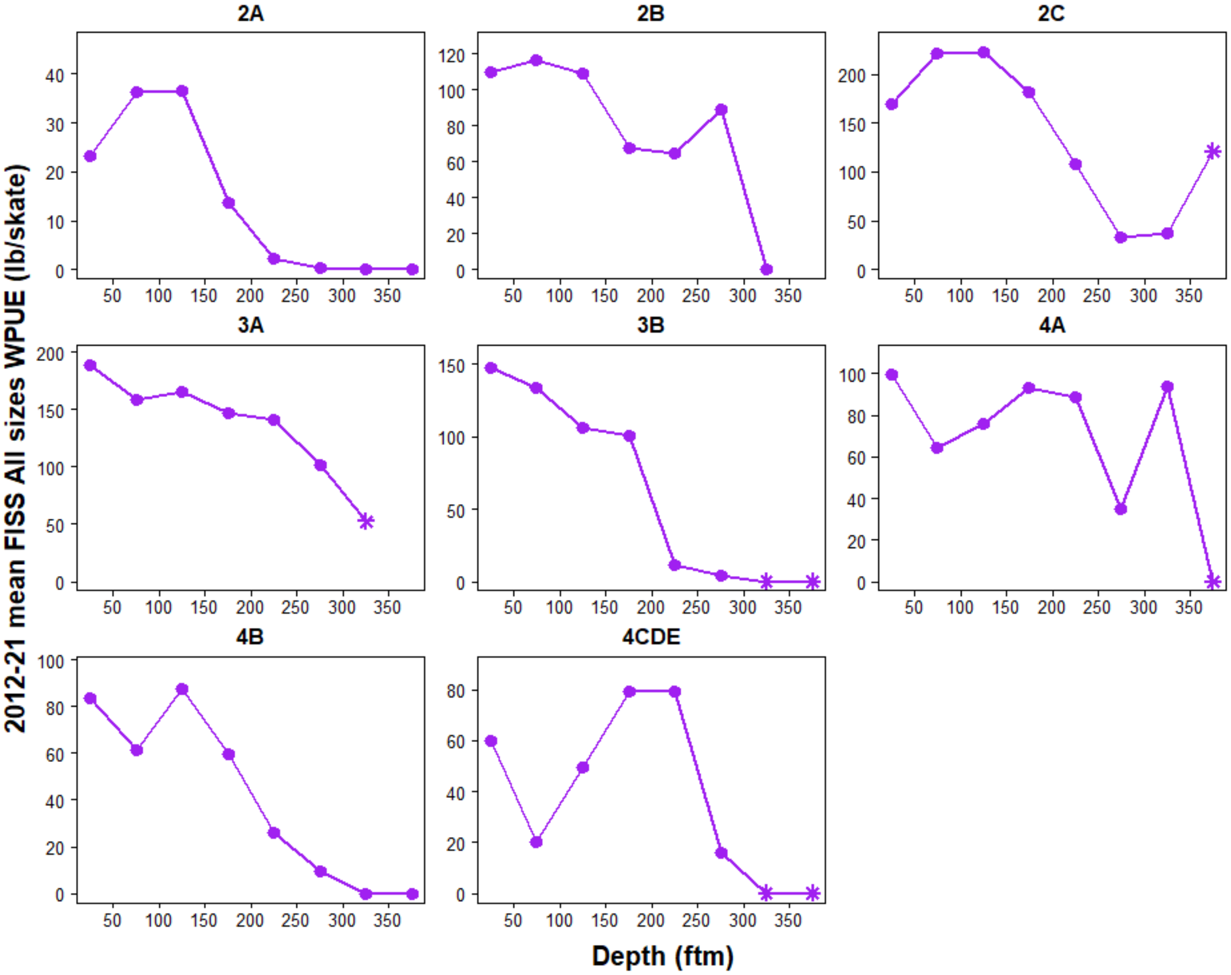

Figure 6. Mean FISS all sizes WPUE by IPHC Regulatory Area for 2012-21 calculated from observed data binned into 50 fathom depth bins. Means based on fewer than five sets are indicated with star symbols.

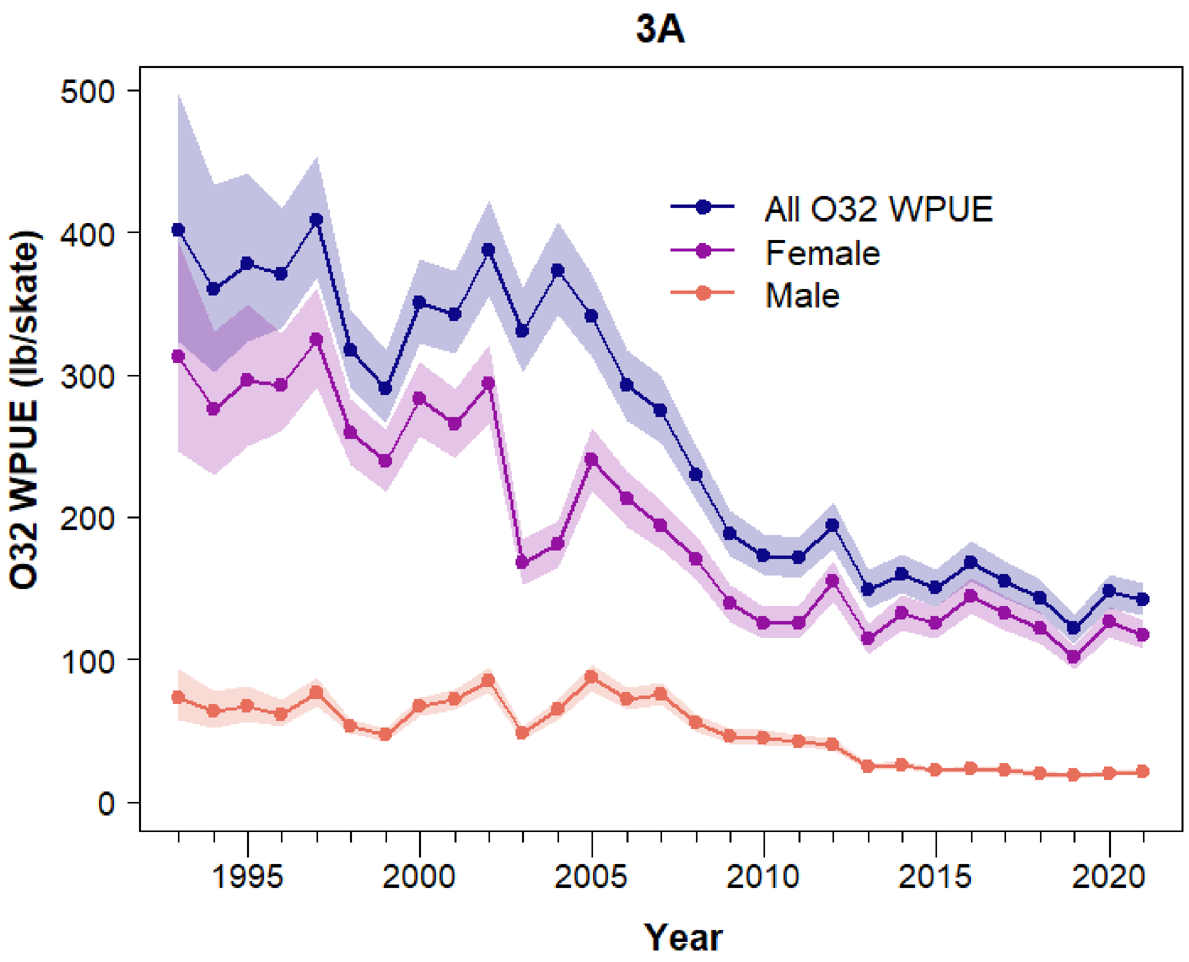

Figure 7. Posterior means (points) and 95% posterior credible intervals (shaded regions) for O32 WPUE for IPHC Regulatory 3A from 1993-2021, for all fish (blue) and those with known sex (purple = females, orange = males).

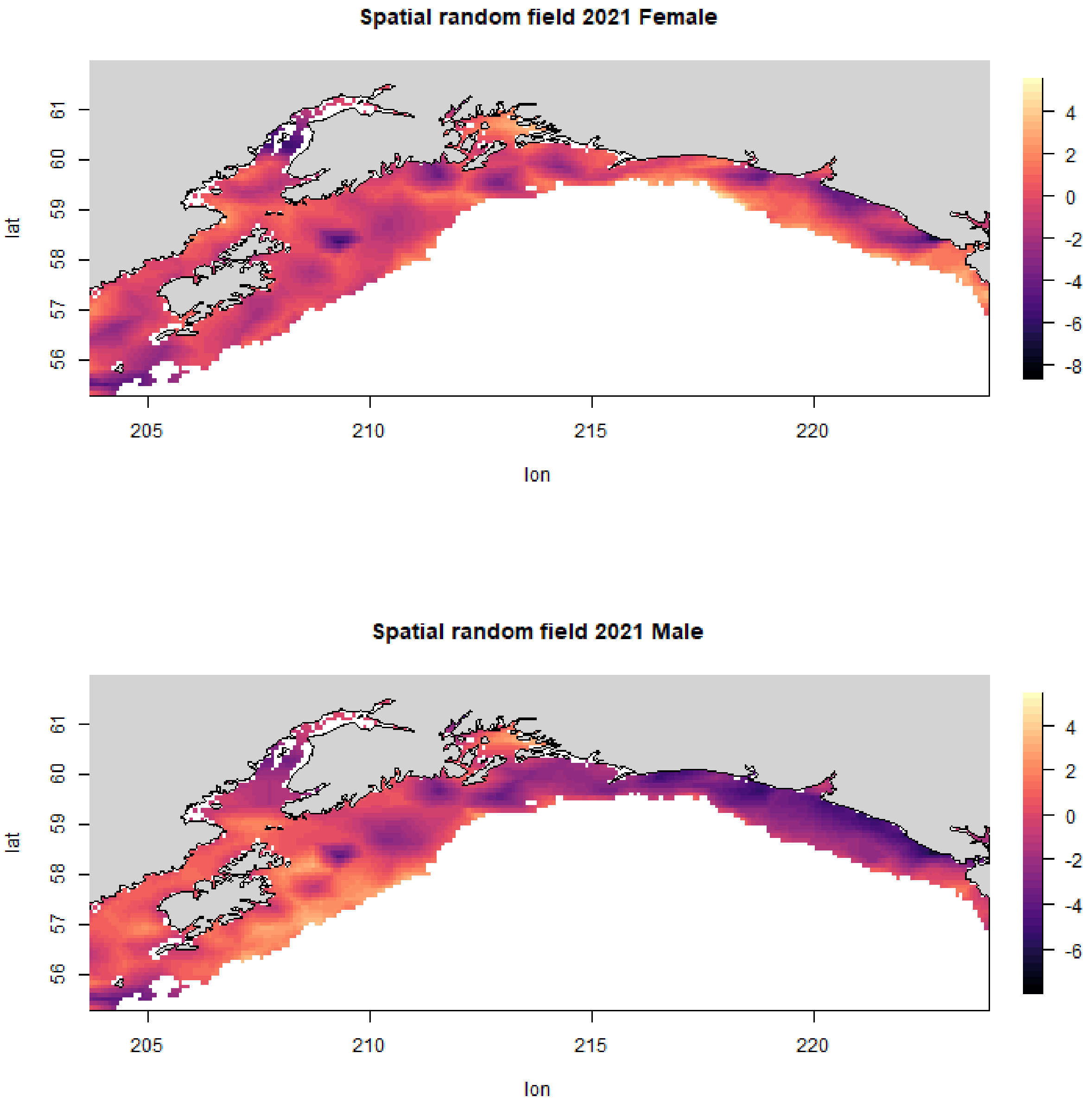

Figure 8. Posterior values of the spatial random field from space-time modelling of female (top panel) and male (bottom panel) Pacific halibut for IPHC Regulatory Area 3A in 2021. Units are log(lb/skate).

IPHC Secretariat MSE Program of Work (2022–2023) and an update on progress

PREPARED BY: IPHC SECRETARIAT (A. HICKS & I. STEWART; 2 MAY & 1 JUNE 2022)

PURPOSE

To provide the Scientific Review Board (SRB) with an update of progress on the Management Strategy Evaluation (MSE) program of work for 2022–2023.

1 INTRODUCTION

The current interim management procedure (MP) at the International Pacific Halibut Commission (IPHC) is shown in Figure 1.

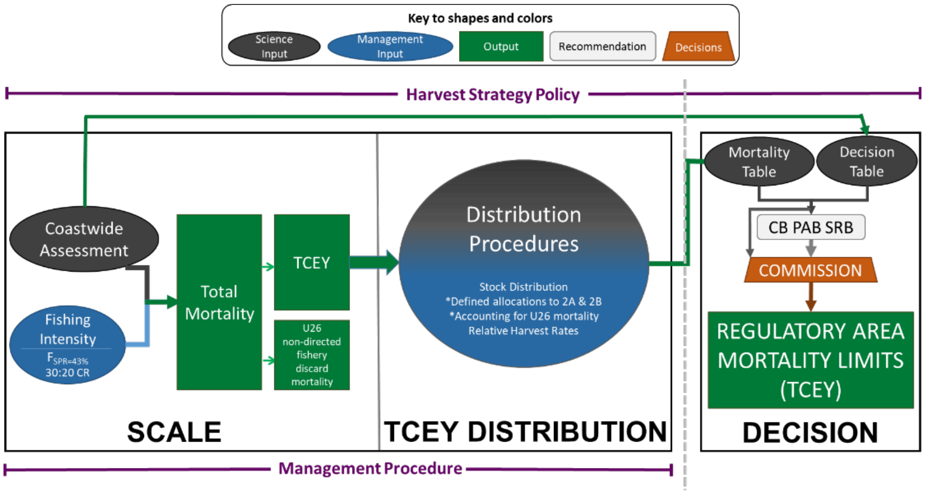

Figure 1. Illustration of the Commission interim IPHC harvest strategy policy (reflecting paragraph ID002 in IPHC-2020-CR-007) showing the coastwide scale and TCEY distribution components that comprise the management procedure. Items with an asterisk are interim agreements in place through 2022. The decision component is the Commission decision-making procedure, which considers inputs from many sources.

The Management Strategy Evaluation (MSE) at the IPHC completed an evaluation in 2021 of management procedures (MPs) relative to the coastwide scale and distribution of the Total Constant Exploitation Yield (TCEY) to IPHC Regulatory Areas for the Pacific halibut fishery using a recently developed closed-loop simulation framework. The development of this closed-loop simulation framework supports the evaluation of the trade-offs between fisheries management scenarios. Descriptions of the MPs evaluated and simulation results are presented in Hicks et al. (2021). Additional tasks were identified at the 11th Special Session of the IPHC (IPHC-2021-SS011-R) to supplement and extend this analysis for future evaluation (Table 1). Document IPHC-2021-MSE-02 contains details of the current MSE Program of Work.

Table 1. Tasks recommended by the Commission at SS011 (IPHC-2021-SS011-R para 7) for inclusion in the IPHC Secretariat MSE Program of Work for 2021–2023.

ID	Category	Task	Deliverable
F.1	Framework	Develop migration scenarios	Develop OMs with alternative migration scenarios
F.2	Framework	Implementation variability	Incorporate additional sources of implementation variability in the framework
F.3	Framework	Develop more realistic simulations of estimation error	Improve the estimation model to more adequately mimic the ensemble stock assessment
F.5	Framework	Develop alternative OMs	Code alternative OMs in addition to the one already under evaluation.
M.1	MPs	Size limits	Identification, evaluation of size limits
M.3	MPs	Multi-year assessments	Evaluation of multi-year assessments
E.3	Evaluation	Presentation of results	Develop methods and outputs that are useful for presenting outcomes to stakeholders and Commissioners

This document provides updates on the progress for the framework related tasks and the MP related tasks. Potential improvements to the evaluation and presentation of results are provided in this document and work will continue in 2022 with input from the MSAB.

2 CLOSED-LOOP SIMULATION FRAMEWORK

The closed-loop framework (Figure 2) with a multi-area operating model (OM) and three options for examining estimation error was initially described in Hicks et al. (2020b). Technical details are updated as needed in IPHC-2022-MSE-01 on the IPHC MSE webpage. Improvements to the framework have been made in accordance with this program of work and a new OM has been developed.

2.1 Development of a new Operating Model

The IPHC stock assessment (Stewart & Hicks 2022) consists of four stock synthesis models integrated into an ensemble to provide probabilistic management advice accounting for observation, process, and structural uncertainty. A similar approach was taken when developing the models for the closed-loop simulation framework along with some other specifications to improve the efficiency when conditioning models and running simulations.

2.1.1 General specifications of the OM

The emerging understanding of Pacific halibut diversity across the geographic range of its stock indicates that IPHC Regulatory Areas should be only considered as management units and do not represent relevant sub-populations (Seitz et al. 2017). Therefore, four Biological Regions (Figure 3) were defined with boundaries that matched some of the IPHC Regulatory Area boundaries (see Hicks et al 2020b for more description). The OM is a multi-regional model with population dynamics modelled within and between each Biological Region, and fisheries mostly operating at the IPHC Regulatory Area scale. Multiple fisheries within a Biological Region may have different selectivity and retention patterns to mimic differences similar to that of areas-as-fleets approach. Thirty-three fisheries were defined for five general sectors consistent with the definitions in the recent IPHC stock assessment:

- **directed commercial** representing the O32 mortality from the directed commercial fisheries including O32 discard mortality (from lost gear or regulatory compliance);
- **directed commercial discard** representing the U32 discard mortality from the directed commercial fisheries, comprised of Pacific halibut discarded due to the minimum size limit;
- **non-directed commercial discard** representing the mortality from incidentally caught Pacific halibut in non-directed commercial fisheries;
- **recreational** representing recreational landings (including landings from commercial leasing) and recreational discard mortality; and
- **subsistence** representing non-commercial, customary, and traditional use of Pacific halibut for direct personal, family, or community consumption or sharing as food, or customary trade.

Additionally, there are four modelled surveys, one for each Biological Region.

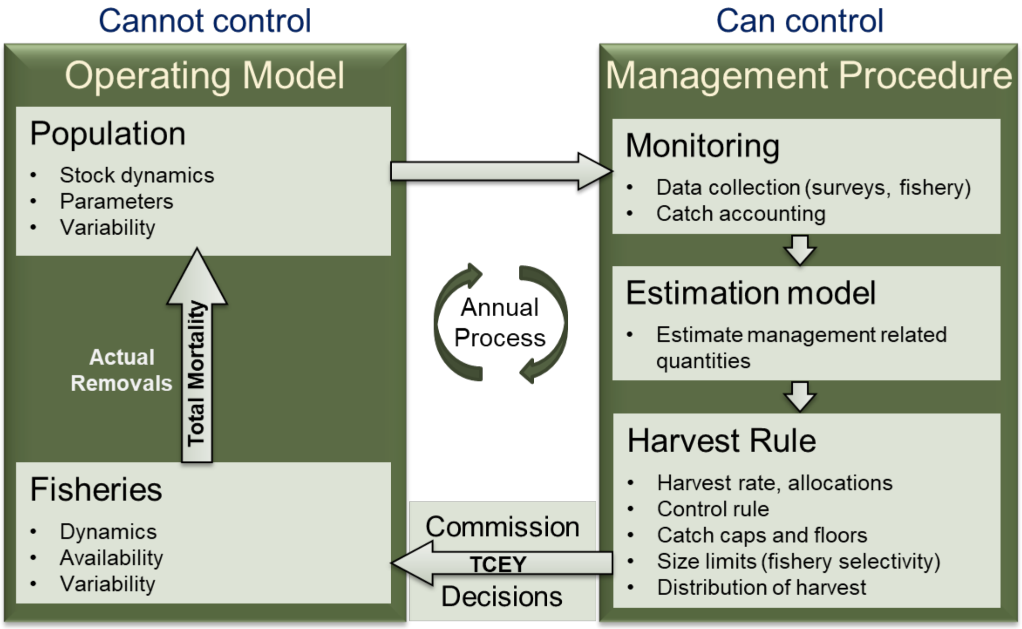

Figure 2. Illustration of the closed-loop simulation framework with the operating model (OM) and the Management Procedure (MP). This is the annual process on a yearly timescale.

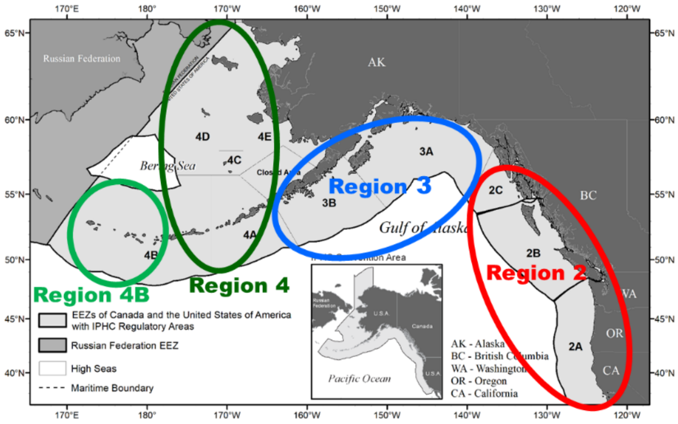

Figure 3. IPHC Regulatory Areas, Biological Regions, and the Pacific halibut geographical range within the territorial waters of Canada and the United States of America.

Two of the four models in the IPHC stock assessment (Stewart & Hicks 2022) consider a long time-series of observations beginning in 1888. One model specifies coastwide fisheries (called the coastwide (CW) long model) and the other model specifies four regions in an areas-as-fleets approach (called the areas-as-fleets (AAF) long model). The previous MSE OM also started in 1888 and simulated the entire time-series up to recent years before starting the forward simulations. However, the early portion of the time-series is challenging to model due to relatively little data, some significant catches in Biological Region 2, and the potential for unknown differences in population dynamics (e.g. movement between Biological Regions) compared to recent periods. To reduce the technical complexity and focus on information contained in the richer data set in the later period, the 2022 OM models were started in 1958. In order to allow for flexible starting conditions, 30 years of initial recruitment and an average fishing mortality were estimated for each fleet. This initialized the models after a bottleneck of potentially high fishing mortality in the 1930’s that is confounded with the estimation of movement, yet allowed for a sufficient period of time to burn-in the population such that projections began with at an appropriate state. The period from 1958 to the present includes major changes in fishery catches, weight-at-age in the population, and population size.

2.1.2 Conditioning the OM and incorporating variability

The OM was parameterised and conditioned using two methods, resulting in two models to be integrated into a single OM. The first model was parameterised from and conditioned to results from the long AAF stock assessment model. The second model was parameterised from and conditioned using results from the long CW stock assessment model. Because these two OM models started in 1958, they are called the medium AAF (medAAF) and medium CW (medCW) models.

Many parameters used in the OM models were drawn from the corresponding stock assessment model. Natural mortality was fixed in each model, separately for males and females. Maturity, mean weight-at-age, recruitment deviations, the relationship between R_0 and the Pacific Decadal Oscillation (PDO), selectivity, and fishing mortality were fixed at the values from the stock assessment.

Parameters estimated during conditioning included

- R_0: initial average recruitment for the low PDO period;
- multinomial logit parameters for recruitment distribution among Biological Regions: there are 6 parameters, 3 defining the proportion among Biological Regions and 3 adjusting those parameters in high PDO years to change the distribution of age-0 recruits;
- a multiplier on initial fishing mortality: increased or decreased the initial fishing mortality input to initialize the population;
- movement from Biological Region 4 to Biological Region 3 (5 parameters) and movement from Biological Region 3 to Biological Region 2 (5 parameters), which were estimated for low PDO and high PDO periods (thus 20 total parameters).

There is considerable confounding between the recruitment distribution and movement parameters (which was evident during the conditioning process), thus some parameters for movement between Biological Regions were fixed at values estimated from previous analyses (see Figure 3 in Hicks et al 2020). The previous OM estimated considerably higher movement rates-at-age from region 2 back to region 3, which was unexpected. Fixing movement from 2 to 3 at values estimated directly from data resulted in more stable estimation with similar outputs.

The models were conditioned to five general sources of information:

- Historical spawning biomass estimated from the corresponding stock assessment. For example, the medAAF model was conditioned to the spawning biomass estimates from 1958 to 1992 from the 2021 long AAF stock assessment model.
- Recent ensemble spawning biomass from the corresponding spatial structure of the stock assessment. For example, the medCW model was conditioned to the spawning biomass estimates from 1993 to 2021 from the integration of the 2021 long CW and short CW stock assessment models.
- Fishery Independent Setline Survey (FISS) indices of abundance for each Biological Region.
- FISS estimates of proportions-at-age for each Biological Region. This component was downweighted compared to other components.
- Proportion of all-sizes weight-per-unit-effort (WPUE) in each Biological Region from the space-time model analysis of FISS observations. This is also called stock distribution and was given the highest weight as this is an important component for the OMs to mimic.

The conditioning was heavily weighted to the stock distribution and spawning biomass components. The goal was to have models adequately predicting stock distribution and spawning biomass in recent years, with some variability.

Even though many parameters were fixed when conditioning the models, variability was propagated from the estimated as well as some fixed parameters. Variances and covariances of parameters estimated in the conditioning process were estimated from the inverse of the Hessian. However, due to multicollinearity and difficulty in finding optimal solutions when all parameters were estimated[1], some parameters were fixed to estimate the Hessian and then supplied a small variance. Variability and correlations for some parameters fixed in the conditioning process were estimated from the stock assessment. This included natural mortality for each sex, recruitment deviations, and steepness (the long stock assessment models were run with a broad prior on steepness only to determine variability in steepness through estimation of the Hessian). The covariance matrices from the conditioning and assessment models were combined without accounting for correlation in parameters between the two sources, but correlations between parameters were accounted for within each source.

The combined covariance matrix was used to sample from a truncated multivariate normal distribution to provide replicate parameter sets for each OM model, providing multiple trajectories from 1958 through 2021 for each model. Bounds were enforced on some parameters, hence the truncated multivariate normal distribution. For example, steepness was bounded between 0.6 and 0.98, probability parameters associated with movement parameterizations were bounded between 0 and 1, and the natural log of recruitment deviations were bounded between -4 and 4. In a few uncommon cases, the standard deviation of a parameter had to be reduced because it was often exceeding a bound (e.g. probability parameters near zero). Parameter sets that resulted in unrealistically low population sizes or extremely poor fits to stock distribution or spawning biomass were rejected. The likelihood thresholds were arbitrarily based on visual fits to the data and investigation of outputs at various likelihood values. This is required because some correlations between parameters are not accounted for that could result in unrealistic combinations.

2.1.3 OM results and outputs

The two OM models showed important structural differences in terms of movement rates-at-age, recruitment distribution, and historical spawning biomass trends. The long AAF and long CW stock assessment models, which are the basis for conditioning each OM model, estimate significantly different historical spawning biomass trajectories before the early 2000s and subtle differences in recent trajectories (Figure 4). These differences are attributable to the very different assumptions about how the stock was distributed and connected via movement in relation to historical fishing mortality, and it is important to capture these differences through movement in the OM.

The two OM models (medAAF and medCW) generally captured these trends in spawning biomass (Figure 5). The uncertainty in the OM also spanned the 2021 ensemble stock assessment uncertainty, except for the low spawning biomass values prior to 2007. Recent spawning biomass was similar between the OM and the stock assessment, with the OM exceeding the upper quantiles of spawning biomass slightly.

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[1] The function ‘optim’ was used in R with abrupt penalties enforced when spawning biomass was predicted below a small inconceivable value or when parameters were out of pre-specified bounds.

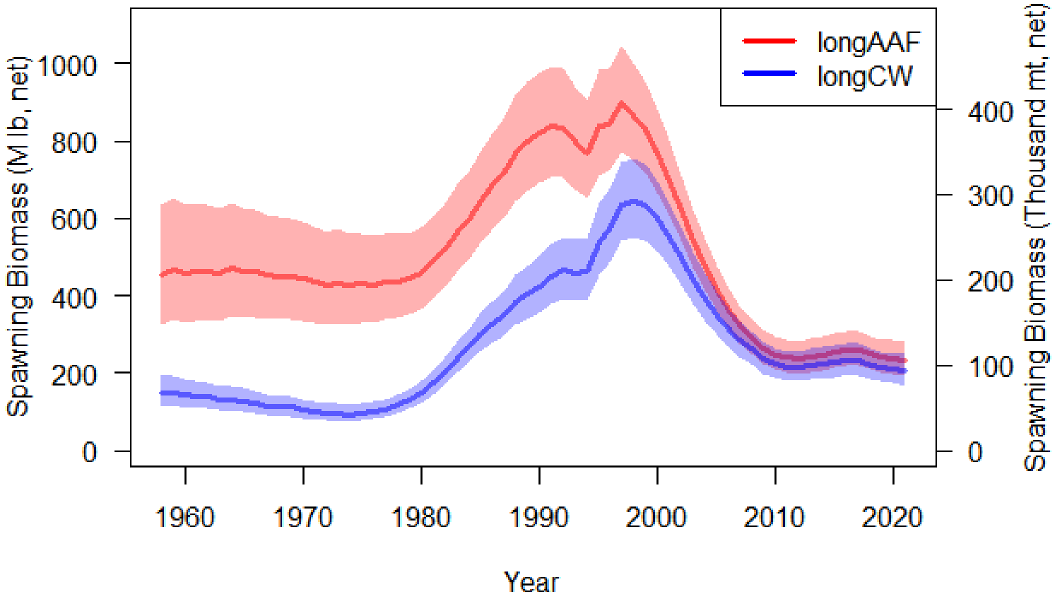

Figure 4. Estimated spawning biomass trajectories from 1958 to 2021 from the 2021 long AAF and long CW stock assessment models (Stewart & Hicks 2022).

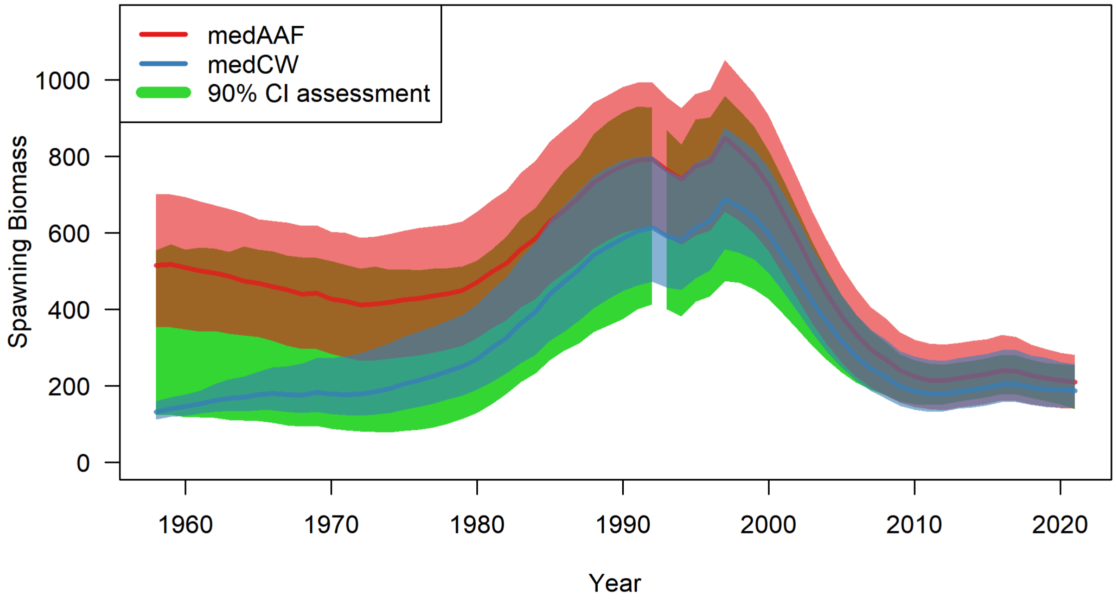

Figure 5. Median, 5th, and 95th quantiles for the medAAF OM model (red) and the medCW OM model (blue). The region between the 5th and 95th quantiles from the 2021 ensemble stock assessment are shown shaded in green.

Stock distribution was fit well by both OM models (Figure 6) and showed very similar patterns of lack of fit for both models in some years. Specifically, the earliest years in Biological Region 4 were overfit by the OM, and recent years overfit in Biological Region 3 corresponding with a slight underfitting in region 4. Both OMs predicted a faster increase in Biological Region 3 since 2018 than the data, but matched closely with the proportion of biomass observed in 2021.

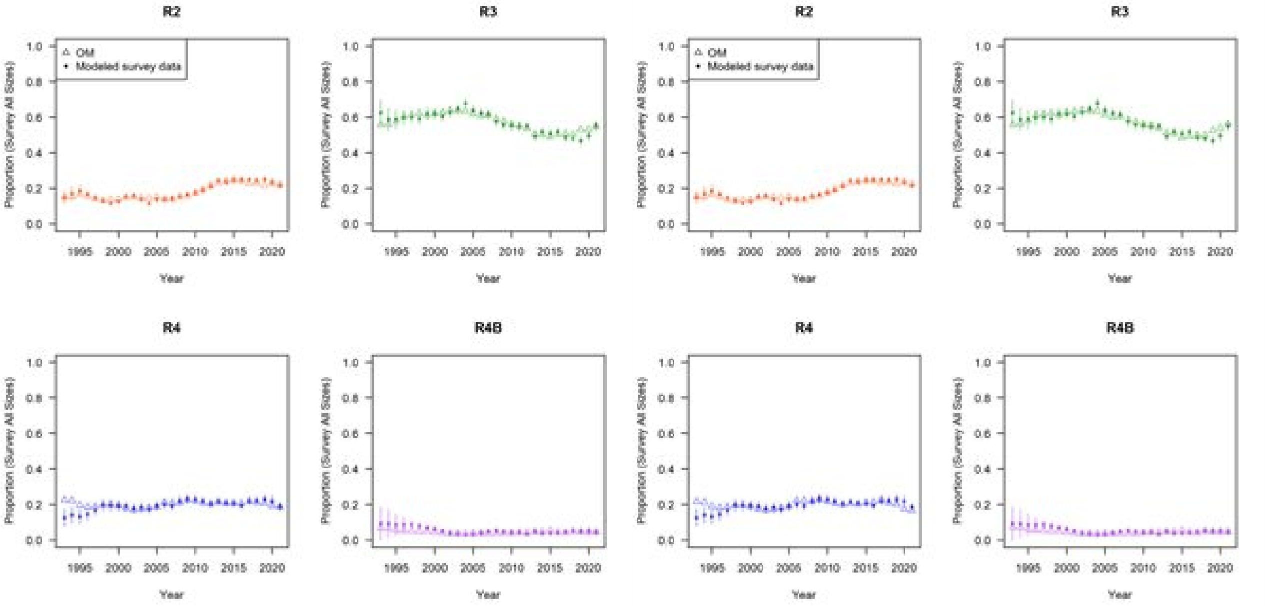

Figure 6. Fits to stock distribution across Biological Regions for each OM model (medAAF on the left and medCW on the right).

Distributions used for sex-specific natural mortality (*M*) and steepness were similar for the two models (Figure 7 and Figure 8). Female natural mortality did not encompass the value of 0.15, which was value fixed at in the two 2021 short stock assessment models, and an improvement to the OM may be to include models with lower *M* values. However, preliminary results from the development of the 2022 stock assessment (see IPHC-2022-SRB020-07) suggest that *M* may be estimated in the short AAF model, and the resulting value is greater than 0.15.

The distribution of age-0 recruits showed a high proportion going to Biological Region 4 in both low and high PDO regimes. Sadorus et al. (2020) found that recruits were more likely to end up in the Bering Sea in “warm years” for most spawning areas in the Gulf of Alaska. Furthermore, “cold years” were likely to have less dispersal to the west in the Bering Sea and “warm years” were more likely to have more dispersal to the northwest from spawning in the Western Gulf of Alaska. The medCW showed a higher proportion of recruits going to Biological Region 4 in high PDO years, but the medAAF model showed a slightly smaller proportion (Figure 9). The variability in the medCW model was smaller than in the medAAF model.

Movement rates between Biological Regions 3 and 2, and Biological Regions 4 and 3 were different between the two OMs (Figure 10). Both models generally showed high movement rates around ages 4 and 5 and slight differences between low and high PDO periods. Movement of fish younger than age 4 was very small from Biological Region 4 to 3 for both models and regimes, but there are few observations of fish younger than age 6 and a number of different movement rates of very young fish in combination with ages 4–7 could achieve similar results.

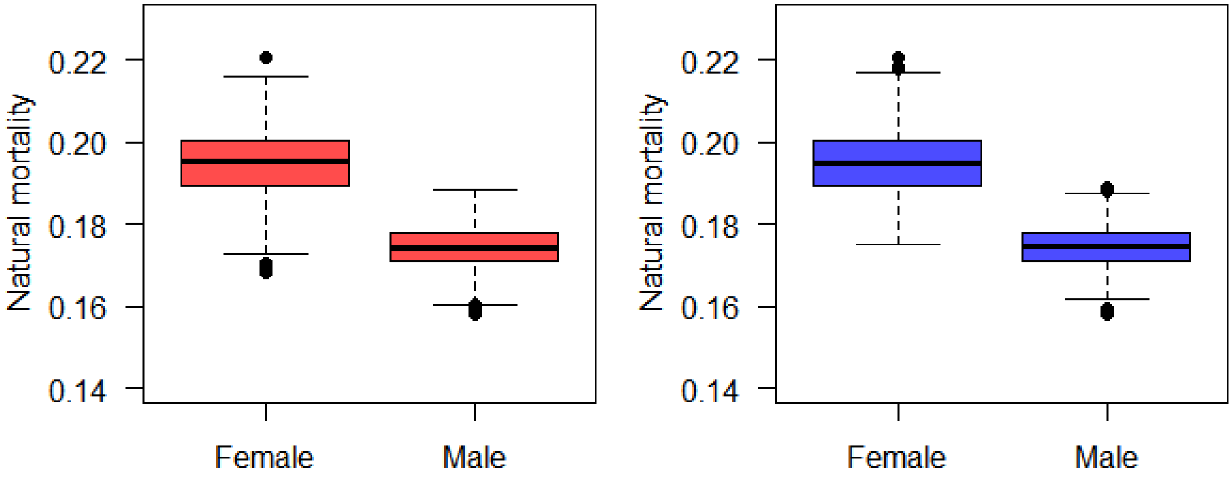

Figure 7. Natural mortality (*M*) distributions used to create multiple trajectories of the medAAF (left) and medCW (right) models.

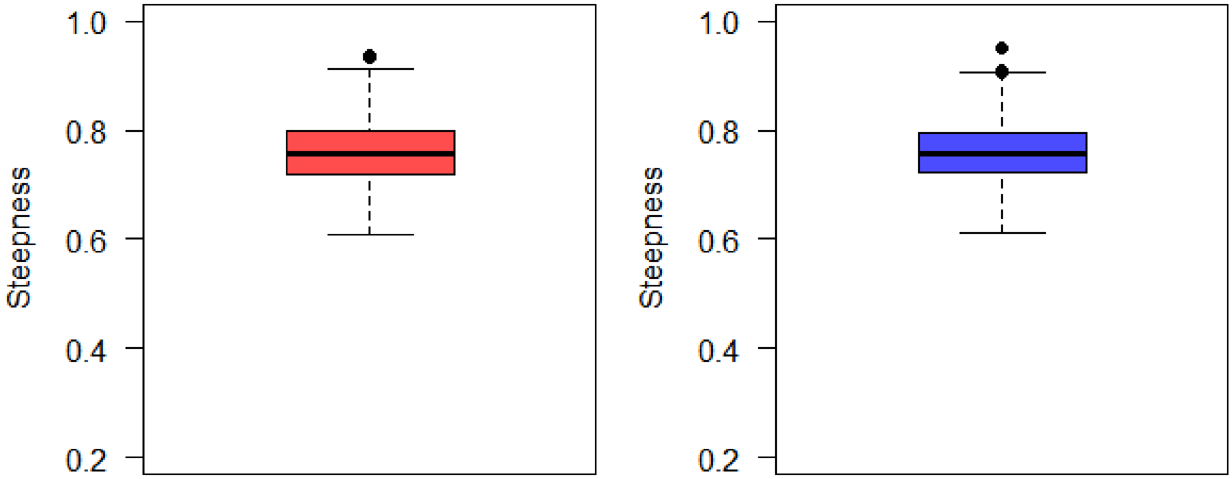

Figure 8. Steepness distributions used to create multiple trajectories in the medAAF (left) and medCW (right) models.

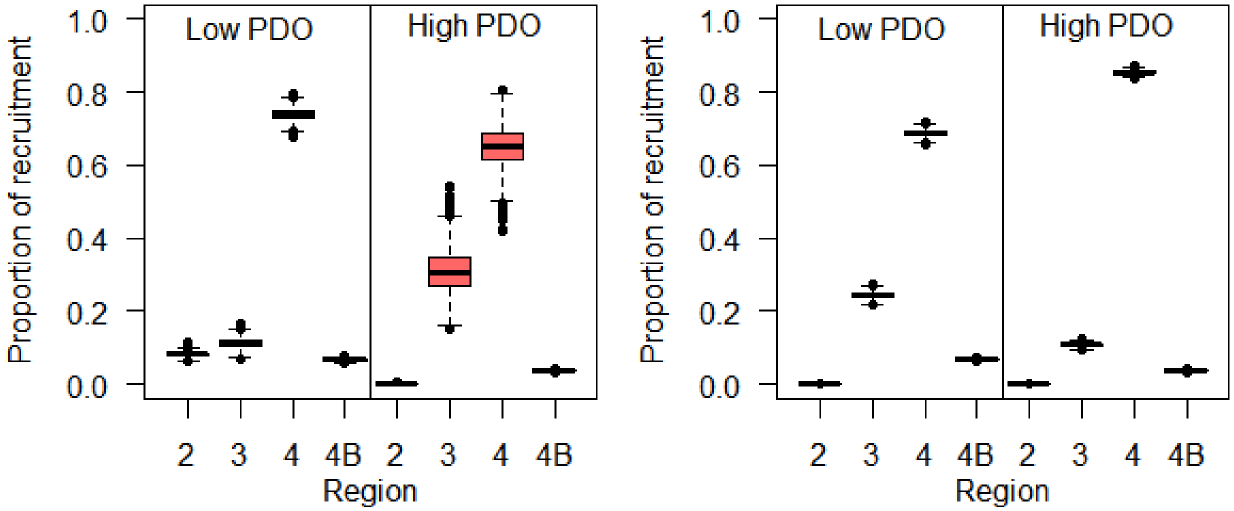

Figure 9. Proportion of recruits in each Biological Region for low and high PDO regimes for the medAAF model (left) and the medCW model (right).

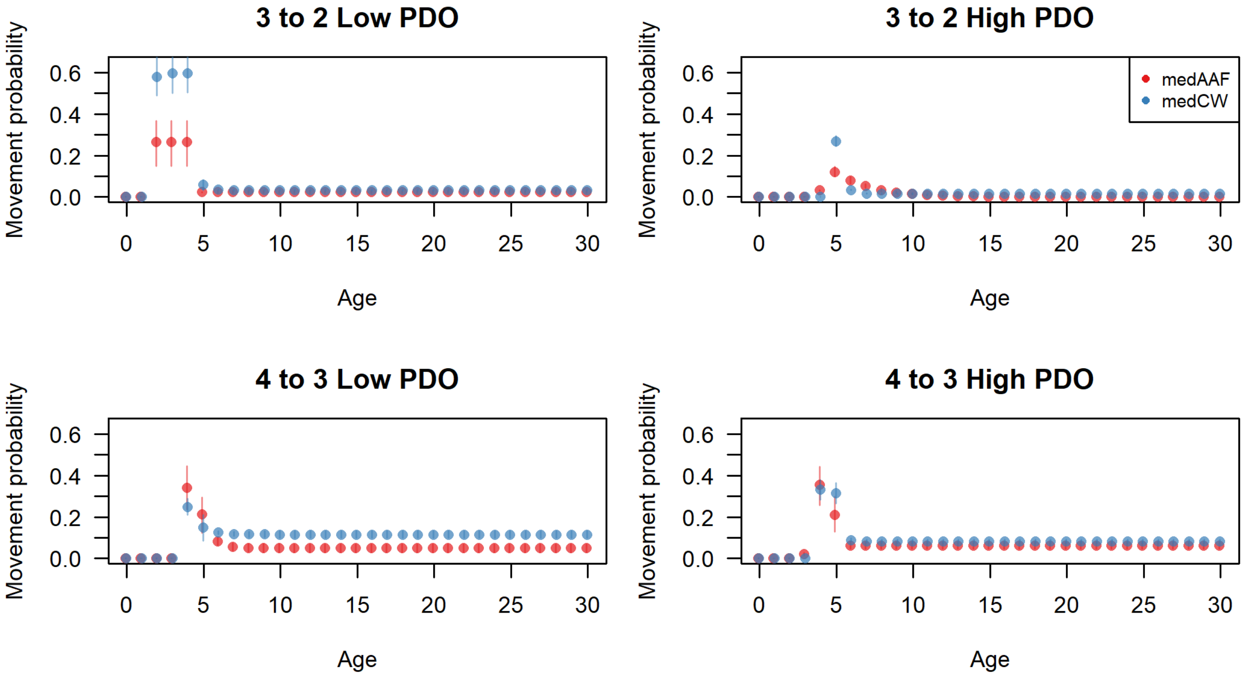

Figure 10. Probability of movement-at-age from Biological Region 3 to region 2 (top) and region 4 to region 3 (bottom) in low PDO (left) and high PDO (right) regimes for the two OM models.

2.2 Projections

The conditioned OM with multiple trajectories is the base of setting up the replicate projections. After which, they are left untouched as the closed-loop simulation projects forward in time using various management procedures (MPs). The simulation of weight-at-age, selectivity/retention deviations, and the environmental regime do not depend on the population dynamics and can be created ahead of time to save time in the simulations. Any of these processes could be dependent on the size of the population, or a certain demographic, and included in the simulation process.

2.2.1 Projected Weight-at-age

Historical weight-at-age varies substantially, and the projections capture that variation using an ARIMA(2,1,0) process that includes deviations from the previous two years. It is important to simulate time-varying weight-at-age because it is an influential contributor to the yield and scale of the Pacific halibut stock. This variability incorporates autocorrelation in a straightforward manner, is determined from past observations, and allows for slight departures between regions and fisheries. The method used to simulate weight-at-age is described in Hicks et al. (2020a) and the 2021 technical document (IPHC-2021-MSE-01).

2.2.2 Modeling discards

Pacific halibut have shown highly variable size- and weight-at-age over time. Studies on growth and analysis of length data continue, but recent population modelling of Pacific halibut has converted numbers-at-age to biomass using observed weight-at-age relationships directly, instead of using intermediate length-at-age calculations. The OM follows the direct weight-at-age method to avoid modelling the complexities of changing length-at-age relationships over time. However, this means that defining size-based quantities, such as needed for size limits or U26/O32 metrics, for example, must be approximated.

A size limit has been in place for directed commercial Pacific halibut fisheries for many decades (Myhre 1973), creating discard mortality which needs to be included in the population modelling. The historical period of the OM follows the same approach as the stock assessment by modelling observed directed discard mortality as a separate fleet. This approach is useful because it uses direct observations (or best estimates) of mortality, can use a separate mean weight-at-age vector which is likely to differ from the landings, and may be a better approach when discards are not directly related to the landings. However, the MSE Program of Work includes the investigation of size limits, and a separate fleet for modelling unknown discard mortality is not as convenient for long-term simulations under variable demographics.

We took the approach of using an age-based retention curve along with age-based selectivity to simulate future landings and discards. The OM does not model length-at-age, thus age-based processes, such as selectivity, must be modelled with deviations included to account for changes in size that may affect the age-based process (Stewart & Martell 2014). Therefore, an approximation must be made to determine retention given changes in size (i.e. weight-at-age).

Using recently reanalysed length-weight relationships (Webster & Stewart 2022) we determined the mean length-at-age given the projected population weight-at-age. Additionally, length-at-age from FISS samples were used to determine an average coefficient of variation (CV) for the variability of length-at-age for each sex separately (0.16 and 0.11 for females and males, respectively). Calculating the proportion of the length-at-age distribution greater than the size limit (1–CDF) provides the probability of retention-at-age (Figure 11).

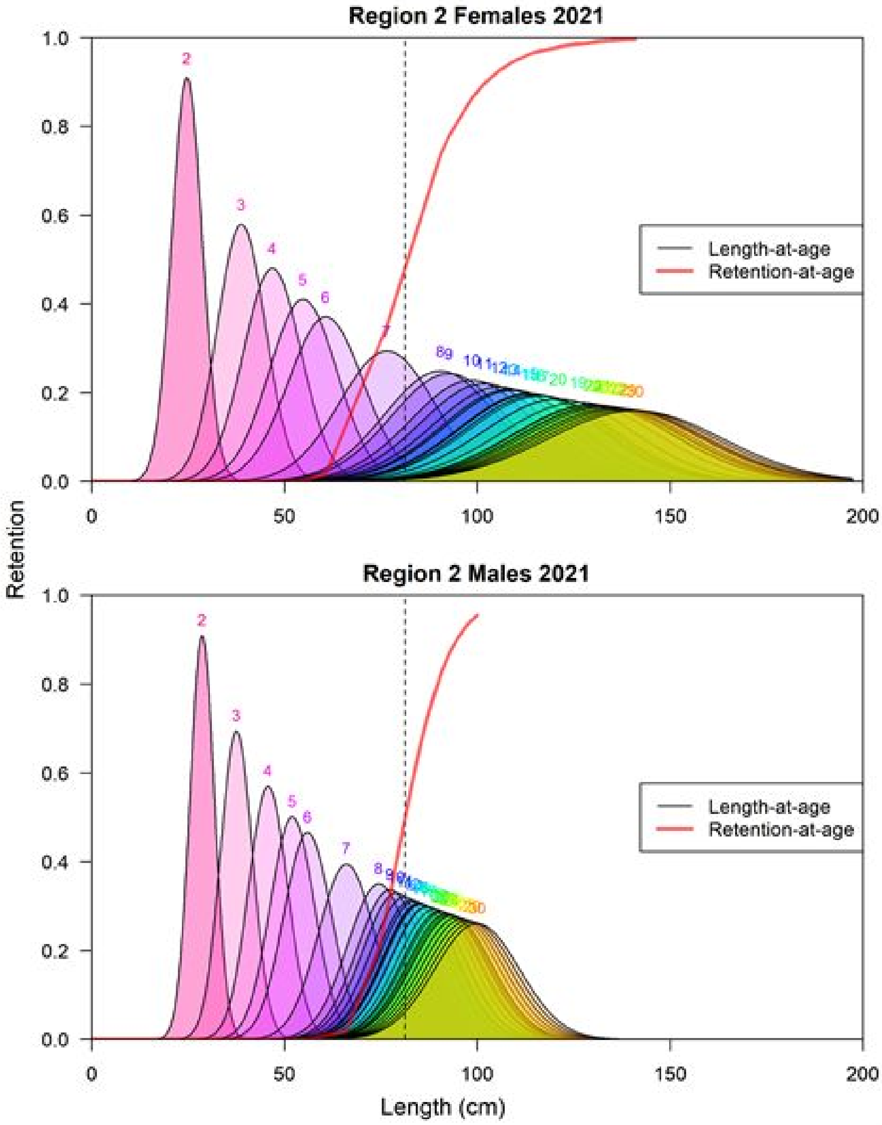

Figure 11. Distributions of length-at-age for females (top) and males (bottom) in Biological Region 2 determined from mean weight-at-age in 2021, length-weight relationships, and coefficients of variation equal to 0.16 and 0.11 for females and males, respectively. The dashed vertical lines represent a size limit at 81.3 cm. The red line is a retention-at-age curve based on the proportion of fish above 81.3 cm in each distribution (noting that the red line does not correspond to the x-axis, but instead the age represented by the peak of each distribution).

Retention-at-age, combined with selectivity-at-age, can separate landings and discards in the OM. However, selectivity in this context encompasses discarded and retained fish, which is not determined in the stock assessment. Fortunately, landings are the product of selectivity-at-age and retention-at-age, which is called 'keep-at-age' here, and the directed commercial fisheries model only landings, thus use keep-at-age. Dividing keep-at-age (from directed commercial fleets) by retention-at-age (from length-at-age distributions and length-weight relationships) determines selectivity-at-age for a fleet that models retention (landings) and discards. O32 discards are a small component of the directed commercial fleet that can be accounted for by reducing the asymptote of the retention curve.

The above method was used to determine selectivity and retention curves for new fleets in the OM that replaces the directed commercial and discard fleets, modelling them as one and accounting for any size limit. The keep curve at young ages was sensitive to small values of retention, and the resulting keep curve was often unrealistically jagged. Therefore the following assumptions were enforced:

- Retention was forced to be zero at ages 5 and under to avoid spikes in selectivity at young ages.
- The retention curve was parameterized to a double logistic formulation before calculating selectivity to smooth it and prepare it for use in the OM.
- The selectivity was parameterized as an asymptotic double normal to smooth the curve and prepare it for use in the OM.

All the curves in this process are shown in Figure 12 for 2021.

To ground-truth this method and determine if any adjustments should be made to the calculated selectivity, the U32 discards were predicted in the OM for the directed commercial fleets in each IPHC Regulatory Area for the years 2010 to 2021, and the peak parameter was adjusted until the predicted discards matched the observed U32 discards. This was done individually for each year because misfitting the discards in one year changes the dynamics in subsequent years. It was also performed separately for each OM model. Only one parameter could be chosen for the adjustment because only one observation is being fitted. The ascending limb was not fit, although estimated ascending limb deviations from the stock assessment are more correlated with weight-at-age than peak devations. However, the peak parameter may be a good choice since the temporal variability in size-at-age is generally consistent across younger age classes.

The adjustment to the peak parameter of the asymptotic double normal selectivity curve differed for each IPHC Regulatory Area and ranged from an adjustment of near 8 years younger to an adjustment of near 4 years older, depending on the year and area (Figure 13). The adjustments for each OM model were similar. Even though the years differed substantially, the general patterns were similar within a Biological Region and are intuitive. First, there was a general trend of shifting selectivity to younger ages. Additionally, IPHC Biological Region 3 often sees a lot of undersized Pacific halibut, and the adjustment was towards the youngest fish in both IPHC Regulatory Areas 3A and 3B. This may be because the fishery is unable to avoid these small fish as well as in other IPHC Regulatory Areas. The range of adjustments in each IPHC

Regulatory Areas could be natural variability as well as a result of uncertainty in the discards entered into the model.

Similarly, an adjustment to the asymptote of the retention curve was estimated using O32 discards (using a grid approach over specific values to save time). This adjustment ranged from near 0 to a deviate slightly more than 0.05 applied to lower the asymptote. Triangle distributions were roughly fit to the estimated adjustments, as shown in Figure 14, and were the same for each OM model. Since regulatory discards and lost gear are not directly related to an evaluation of size limits, and these are added into the directed commercial fishery landings in the stock assessment, it is undecided whether this adjustment should be applied, or if O32 discards should simply be included in the retained mortality to reduce complexity. If included, the deviation to the retention asymptote will be sampled from the triangle distributions shown in Figure 14.

This method was used to parameterize a directed commercial retention fleet in the OM for each IPHC Regulatory Area. Eight additional fleets, duplicating the directed commercial and directed discard fleets, were added to each OM model and parameterized with selectivity and retention using the methods above. The median values for each OM model and IPHC Regulatory Area from the ground-truthing exercise (Figure 13) were used to determine the base selectivity for these directed commercial retention fleets. The projections, starting in 2022, assigned directed commercial fishing retained mortality to these fleets and zero fishing mortality was assigned to the original directed commercial and directed discard fleets. Directed commercial discards are therefore a result of the OM and not directly needed as an input. This allows for the MP to account for directed commercial discards using the methods currently in practice, whereas realized directed commercial discards may differ from what was assumed when setting mortality limits. The greatest benefit of this formulation is that any size limit can be consistently evaluated, and appropriately linked to changing weight-at-age.

A benefit of modelling landings and discards separately is that separate mean weight-at-age vectors could be used for each mortality type, effectively accounting for potentially smaller sized fish at each age being discarded. This benefit was maintained in the OM directed commercial retention fleets by allowing for different mean weight-at-age vectors in the kept and discard components of the fishing mortality.

2.2.2.1 Selectivity and retention deviations

When projecting the population and fisheries, mean weight-at-age is dynamic, thus the retention and selectivity curves must be recalculated based on current mean weight-at-age. The stock assessment applies annual deviations to the peak and ascending limb parameters of selectivity to account for temporal changes in mean weight-at-age; the annual recalculation of retention and selectivity mimics this process. Deviations are applied to the peak parameter based on a random draw from distributions representing the range of adjustments observed in Figure 13. Deviations, drawn from the triangle distributions shown in Figure 14 are applied to the retention asymptote to account for O32 discards.

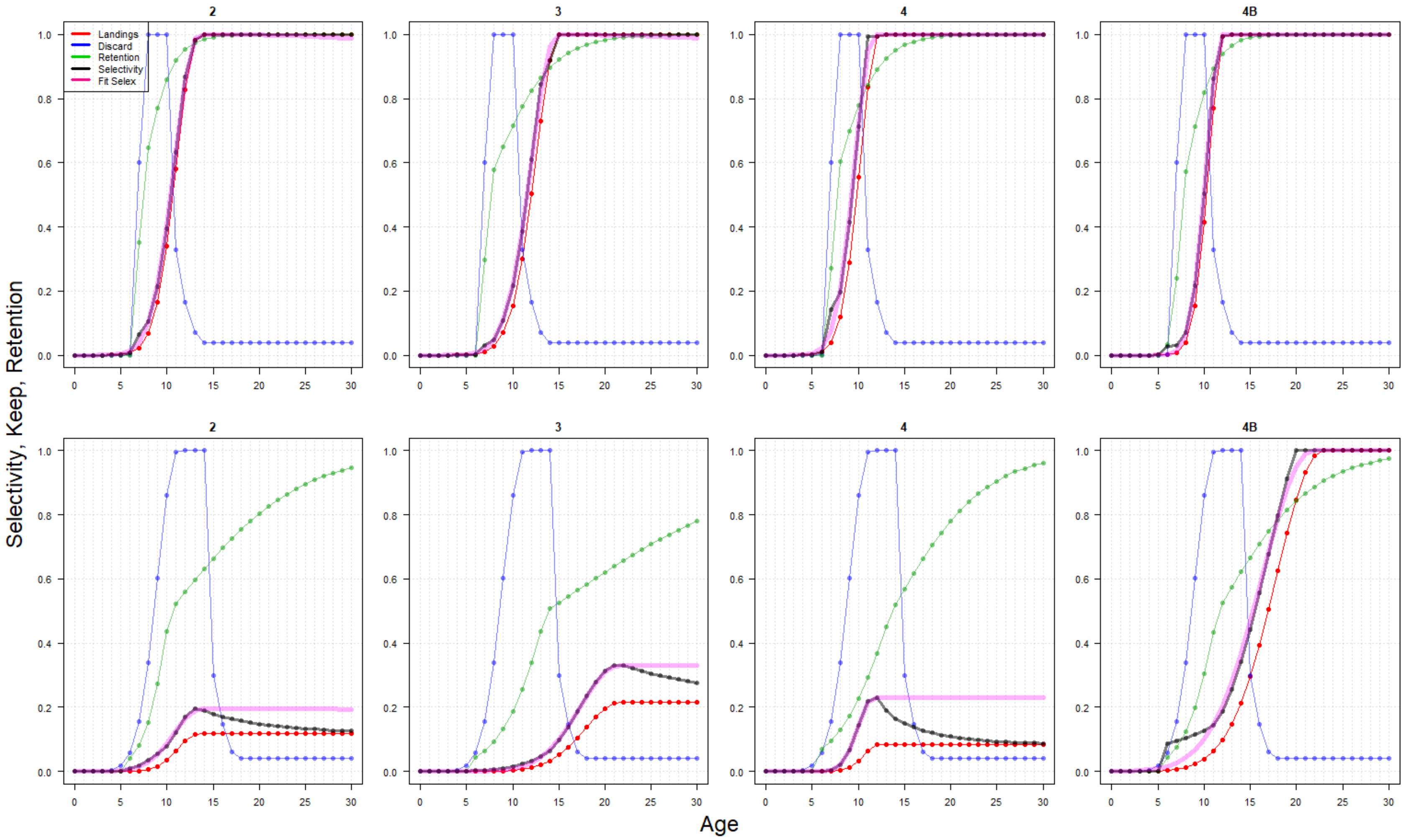

Figure 12. Selectivity, retention, and keep curves for each Biological Region (columns) and sex (rows, females in the top panels, males on the bottom panels) calculated using values from 2021. Landings is the keep curve for the directed commercial fleet as entered in the OM (red curve with dots). Discard (blue) is the selectivity curve for directed discard mortality as entered in the OM. Retention (green) is the double logistic parameterization of the retention calculated from weight-at-age, length-at-weight, and length-at-age relationships. Selectivity (black) is the selectivity-at-age determined from keep and retention. The selectivity curve fitted to selectivity using a asymptotic double normal parameterization is shown in pink.

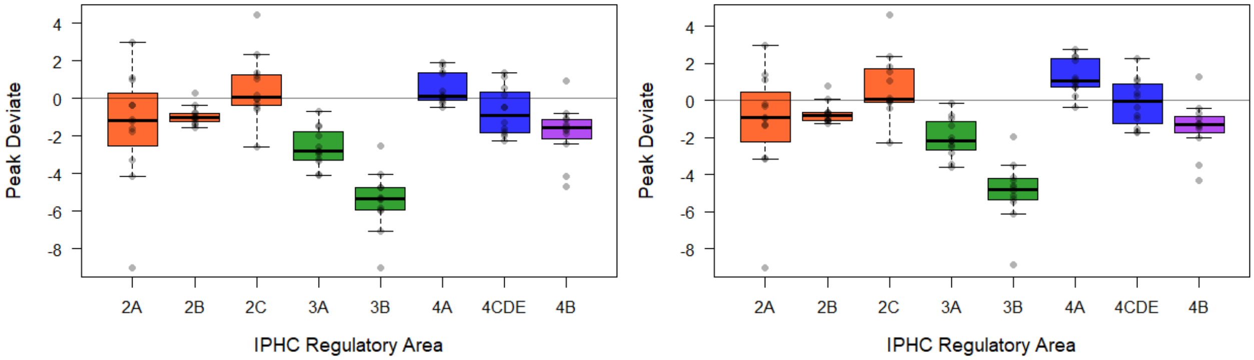

Figure 13. Estimated deviations (in age) from the peak parameter for selectivity for the medAAF (left) and medCW (right) OM models and IPHC Regulatory Area across the years 2010 to 2021. Colors are associated with each Biological Region. Dots indicate each individual year.

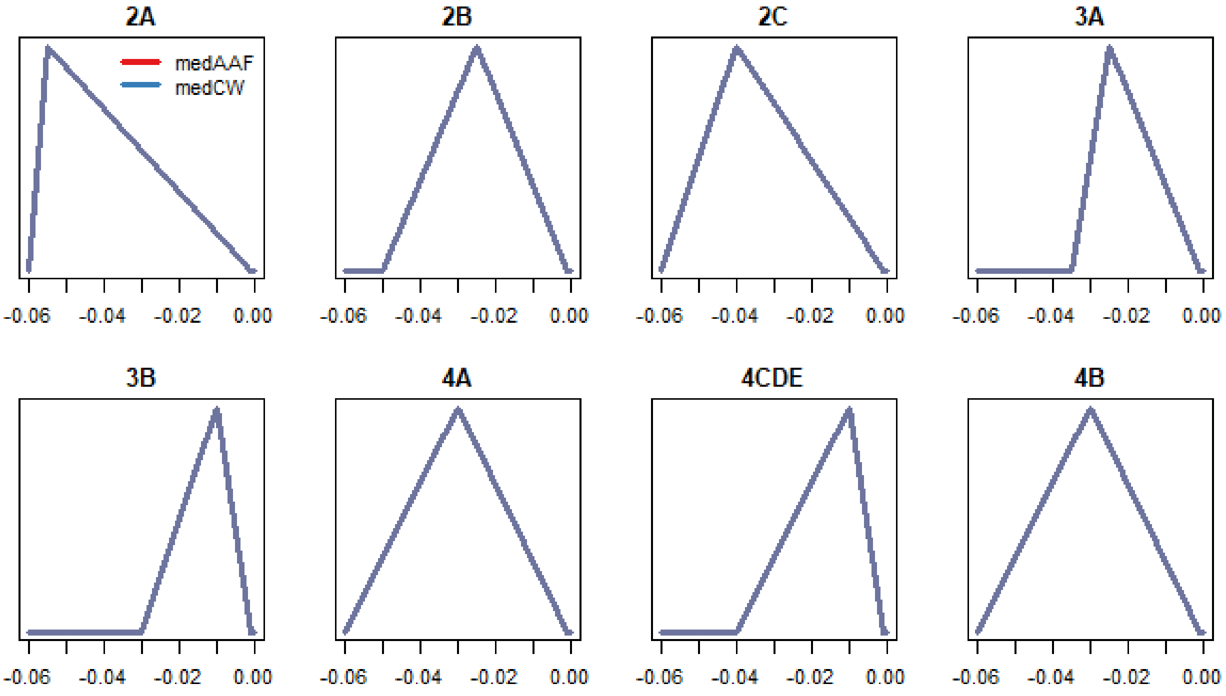

Figure 14. Triangle distributions used to draw random deviates for the retention asymptote. The distributions are the same for each OM model.

2.2.3 Implementation variability and uncertainty

Implementation variability is defined as the deviation of the fishing mortality from the mortality limit determined from an MP. It can be thought of as what actually (or is believed to have) happened compared to the limits that were set. It is useful to define four different fishing mortalities that are subject to different types of implementation variability.

- **MP mortality limit**: This is the mortality limit determined from the management procedure which is calculated from a defined method without ambiguity and is repeatable.
- **Adopted mortality limit**: This is the mortality limit set by the Commission after reviewing all inputs from the stock assessment, subsidiary bodies, and public. It is determined in the "decision" step of Figure 1.
- **Estimated fishing mortality**: This is the perceived mortality after fishing occurs that is determined from landings, at-sea samples, discard mortality rates, and any other observations used in catch accounting. It may also be determined from methods or assumptions that do not use direct observations of catches or landings (e.g. effort). These estimates have sampling uncertainty and are used in estimation models, such as the stock assessment.
- **Actual fishing mortality**: This is the mortality that actually occurred from fishing activities. It is unknown in reality but is used in the OM which simulates the Pacific halibut population. Estimated fishing mortality may affect actual fishing mortality in cases where in-season management uses estimates of fishing mortality to determine if fisheries should be closed or opened.

These four types of mortality are hierarchically related to each other as shown in Figure 15. There are multiple pathways for modelling estimated and actual fishing mortalities. For example, estimated fishing mortality may modelled as a function of the adopted mortality limit or as a function of the actual fishing mortality. Actual fishing mortality may be modelled as a function of the adopted mortality limit or as a function of the estimated fishing mortality. These pathways may differ for different sectors.

We have identified three types of implementation variability that define these relationships. If there is no implementation variability, then all four types of fishing mortality are equal to each other.

1. **Decision-making** variability is the difference between the MP mortality limits and the adopted mortality limits set by the Commission.
2. **Realized** variability is the difference between the adopted mortality limits set by the Commission and the actual mortality resulting from fishing.
3. **Perceived** variability is the variation that determines the estimated fishing mortality, which can differ importantly from actual mortality and the adopted mortality.

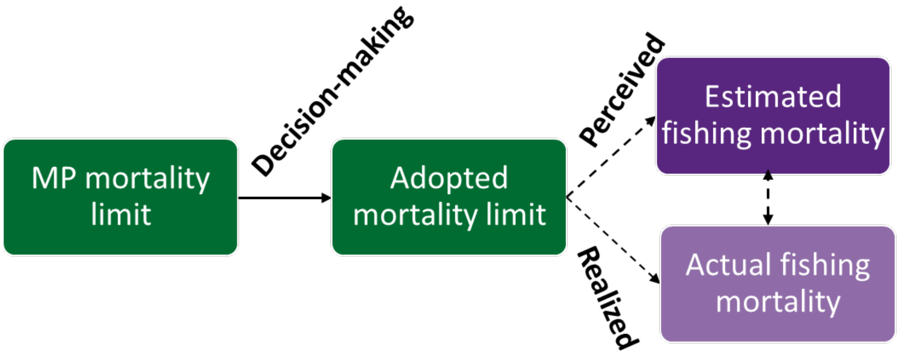

Figure 15. The hierarchy between four fishing mortality types (boxes: green indicates known quantities, light purple indicates unknown, and dark purple indicates observed with error) and where implementation variability occurs (black text). Dashed lines indicate that the estimated and actual fishing mortalities could be modelled from different pathways (e.g., estimated fishing mortality is a function of the adopted mortality limit or a function of the actual fishing mortality). The OM calculates estimated and actual fishing mortality, and uses each of these quantities in different parts of the simulation process.

Variability is defined as the inherent heterogeneity in the data or population, which cannot be reduced. On the other hand, uncertainty is defined as the incomplete understanding of the data, estimate, or process. Uncertainty can be reduced to zero with increased sampling. With these definitions, we refer to historical variations in implementation of mortality limits as implementation variability, and the future simulation of potential variations in the implementation of mortality limits as implementation uncertainty. Variability has already happened in the past and can be determined and not changed, whereas future simulations are uncertain about the variations, thus simulate a range of possible deviations.

To identify reasonable methods to simulate implementation uncertainty in the MSE, we considered some possible hypotheses and looked at historical implementation variability. First, decision-making uncertainty can be applied to the MP mortality limit ($TCEY_t$) as a multiplier.

$$\widetilde{TCEY}_t = TCEY_t \varepsilon_I$$

where $\widetilde{TCEY}_t$ is the adopted mortality and ε_I is the multiplier. Using observations from 2014 to 2021 of the MP mortality limit determined from the interim management procedure and the adopted mortality limits set by the Commission for that year and IPHC Regulatory Area, the multipliers are shown in Figure 16. These years were chosen because they used a relatively consistent management procedure, although as noted in the following paragraphs from Annual Meeting reports, explicit use of SPR was added in 2017, additional agreements were added in 2019 and 2020, and the reference SPR changed from 46% to 43% in 2021.

> ***IPHC-2017-AM093–R (para. 29) NOTING** that the IPHC Secretariat and the IPHC Scientific Review Board (SRB) have demonstrated that Ebio is outdated and inconsistent with current assessment results, and that numerous elements of the current harvest policy*

are reliant on Ebio, and that the Commission has agreed that the current harvest policy is considered to be outdated (IPHC–2016–IM092–R, items 21, 22), the Commission ***RECOMMENDED*** *IPHC–2017–AM093–R Page 8 of 61 that reference to all elements of the current harvest policy reliant on Ebio, as well as the use of the Blue line, be eliminated subsequent to the close of the 93rd Session of the Commission. The "status quo SPR" (F46%) may serve as an interim "hand rail" that allows all participants to gauge this and future years' catch limit discussions in comparison to previous years.*

IPHC-2020-AM096-R ***(para. 97)*** *The Commission* ***ADOPTED****: a)[…]; and b) a fixed TCEY for IPHC Regulatory Area 2A of 1.65 million pounds is intended to apply for a period from 2019-2022, subject to any substantive conservation concerns; and c) a share-based allocation for IPHC Regulatory Area 2B. The share will be defined based on a weighted average that assigns 30% weight to the current interim management procedure's target TCEY distribution and 70% on 2B's recent historical average share of 20%. This formula for defining IPHC Regulatory Areas 2B's annual allocation is intended to apply for a period of 2019 to 2022. For 2020, this equates to a share of 18.2% before accounting for U26; and […]*

IPHC-2020-CR-007 ***(ID002).*** *The Commission* ***RECOMMENDED*** *a reference SPR fishing intensity of 43% with a 30:20 control rule be used as an updated interim harvest policy consistent with MSE results pending delivery of the final MSE results at AM097 […]*

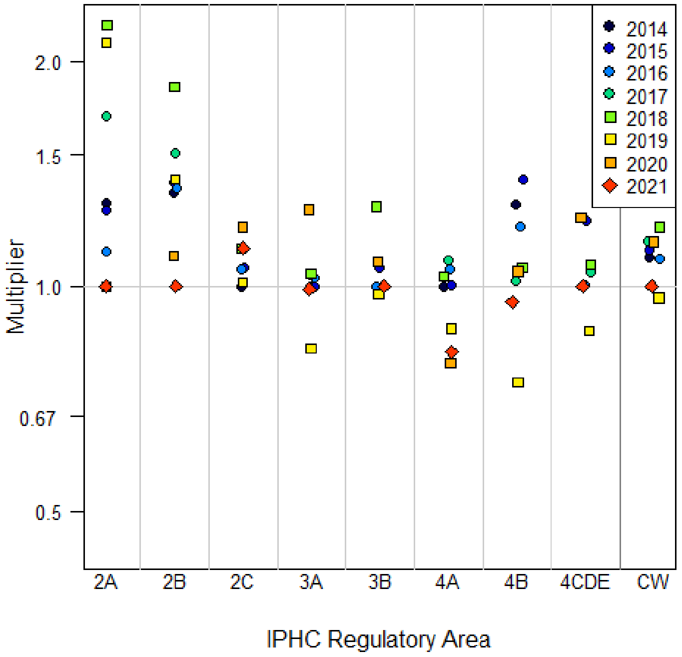

Figure 16. Multipliers for the difference between MP mortality limits and adopted mortality limits from 2014 to 2021. "CW" refers to coastwide.

This investigation of past decisions can inform the development of methods to simulate decision-making uncertainty. To further aid in the development, six potential decision-making response hypotheses were identified from discussions with the SRB and Management Strategy Advisory Board (MSAB), as well as from past observations.

1) When the TCEY is high the Commission may be less inclined to increase the coastwide TCEY above the MP TCEY (the multipliers become closer to 1).
2) When the TCEY is decreasing from the previous year, the multiplier is typically above 1, whereas when the TCEY is increasing, it is typically around 1. The SRB made a recommendation related to this scenario.

   SRB019–Rec.06 (para. 35) ***NOTING*** *the inclusion of uncertainty stemming from implementation* ***uncertainty****, the SRB* ***RECOMMENDED*** *that the IPHC Secretariat develop, for presentation at SRB020, alternative scenarios that represent implementation* ***bias****, i.e. the potential for quota reductions called for by the management procedure to be less likely implemented than quota increases.*

3) When the stock status is less than 30%, the Commission may deviate (increased fishing intensity/higher TCEY) from the MP. An extreme example is that they may decide to not set the TCEY to zero when the relative spawning biomass is less than 20%, as defined by the interim control rule.
4) When coastwide stock status is above 30% (trigger point of CR) the multiplier may be increasingly greater than one as the TCEY becomes lower or is below some threshold.
5) When the decision table from the assessment indicates a lower risk of stock decline or falling below 30% RSB, the multiplier may become increasingly greater than 1.
6) When there is an agreement for an IPHC Regulatory Area, the implementation variability is much less, or near 1.0 for these areas.

2.2.3.1 Method to simulate decision-making uncertainty

The multiplier to simulate decision-making uncertainty is drawn from a lognormal distribution with correlation between multipliers for each IPHC Regulatory Area. The mean ($\boldsymbol{\mu_\varepsilon}$) and standard deviation ($\boldsymbol{\sigma_\varepsilon}$) of that distribution are modified as follows depending on the TCEY from the MP.

$$\boldsymbol{\mu_\varepsilon}\ or\ \boldsymbol{\sigma_\varepsilon} = \begin{cases} \boldsymbol{\bar{x}}\ or\ \boldsymbol{s} & TCEY < TCEY_{low} \\ \boldsymbol{a} + \boldsymbol{b} * TCEY & TCEY_{low} \le TCEY \le TCEY_{high} \\ \mathbf{1.0}\ or\ \boldsymbol{s}/\mathbf{2} & TCEY > TCEY_{high} \end{cases}$$

Using IPHC Regulatory Area 2A as an example (without a TCEY agreement in place), with a coastwide $TCEY_{low}$ of 30 Mlbs and a coastwide $TCEY_{high}$ equal to 60 Mlbs, the distribution of simulated multipliers gets closer to 1 as the TCEY increases (Figure 17).

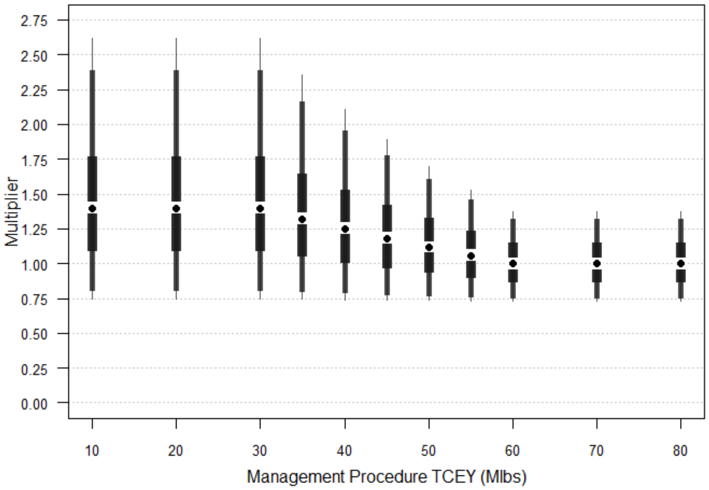

Figure 17. Simulated multipliers for IPHC Regulatory 2A at different values of the coastwide TCEY (without the recent agreement on the 2A TCEY). The thickest portion of the vertical bar represents the 25th and 75th percentiles, followed by the 5th and 95th percentiles, and then the 2.5th and 97.5th percentiles.

This method directly addresses hypotheses 1 and 4, and could be easily modified to address 2, 3, and 6. Hypothesis 5 could be approximated with additional investigation and modification.

Actual decision-making variability is likely more complex than this simple method. In fact, some IPHC Regulatory Areas show a consistent adopted TCEY over a range of MP TCEYs (e.g., 4B in Figure 18). However, the goal of including decision-making uncertainty in the MSE simulations isn't to exactly simulate what the pattern is, but to identify the effect of decision-making uncertainty and identify MPs that are robust to a plausible amount of uncertainty. Therefore, simulations will be done with and without decision-making uncertainty to identify MPs that are robust to this uncertainty. Various modifications may be made to decision-making uncertainty to explore sensitivity to various hypotheses. For example, different offsets depending on the trend in the population or TCEY, as suggested by the SRB (SRB019–Rec.06, para. 35).

2.2.3.2 Methods to simulate realized and perceived implementation uncertainty

Realized uncertainty is currently implemented in the OM by simulating a range of actual non-directed discard mortality, recreational mortality, and subsistence mortality. These are likely the largest sources of realized variability in the Pacific halibut fisheries, which is relatively small compared to many fisheries.

Perceived uncertainty is currently not simulated in the OM but will be considered as work progresses.

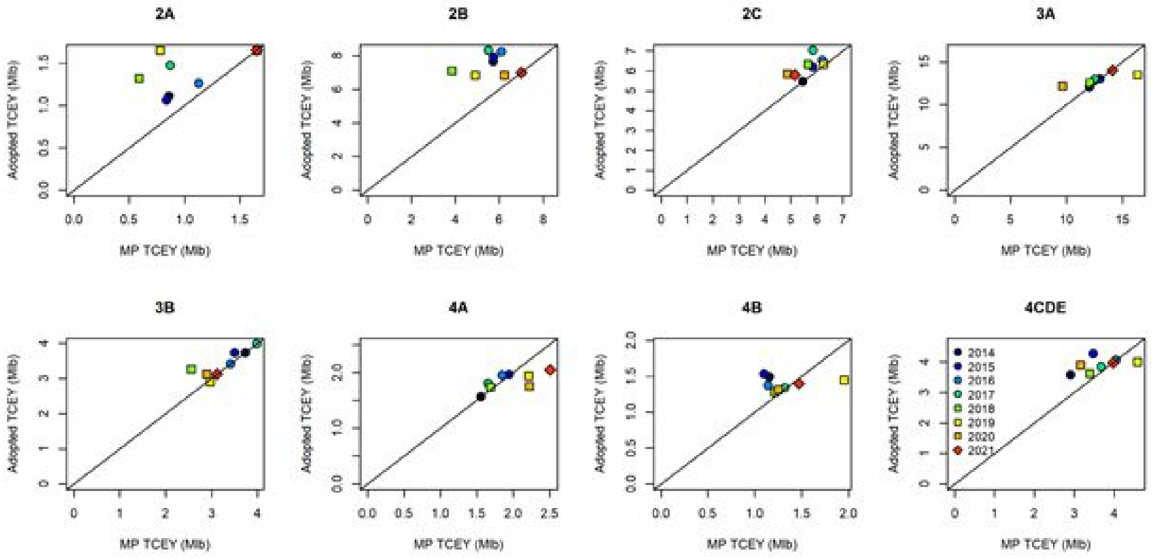

Figure 18. Adopted TCEYs plotted against MP TCEYs for each IPHC Regulatory Area and years 2014 to 2021.

2.2.4 Projections with no fishing mortality

Projections with the OM incorporating parameter variability and projection variability produced a wide range of spawning biomass trajectories. Figure 19 shows fifty projected trajectories without fishing, variable weight-at-age, and an environmental regime switching on average every 30 years. An individual trajectory may cover a wide range of spawning biomass values in this 90-year period. The variability looks like it has reached its full range after 30 years, but there is still cyclic behavior which is due to the long period of the environmental regime.

Figure 20 shows the percentage of time that the simulated PDO is in a positive phase. With a thirty-year average time remaining in a phase, a 90 year projection has little opportunity to show a mixing of negative and positive phases. There is very little probability of a positive phase approximately 40 years in the projections and almost very high probability of a positive phase approximately 60 years in the projections (noting that there is something incorrect in the simulation with an almost instantaneous return to a positive phase around 2075). Longer simulations would provide better mixing while retaining the long period of a single phase, but at the expense of very long simulation times. To better characterize the uncertainty of the environmental effect on recruitment while retaining the cumulative effects on the population of potentially long periods of a single phase, the average period of a phase was reduced to 20 year and the slope of the logistic function defining the probabilities based on the period of the current phase was made shallower (Figure 21). This is also justified by a recent potentially short negative phase (Figure 52 in IPHC-2022-SA-02). Additionally, the environmental regime will be modelled external to the C++ operating model code to save simulation time, allow for the exact same pattern across MP simulations, and ensure that the environmental regime behaves as expected (Figure 22).

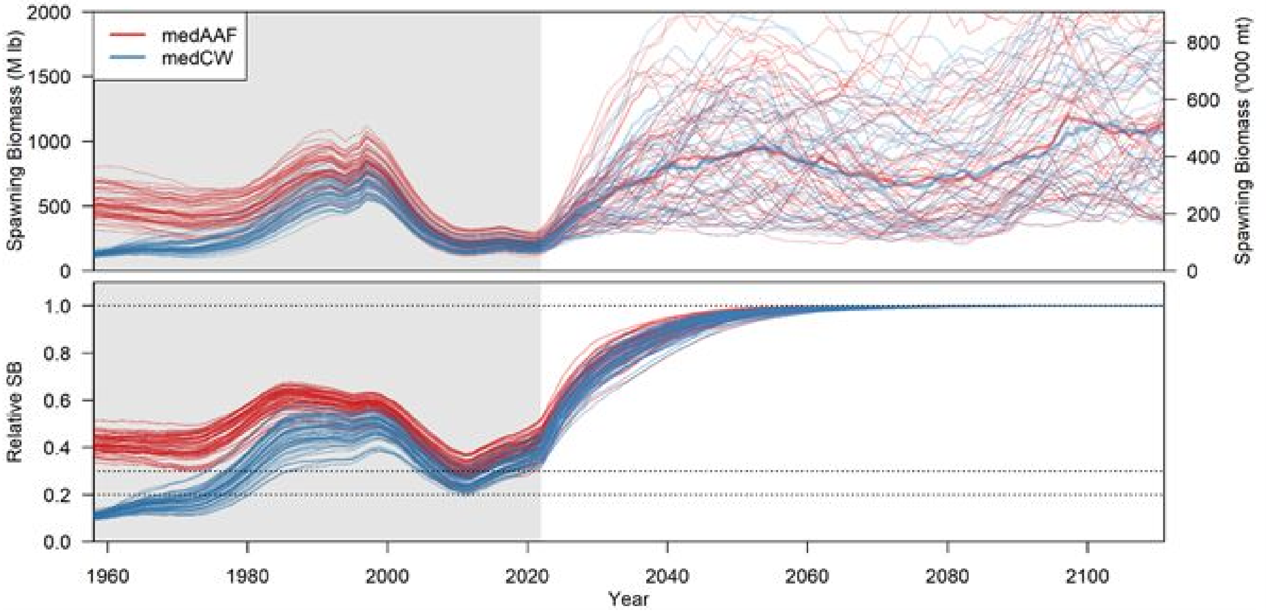

Figure 19: Fifty projections of spawning biomass and median spawning biomass (top) and relative spawning biomass (bottom) for 90 years without fishing mortality for each OM model. An environmental regime is simulated with an average period of 30 years before switching to the opposite regime.

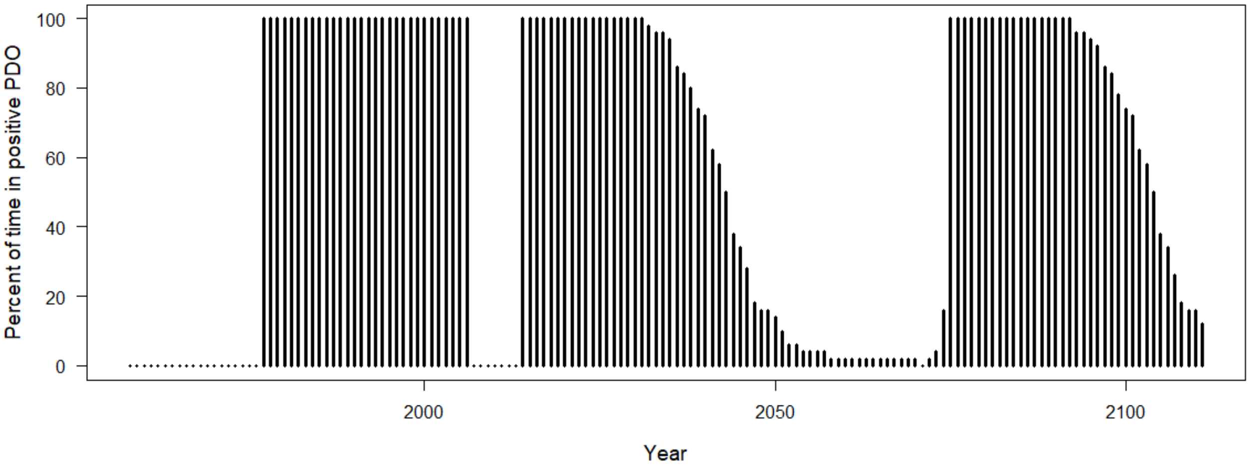

Figure 20. Percent of simulations where the PDO is in a positive phase. Simulations start in 2022 and the PDO phase is fixed before then.

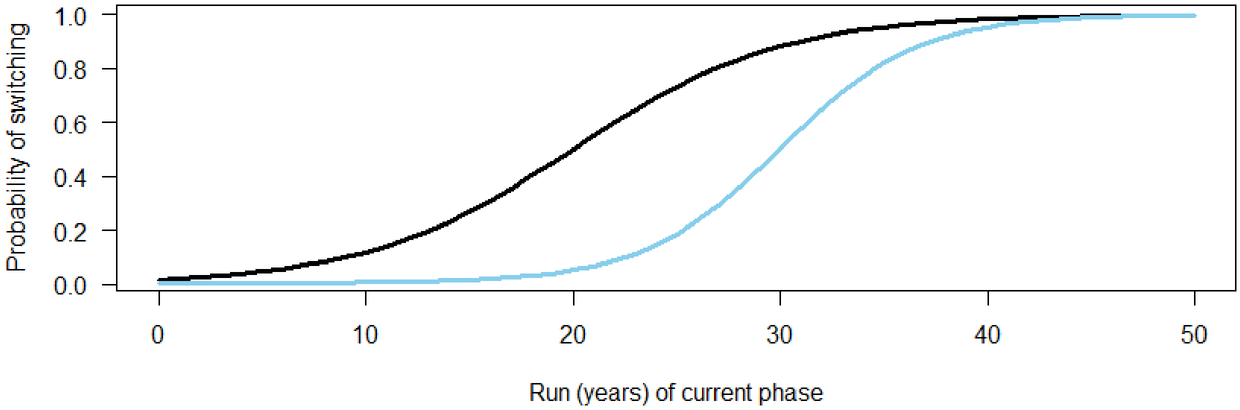

Figure 21. Modelled probability of the environmental regime switching to the opposite regime based on the number of years (run) of the current regime. The blue line is the parameterization used in Figure 20 and the black line is the proposed new parameterization to ensure adequate uncertainty in the phases.

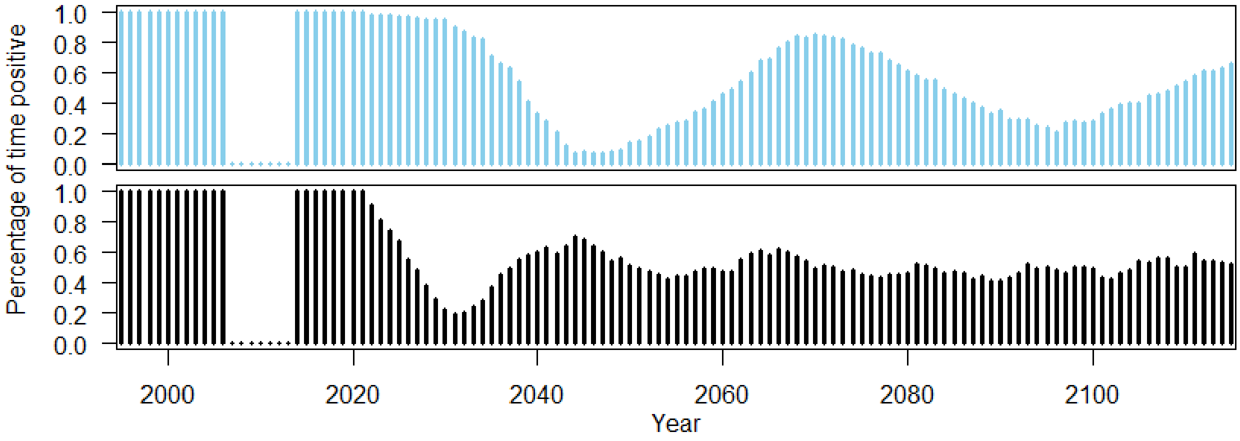

Figure 22. Percentage of simulations that the simulated PDO was positive for two parameterizations of the probability that the PDO switches. The top and bottom plots correspond to Figure 21. The top has a 0.5 probability of change at 30 years while the bottom plot is 20 years. The slope and y intercept of the logistic function is 0.3 and 0.005 in the top plot and 0.2 and 0.0 in the bottom plot.

2.3 Runs and Scenarios

The primary closed-loop simulations will consist of integrating the two OM models with equal weight by simulating an equal number of trajectories/projections from each model. The results from the full set of projections will be used to calculate the performance metrics. Implementation variability will be the symmetric method described above. Additional scenarios may be evaluated that include OM models with lower M values, different assumptions of migration, or different scenarios of implementation error.

3 MANAGEMENT PROCEDURES

Two categories of MPs were prioritised in the MSE Program of Work for 2021–2023. One was the investigation of size limits (M.1) and the other was to investigate multi-year stock assessments (i.e. not conducting the stock assessment annually; M.3). Due to improvements in the MSE framework and changes in the OM, select MPs from the set evaluated in 2021 may need to be reanalysed.

3.1 Size limits

Since 1973, IPHC has restricted the directed commercial fishery for Pacific halibut with a 32 inch (81.3 cm) minimum size limit, although other forms of size limits have been in place since 1940 (Myhre 1973). Many investigations of size limits have been completed since then including IPHC (1960), Clark & Parma (1995), Parma (1999), Valero & Hare (2012), Martell et al. (2015a), Martell et al. (2015b), Stewart & Hicks (2018), and Stewart et al (2021). Most of these analyses have focused on short-term effects or effects on reference points. The novelty of this analysis using the MSE framework will be to examine long-term effects of different size limits in relation to defined conservation and fishery objectives. Additionally, long-term changes to the stock and fishery distribution as well as changes in productivity will be examined.

The Commission requested that three size limits be investigated: 32 inches, 26 inches, and no size limit.

> **IPHC-2022-AM098-R, para. 61**: *The Commission RECALLED SS011-Rec.01 and REQUESTED that the current size limit (32 inches), a 26 inch size limit, and no size limit be investigated. to understand the long-term effects of a change in the size limit.*

As noted in Section 2.2.2, even though some approximations need to be made, any size limit can be investigated. Additional size limits will be added if necessary to gain a better understanding of the trade-offs.

It is uncertain how selectivity of the directed commercial fisheries may change with the implementation of a different size limit than the current 32 inches. Fisheries may choose to target smaller fish to increase efficiency, they may maintain current practices, or they may target larger fish if that provides improved economic gains. Some sensitivities to changes in selectivity may be investigated.

An important concept to bring into the evaluation of size limits is market considerations. Stewart et al. (2021) used the ratio between the U32 price and O32 price for Pacific halibut to determine what ratio is necessary for the fishery to break even economically. It is unknown what prices will be for U32 Pacific halibut if a size limit was removed, but the FISS has recently begun selling U32 fish, which may be an indicator for future market conditions of small fish. Regardless, a performance metric related to economics will be important to consider in this evaluation.

3.2 Multi-year assessments

Management procedures with multi-year assessments incorporate a process where the stock assessment occurs at intervals longer than annually. The mortality limits in a year with the stock assessment can be determined as in previously defined MPs, but in years without a stock assessment, the mortality limits would need an alternative approach. This may be as simple as maintaining the same mortality limits for each IPHC Regulatory Area in years with no stock assessment, or as complicated as invoking an alternative MP that does not require a stock assessment (such as an empirical-based MP relying only on data/observations). Potential MPs for years without an assessment that may be evaluated include the following.

a. The same TCEY from the previous year for each IPHC Regulatory Area.
b. Setting multi-year TCEYs using projections from the stock assessment.
c. Updating the distribution of the TCEY in non-assessment years using FISS results and/or other data sources, but maintaining the same coastwide TCEY.
d. Updating the coastwide TCEY in non-assessment years using FISS results and/or other data sources, and then distributing the coastwide TCEY using a distribution procedure.
e. Updating the TCEY within each IPHC Regulatory Area separately using FISS results and/or other data sources, resulting in a change to the coastwide TCEY.

The Commission requested that the Secretariat investigate biennial assessments and potentially longer intervals as time allows. Specific approaches for non-assessment years will be developed by the Secretariat.

> **IPHC-2022-AM098-R, para 64**: *The Commission REQUESTED that multi-year management procedures include the following concepts:*
>
> > *a) The stock assessment occurs biennially (and possibly triennial if time in 2022 allows) and no changes would occur to the FISS (i.e. remains annual);*
> >
> > *b) The TCEY within IPHC Regulatory Areas for non-assessment years:*
> >
> > > *i. remains the same as defined in the previous assessment year, or*
> > >
> > > *ii. changes within IPHC Regulatory Areas using simple empirical rules, to be developed by the IPHC Secretariat, that incorporate FISS data.*

An alternative approach that would not require a stock assessment for setting mortality limits in any year would be to adopt an empirical-based MP as the method for setting annual mortality limits. The stock assessment would be used at a defined interval to verify that management is effective and to potentially tune the MSE OM and existing MP (Cox and Kronlund 2008). Any of the MPs mentioned in this section, empirical- or model-based or a hybrid of the two, can be evaluated using the current MSE framework, and the evaluation of multi-year assessments with an empirical rule will be a useful path to evaluating an annual empirical MP without a stock assessment.

The Commission has realized that there are some benefits to multi-year assessments, including time for development/improvement of the stock assessment, the potential to address additional topics at meetings in years without a stock assessment, and the potential for increased collaboration across branches within the IPHC Secretariat. However, there may be some costs associated with multi-year assessments. For example, detailed harvest advice will not be available every year.

It is also important to consider costs and benefits associated with an annual assessment. In particular, the annual preparation of a stock assessment occupies many staff in terms of preparing and providing data in a timely manner, writing documents to support associated data and analyses, conducting the stock assessment, preparing the stock assessment document and presentations, and participating in public outreach associated with a new stock assessment.

The Commission has asked the SRB to assist the Secretariat in identifying potential costs and benefits of not conducting an annual stock assessment.

> **IPHC-2022-AM098-R, para 63:** *The Commission REQUESTED that the IPHC Secretariat work with the SRB and others as necessary to identify potential costs and benefits of not conducting an annual stock assessment. This will include a prioritized list of work items that could be accomplished in its place.*

It may be premature to begin identifying detailed costs and benefits of multi-year assessments until an evaluation has been done to determine whether or not multi-year assessments may meet the Commission objectives already defined. An evaluation of multi-year assessments using Commission conservation and fishery objectives will be presented at SRB021, after which a discussion of detailed costs and benefits would be informative.

3.3 Modelling distribution

The fisheries in the OM are specified by IPHC Regulatory Area because many of the Commission objectives used to evaluate MPs are specific to IPHC Regulatory Areas and the OM is spatially structured by Biological Region. This makes it necessary to distribute the TCEY across the fisheries to appropriately remove biomass from each Biological Region and allow for the calculation of necessary performance metrics. Distribution procedures have been evaluated (Hicks et al. 2021), but a specific MP has not been implemented. Even though distribution procedures are not currently being evaluated and there is no specific agreement on a single distribution procedure, they are part of the MP and need to be included in the simulations. Therefore, the Commission has recommended five different distribution procedures representing a practicable range to provide a robust analysis of size limits and multi-year assessments.

> **IPHC-2022-SS012-R, para 11**: *The Commission RECOMMENDED the following five distribution procedures to be used in the management strategy evaluation of size limits and multi-year assessments, noting that these distribution procedures are for analytical purposes only and are not endorsed by both parties, thus would be reviewed in the future if the Commission wishes to evaluate them for implementation.*
>
> > *a) Baseline based on recent year O32 FISS results, relative harvest rates of 1.0 for IPHC Regulatory Areas 2-3A, relative harvest rates of 0.75 for IPHC Regulatory Areas 3B-4, and no application of the current interim agreements for 2A and 2B;*

b) Baseline based on recent year O32 FISS results, relative harvest rates of 1.0 for IPHC Regulatory Areas 2-3A, relative harvest rates of 0.75 for IPHC Regulatory Areas 3B-4, and current interim agreements for 2A and 2B;

c) Baseline based on recent year O32 FISS results with 1.65 Mlbs to 2A and 20% of the coastwide TCEY to 2B;

d) Baseline based on recent year O32 FISS results, relative harvest rates of 1.0 for IPHC Regulatory Areas 2-3, 4A, and 4CDE, a relative harvest rate of 0.75 for IPHC Regulatory Area 4B, and no agreements for 2A and 2B;

e) Baseline based on recent year O32 FISS results, relative harvest rates of 1.0 for IPHC Regulatory Areas 2-3, 4A, and 4CDE, a relative harvest rate of 0.75 for IPHC Regulatory Area 4B, and current interim agreements for IPHC Regulatory Areas 2A and 2B

3.4 MP combinations

It is easy in any MSE to specify a large set of runs due to the combination of many MP elements. Given that the simulation time for a single MP may be days, it is useful to identify a small set of runs that will provide insight into the performance of each element of the MP of interest. The three components presented above have multiple elements which will be combined as shown in Table 2 to form the primary set of twenty-five MPs. For each MP, an SPR of 43% will be used.

A secondary set of MPs will be developed based on the performance of the primary set. This may include crossing size limits with biennial assessments, investigating alternative SPR values, and incorporating various forms of implementation variability. This secondary set will not be a full factorial, but instead a specific investigation of relevant factors, and to refine the best performing MPs relative to stock and fishery objectives.

Furthermore, a set of sensitivities will be done using alternative scenarios such as different migration hypotheses, different assumptions about natural mortality, and shifts in selectivity to mimic changes in fishery practices. These will be performed on a small set of the best performing MPs.

EVALUATION

The twenty-five MPs in Table 2 will be integrated across the distribution procedures, resulting in the five MPs in Table 3. Therefore, performance metrics will only be reported for the five MPs in Table 3 and distribution will be considered an uncertainty in this evaluation.

The methods to evaluate simulation results and present those for decision-making are always being improved. Current tasks specifically include updates to the MSE Explorer tool, improving the ranking procedure to identify best performing management procedures, determining new methods to identify best performing management procedures, and providing new types of plots and tables that effectively communicate the results. This task will benefit from interactions with stakeholders and management agencies, which may include MSAB meetings.

Table 2. Primary MPs to be evaluated. The multi-year assessment specifies the frequency of the stock assessment and the procedure for years without a stock assessment. The distribution procedure corresponds to the letter in IPHC-2022-SS012-R, para 11 and quoted in this text.

#	MP ID	Multi-year assessment	Size Limit (inches)	Distribution
1	MP-A32a	Annual	32	a
2	MP-A32b	Annual	32	b
3	MP-A32c	Annual	32	c
4	MP-A32d	Annual	32	d
5	MP-A32e	Annual	32	e
6	MP-Bc32a	Biennial, constant TCEY	32	a
7	MP-Bc32b	Biennial, constant TCEY	32	b
8	MP-Bc32c	Biennial, constant TCEY	32	c
9	MP-Bc32d	Biennial, constant TCEY	32	d
10	MP-Bc32e	Biennial, constant TCEY	32	e
11	MP-Be32a	Biennial, empirical rule	32	a
12	MP-Be32b	Biennial, empirical rule	32	b
13	MP-Be32c	Biennial, empirical rule	32	c
14	MP-Be32d	Biennial, empirical rule	32	d
15	MP-Be32e	Biennial, empirical rule	32	e
16	MP-A26a	Annual	26	a
17	MP-A26b	Annual	26	b
18	MP-A26c	Annual	26	c
19	MP-A26d	Annual	26	d
20	MP-A26e	Annual	26	e
21	MP-A0a	Annual	0	a
22	MP-A0b	Annual	0	b
23	MP-A0c	Annual	0	c
24	MP-A0d	Annual	0	d
25	MP-A0e	Annual	0	e

Table 3. Primary MPs to be evaluated. The multi-year assessment specifies the frequency of the stock assessment and the procedure for years without a stock assessment.

MP ID	Multi-year assessment	Size Limit (inches)
MP-A32	Annual	32
MP-Bc32	Biennial, constant TCEY	32
MP-Be32	Biennial, empirical rule	32
MP-A26	Annual	26
MP-A0	Annual	0

RECOMMENDATION/S

That the SRB

a) **NOTE** paper IPHC-2022-SRB020-06 Rev_1 describing improvements to the closed-loop simulation framework, methods to simulate implementation variability, two types of management procedures to simulate and evaluate in 2022, and potential areas of improvement to the evaluation process.

b) **NOTE** two new population models conditioned using assumptions and outputs from the two long models from the recent stock assessment will be integrated and used as an OM.

c) **NOTE** that improvements to the closed-loop simulation framework allow for a more direct method of evaluating size limits without specifically modelling a growth curve.

d) **NOTE** the methods for simulating implementation error based on past management outcomes.

e) **NOTE** that there are costs and benefits to not conducting annual stock assessments, which may affect research opportunities.

f) **NOTE** that five primary MPs investigating three size-limits, and annual and biennial assessments will be evaluated in 2022, with five distribution procedures treated as uncertainty. Sensitivities will be performed using the best performing MPs.

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APPENDICES

Appendix A: Supplementary material

APPENDICES

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In addition to this document, an MSE technical document is available electronically. This is document IPHC-2022-MSE-01 and is available on the IPHC MSE page (https://www.iphc.int/management/science-and-research/management-strategy-evaluation).

IPHC-2022-SRB020-07

Development of the 2022 Pacific halibut (*Hippoglossus stenolepis*) stock assessment

PREPARED BY: IPHC SECRETARIAT (I. STEWART AND A. HICKS; 11 MAY 2022)

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Summary

This document reports preliminary analyses in development of the 2022 Pacific halibut (*Hippoglossus stenolepis*) stock assessment. It follows the previous full stock assessment and independent peer review conducted in 2019 (Stewart and Hicks 2019b; Stewart and Hicks 2020; Stokes 2019), and subsequent updates to that assessment in 2020 (Stewart and Hicks 2021), and 2021(Stewart and Hicks 2022). Following the review of this document in June 2022 (SRB020), requested revisions will be considered and presented for additional review in September 2022 (SRB021), and the final 2022 assessment will be produced for the IPHC's Interim (IM098) and Annual (AM099) meetings. Updated data sources, including the results of the 2022 Fishery-Independent Setline Survey (FISS), logbook and biological data from the 2022 commercial fishery, and sex-ratio information from the 2021 commercial landings-at-age will be included for the final 2022 analysis.

Creating robust, stable, and well-performing stock assessment models for the Pacific halibut stock has historically proven to be challenging 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). The use of multiple models provides a solution to the endless search for a better stock assessment model and allows for structural as well as estimation uncertainty to be better captured. The IPHC adopted the ensemble approach for its 2012 stock assessment (Stewart et al. 2013a) and has continued to develop and refine the set of models used to provide tactical management information each year. The ensemble approach integrates the results of multiple hypotheses with the uncertainty associated with parameter estimation (Stewart and Martell 2015). This reduces potential for abrupt changes in management quantities as improvements and additional data are added to individual models (Stewart and Hicks 2018), and provides a more realistic perception of uncertainty than any single model, and therefore a stronger basis for probabilistic risk assessment.

Development of the current ensemble of stock assessment models began in 2012 with a single model using three alternative fixed values of natural mortality (Stewart et al. 2013a). In subsequent years, ensemble development included exploration of highly varied model approaches, including a Virtual Population Analysis (VPA) and a simple biomass production model (Cox et al. 2014) and a spatially explicit model including migration rates and recruitment distribution (Cox et al. 2017). The treatment of the historical data through long and short modelled time-series, and the treatment of spatial patterns via coastwide aggregation of data and an Areas-As-Fleets (AAF) approach have emerged as two critically important axes over which to describe the uncertainty in both the scale and trends of the Pacific halibut stock and population dynamics. Therefore, recent ensembles have included four equally weighted models representing a two-way cross of time-series length (short and long) and data aggregation (coastwide and by Biological Region).

Starting with the 2021 stock assessment data, models and results (Stewart and Webster 2022; Stewart and Hicks 2022), this analysis provides a sequentially updated 'bridge' of the changes made thus far toward a preliminary assessment for 2022. This bridging analysis included a series of steps for which intermediate results and comparisons are provided. These steps included:

1) Extending the time series to include projected mortality based on limits adopted for 2022 (IPHC 2022),
2) updating to the newest stock synthesis software version (3.30.19; Methot Jr et al. 2021a),
3) expanding the treatment of natural mortality (*M*) to include an informative prior and increased values at the youngest ages based on meta-analyses,
4) improving the basis for data weighting via use of bootstrapped effective sample sizes based on the FISS and fishery sampling programs as model inputs (rather than the raw number of sets/trips),
5) re-tuning the process and observation error components of these models to achieve internal consistency within each,
6) allowing for interannual variability in the sex-ratio of the commercial fishery selectivity,
7) and exploring whether female *M* in the short models was estimable (male *M* and *M* for both sexes in the long models was already estimated).

Briefly, software versions, use of a prior on *M* and age-specific *M* for the youngest ages had little to no effect on individual model results. Time varying sex-ratio in selectivity for the commercial fishery and *M* in the short AAF model were both found to be robustly estimated. Retuning the sample sizes and process error variance terms provided for internal model consistency, and effects on results were similar to those in previous assessments. Convergence, sensitivity and retrospective analyses were performed on all models contributing to the ensemble. Alternatives to the treatment of the PDO as a covariate to average recruitment (long models only) were explored, but none were found that outperformed the *status quo*. All models were sensitive to the estimated or fixed value of female *M*, with increasing *M* always resulting in larger estimates of spawning biomass. After including time-varying sex-ratio of the commercial fishery selectivity, retrospective analyses were much more stable than in previous assessments and showed little trend as data were removed. Jitter analyses indicate that the long AAF model was the least robust to a wide range of initial parameter estimates; however, convergence did appear to be achieved.

After evaluating individual models, the analysis also included an exploration of model weighting within the ensemble; models have been equally weighted since the 2013 stock assessment. The Mean Absolute Scaled Error (MASE; Hyndman and Koehler 2006) of one-year-ahead projections of the FISS coastwide index of abundance suggested that all four preliminary models performed appreciably better than the naïve projection (last year's index). When this performance was used to weight the models, weights ranged from 9 to 38% across a 1-4 year historical window. The highest weights were generally assigned to the coastwide long model, and the lowest to the AAF short model. A MASE-weighting approach would provide a self-updating approach for model weights within the ensemble that is logically linked to the prediction skill of the quantity most relevant to management decision-making and is proposed for use in the final 2022 assessment. In aggregate, the results of the preliminary ensemble across a range of individual model weights remain consistent with those from recent assessments. The uncertainty in stock dynamics also remains similar and high relative to that frequently reported for many single-model or simple stock assessment analyses. This uncertainty will continue to be captured via the annual decision table (Stewart and Hicks 2022), reporting the trade-offs between yield and various stock and fishery risks.

Given the challenges and uncertainties of the Pacific halibut population dynamics and stock assessment it is unlikely that future assessment models will provide substantially more precise and stable results, even as data time-series grow longer. In light of the uncertainty and variability within which the Pacific halibut management occurs, a robust management procedure, tested via the IPHC's Management Strategy Evaluation (MSE) process (Hicks and Stewart 2022) may provide a stronger basis for future management success and stability than annual decisions based on stock assessment results.

Data sources

The Pacific halibut data sources are collected with sampling designs created to produce results first for each IPHC Regulatory Area, and then to be aggregated to Biological Regions and to the entire range of the species in U.S. and Canadian waters (Figure 1). This section provides a brief overview of the key types of data available for analysis. A more in-depth summary can be found in the annual overview of data sources created each year and most recently for the 2018 stock assessment (Stewart and Webster 2019). Where specific improvements to existing data sources have been included in this assessment (i.e., sex-ratios from the 2017 commercial landings and the revised modelled survey time-series) changes are described below.

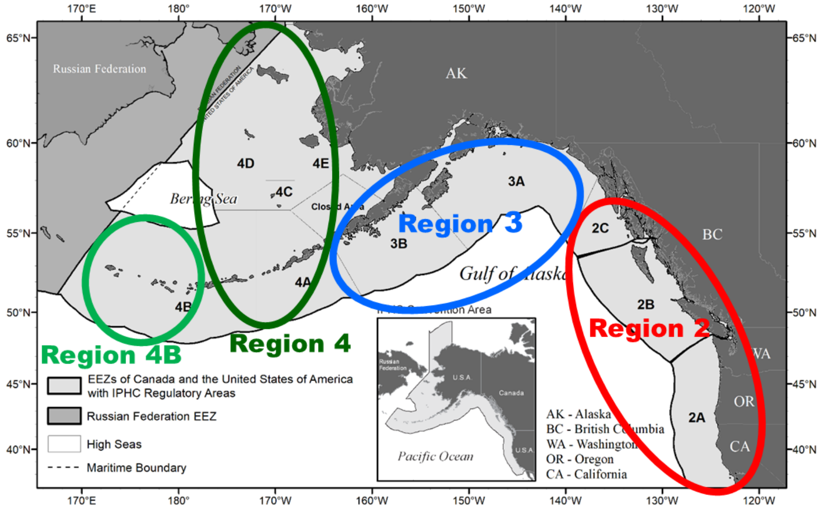

Figure 1. IPHC Regulatory Areas, Biological Regions, and the Pacific halibut geographical range within the territorial waters of Canada and the United States of America.

Overview of existing data

The time-series' of Pacific halibut data (described and plotted in much more detail in Stewart and Webster 2022) provide a rich historical record including mortality estimates, abundance indices (Catch-Per-Unit-Effort; CPUE) and age-composition data that extend back to the late 1800s and early 1900s (Figure 2). The IPHC's Fishery Independent Setline Survey (Ualesi et al. 2022; Webster 2022) provides the primary index of abundance and the most rich source of demographic information via individual weight, length and age data. The FISS includes Pacific halibut as young as 4-5 years old, which are below the IPHC's 32 inch (82 cm) minimum size limit (Stewart et al. 2021). Thus, these fish are observed several years prior to entry into the retained fishery landings which are sampled at the point of landing (Kong et al. 2022) and do not contain biological or catch-rate information on younger fish. Annual mortality estimates are provided to the IPHC from a variety of sources (Kong et al. 2022) including the directed halibut fisheries (commercial, recreational and subsistence) as well as incidental mortality associated with discards in directed fisheries and discard mortality in non-directed fisheries ('bycatch') that are not allowed to legally retain Pacific halibut. Each of these sources have differing levels of precision and likely accuracy associated with the estimates used for stock assessment.

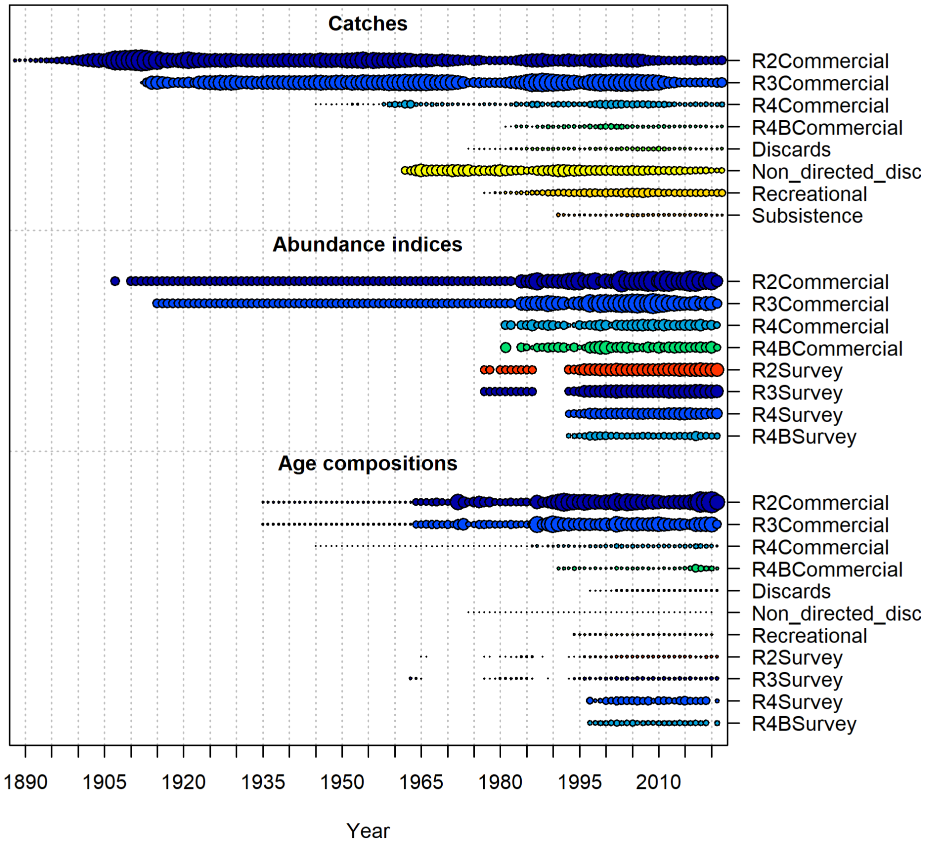

Figure 2. Data used in the stock assessment. Circle size is proportional to the magnitude of mortality (catches), inversely proportional to the variance (abundance indices) or proportional to the sample size (age-composition data).

Mortality

The industrial Pacific halibut fishery developed first off the west coast of the United States and Canada and sequentially moved to the north (Stewart and Webster 2022), only reaching full exploitation across all spatial areas in the last several decades. Mortality from non-directed discards increased rapidly with the arrival of foreign fleets into U.S. and Canadian waters in the 1960s. Recreational mortality has also increased over the time-series, although somewhat more gradually, since its initiation in the 1970s (Figure 3).

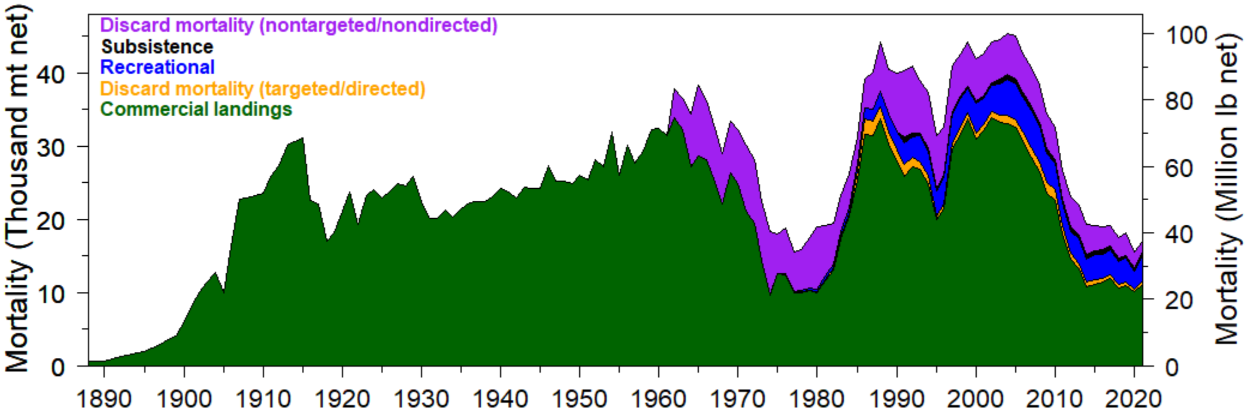

Figure 3. Time-series of mortality estimates by source.

Index data

The IPHC's FISS comprises the primary index of recent abundance and the primary source of biological data for use in the stock assessment. Index values (Table 1) are used in this assessment in numbers of halibut captured per unit effort (NPUE). The recent time-series (1993-2021) is based on the output of the IPHC's space-time model (Webster 2022; Webster et al. 2020) which estimates the degree of spatial and temporal correlation among survey stations in order to predict trends in biomass and abundance across the entire range of Pacific halibut within the IPHC Convention Area. This index provides precise trend information by IPHC Regulatory Area, which are weighted by the relative spatial bottom area and combined to Biological Regions and a coastwide index. The variances are summed, accounting for the square of the weights, and converted to log(SE) for use in the assessment model assuming log-normal error. There were geographically limited surveys conducting during 1963-1989, with summarized catch rates, but no variance estimates available from 1977 (Table 1). For the period prior to 1993 where there are no variance estimates, twice the recent average value is used, and for the coastwide series where spatial coverage is incomplete values are doubled again.

Commercial fishery CPUE (generally referred to as Weight-Per-Unit-Effort or WPUE as landings are recorded in weight) is reported through mandatory logbooks (voluntary only for vessels under 26 feet, 7.9 m, in length), collected by IPHC port samplers, or returned directly to the IPHC by mail. Commercial CPUE is available as far back as the early 1900s (Stewart and Webster 2022) providing a valuable historical record, but spanning a period of continuous fishery development and change, including an important transition to circle hooks in 1984 that substantially increased average catchability (Table 2-4).

Table 1. Modelled survey Numbers-Per-Unit-Effort (NPUE) and log(SE) 1993-2021, raw average observed NPUE 1977-1986; assumed values in italics.

	Region 2		Region 3		Region 4		Region 4B		Coastwide	
Year	Index	log(SE)	Index	log(SE)	Index	log(SE)	Index	log(SE)	Index	log(SE)
1977	0.60	*0.109*	2.00	*0.108*	--	--	--	--	1.47	*0.153*
1978	0.80	*0.109*	1.30	*0.108*	--	--	--	--	1.11	*0.153*
1979	--	--	1.90	*0.108*	--	--	--	--	--	--
1980	1.20	*0.109*	2.50	*0.108*	--	--	--	--	2.01	*0.153*
1981	0.80	*0.109*	3.80	*0.108*	--	--	--	--	2.67	*0.153*
1982	1.84	*0.109*	3.80	*0.108*	--	--	--	--	2.87	*0.153*
1983	2.30	*0.109*	3.40	*0.108*	--	--	--	--	2.88	*0.153*
1984	6.74	*0.109*	11.60	*0.108*	--	--	--	--	9.30	*0.153*
1985	5.65	*0.109*	11.90	*0.108*	--	--	--	--	8.94	*0.153*
1986	4.54	*0.109*	7.80	*0.108*	--	--	--	--	6.26	*0.153*
1993	6.19	0.102	24.17	0.123	1.90	0.147	10.34	0.329	7.40	0.088
1994	7.42	0.106	23.80	0.100	2.16	0.127	10.58	0.298	7.70	0.070
1995	8.85	0.074	25.55	0.089	2.15	0.119	10.80	0.244	8.28	0.061
1996	7.90	0.059	26.35	0.059	2.34	0.099	11.05	0.187	8.41	0.043
1997	7.19	0.055	28.31	0.055	2.54	0.069	11.23	0.115	8.81	0.039
1998	6.13	0.055	24.55	0.056	2.65	0.069	11.17	0.114	7.96	0.039
1999	5.09	0.053	23.82	0.058	2.38	0.073	9.47	0.125	7.41	0.041
2000	5.61	0.054	25.66	0.050	2.50	0.069	8.64	0.132	7.88	0.037
2001	6.49	0.052	22.46	0.050	2.35	0.066	6.74	0.161	7.20	0.036
2002	6.45	0.050	24.98	0.046	2.26	0.069	4.92	0.178	7.56	0.034
2003	5.52	0.052	24.64	0.050	2.16	0.069	4.08	0.206	7.24	0.037
2004	5.06	0.053	27.74	0.048	2.15	0.068	3.83	0.201	7.76	0.037
2005	5.53	0.053	23.25	0.048	2.23	0.068	3.68	0.208	6.99	0.036
2006	5.47	0.051	22.29	0.049	2.31	0.061	4.25	0.192	6.87	0.035
2007	6.09	0.053	23.75	0.048	2.26	0.064	5.42	0.178	7.28	0.035
2008	6.08	0.051	21.49	0.049	2.51	0.069	5.22	0.176	6.97	0.034
2009	6.17	0.052	20.14	0.049	2.49	0.065	4.40	0.188	6.67	0.034
2010	6.16	0.051	20.48	0.048	2.39	0.062	4.17	0.188	6.66	0.034
2011	6.16	0.049	20.78	0.048	2.27	0.061	4.21	0.173	6.65	0.034
2012	7.20	0.048	21.20	0.046	2.22	0.057	3.84	0.184	6.85	0.031
2013	6.97	0.047	16.45	0.046	2.01	0.058	5.29	0.146	5.82	0.031
2014	7.21	0.046	19.31	0.044	2.04	0.051	4.72	0.163	6.42	0.030
2015	7.96	0.048	19.43	0.044	2.07	0.054	4.69	0.149	6.57	0.030
2016	8.10	0.046	19.80	0.046	1.96	0.056	5.25	0.137	6.63	0.031
2017	5.85	0.045	13.99	0.042	1.82	0.061	4.11	0.090	4.98	0.028
2018	5.19	0.043	12.75	0.042	1.71	0.063	4.30	0.137	4.58	0.029
2019	5.30	0.045	11.53	0.044	1.70	0.066	4.31	0.166	4.34	0.031
2020	4.98	0.046	11.85	0.046	1.65	0.083	4.34	0.204	4.33	0.034
2021	5.72	0.046	15.19	0.048	1.60	0.071	4.25	0.183	5.08	0.034

Table 2. Commercial fishery Weight-Per-Unit-Effort (WPUE) 1907-1949 and estimated log(SE); assumed values in italics.

	Region 2		Region 3		Region 4		Region 4B		Coastwide	
Year	Index	log(SE)	Index	log(SE)	Index	log(SE)	Index	log(SE)	Index	log(SE)
1907	280.00	*0.100*	--	--	--	--	--	--	280.00	*0.100*
1910	271.00	*0.100*	--	--	--	--	--	--	271.00	*0.100*
1911	237.00	*0.100*	--	--	--	--	--	--	237.00	*0.100*
1912	176.00	*0.100*	--	--	--	--	--	--	176.00	*0.100*
1913	128.94	*0.100*	--	--	--	--	--	--	129.00	*0.100*
1914	124.13	*0.100*	--	--	--	--	--	--	124.00	*0.100*
1915	118.02	*0.100*	266.10	*0.100*	--	--	--	--	118.00	*0.100*
1916	114.60	*0.100*	202.80	*0.100*	--	--	--	--	137.00	*0.100*
1917	81.80	*0.100*	157.90	*0.100*	--	--	--	--	98.00	*0.100*
1918	87.50	*0.100*	125.40	*0.100*	--	--	--	--	96.00	*0.100*
1919	82.30	*0.100*	129.90	*0.100*	--	--	--	--	93.00	*0.100*
1920	84.10	*0.100*	147.90	*0.100*	--	--	--	--	96.00	*0.100*
1921	76.46	*0.100*	141.17	*0.100*	--	--	--	--	88.00	*0.100*
1922	62.44	*0.100*	133.79	*0.100*	--	--	--	--	73.00	*0.100*
1923	56.68	*0.100*	149.97	*0.100*	--	--	--	--	78.00	*0.100*
1924	55.39	*0.100*	109.13	*0.100*	--	--	--	--	74.00	*0.100*
1925	51.21	*0.100*	94.63	*0.100*	--	--	--	--	68.00	*0.100*
1926	51.67	*0.100*	93.73	*0.100*	--	--	--	--	67.00	*0.100*
1927	48.83	*0.100*	86.32	*0.100*	--	--	--	--	65.00	*0.100*
1928	47.27	*0.100*	72.34	*0.100*	--	--	--	--	58.00	*0.100*
1929	38.55	*0.100*	70.79	*0.100*	--	--	--	--	51.00	*0.100*
1930	34.44	*0.100*	65.91	*0.100*	--	--	--	--	46.00	*0.100*
1931	38.48	*0.100*	76.17	*0.100*	--	--	--	--	50.00	*0.100*
1932	47.50	*0.100*	83.49	*0.100*	--	--	--	--	60.00	*0.100*
1933	50.16	*0.100*	83.99	*0.100*	--	--	--	--	63.00	*0.100*
1934	54.07	*0.100*	74.97	*0.100*	--	--	--	--	62.00	*0.100*
1935	61.77	*0.100*	97.57	*0.100*	--	--	--	--	76.00	*0.100*
1936	54.66	*0.100*	96.70	*0.100*	--	--	--	--	71.00	*0.100*
1937	61.48	*0.100*	109.99	*0.100*	--	--	--	--	80.00	*0.100*
1938	70.33	*0.100*	114.29	*0.100*	--	--	--	--	88.00	*0.100*
1939	61.90	*0.100*	112.21	*0.100*	--	--	--	--	80.00	*0.100*
1940	61.71	*0.100*	116.38	*0.100*	--	--	--	--	81.00	*0.100*
1941	62.54	*0.100*	122.26	*0.100*	--	--	--	--	85.00	*0.100*
1942	65.43	*0.100*	132.54	*0.100*	--	--	--	--	90.00	*0.100*
1943	72.24	*0.100*	131.27	*0.100*	--	--	--	--	95.00	*0.100*
1944	86.84	*0.100*	149.23	*0.100*	--	--	--	--	110.00	*0.100*
1945	79.69	*0.100*	130.86	*0.100*	--	--	--	--	102.00	*0.100*
1946	83.78	*0.100*	123.82	*0.100*	--	--	--	--	101.00	*0.100*
1947	86.30	*0.100*	114.56	*0.100*	--	--	--	--	99.00	*0.100*
1948	88.61	*0.100*	112.20	*0.100*	--	--	--	--	99.00	*0.100*
1949	85.01	*0.100*	105.89	*0.100*	--	--	--	--	95.00	*0.100*

Table 3. Commercial fishery Weight-Per-Unit-Effort (WPUE) 1950-1991 and estimated log(SE); assumed values in italics.

	Region 2		Region 3		Region 4		Region 4B		Coastwide	
Year	Index	log(SE)	Index	log(SE)	Index	log(SE)	Index	log(SE)	Index	log(SE)
1950	87.66	*0.100*	103.60	*0.100*	--	--	--	--	95.00	*0.100*
1951	87.63	*0.100*	108.93	*0.100*	--	--	--	--	96.00	*0.100*
1952	95.58	*0.100*	128.86	*0.100*	--	--	--	--	110.00	*0.100*
1953	128.65	*0.100*	134.32	*0.100*	--	--	--	--	131.00	*0.100*
1954	137.97	*0.100*	127.43	*0.100*	--	--	--	--	133.00	*0.100*
1955	122.20	*0.100*	116.32	*0.100*	--	--	--	--	119.00	*0.100*
1956	132.02	*0.100*	126.05	*0.100*	--	--	--	--	129.00	*0.100*
1957	100.95	*0.100*	119.84	*0.100*	--	--	--	--	110.00	*0.100*
1958	101.96	*0.100*	139.96	*0.100*	--	--	--	--	121.00	*0.100*
1959	98.67	*0.100*	160.62	*0.100*	--	--	--	--	129.00	*0.100*
1960	105.02	*0.100*	156.08	*0.100*	--	--	--	--	132.00	*0.100*
1961	96.00	*0.100*	159.79	*0.100*	--	--	--	--	127.00	*0.100*
1962	84.76	*0.100*	136.89	*0.100*	--	--	--	--	115.00	*0.100*
1963	77.73	*0.100*	123.89	*0.100*	--	--	--	--	105.00	*0.100*
1964	75.27	*0.100*	120.10	*0.100*	--	--	--	--	100.00	*0.100*
1965	86.47	*0.100*	107.07	*0.100*	--	--	--	--	99.00	*0.100*
1966	82.59	*0.100*	112.72	*0.100*	--	--	--	--	100.00	*0.100*
1967	81.44	*0.100*	113.00	*0.100*	--	--	--	--	101.00	*0.100*
1968	86.58	*0.100*	111.62	*0.100*	--	--	--	--	103.00	*0.100*
1969	81.53	*0.100*	105.07	*0.100*	--	--	--	--	95.00	*0.100*
1970	73.62	*0.100*	103.67	*0.100*	--	--	--	--	91.00	*0.100*
1971	76.05	*0.100*	96.31	*0.100*	--	--	--	--	89.00	*0.100*
1972	69.47	*0.100*	82.87	*0.100*	--	--	--	--	78.00	*0.100*
1973	64.41	*0.100*	62.13	*0.100*	--	--	--	--	63.00	*0.100*
1974	60.89	*0.100*	61.95	*0.100*	--	--	--	--	61.00	*0.100*
1975	61.87	*0.100*	66.76	*0.100*	--	--	--	--	61.00	*0.100*
1976	44.39	*0.100*	61.91	*0.100*	--	--	--	--	55.00	*0.100*
1977	64.17	*0.100*	65.57	*0.100*	--	--	--	--	63.00	*0.100*
1978	54.06	*0.100*	68.47	*0.100*	--	--	--	--	71.00	*0.100*
1979	55.80	*0.100*	67.33	*0.100*	--	--	--	--	75.00	*0.100*
1980	59.54	*0.100*	116.09	*0.100*	--	--	--	--	94.00	*0.100*
1981	73.84	*0.100*	148.86	*0.100*	136.84	*0.100*	99.00	0.078	111.00	*0.100*
1982	71.85	*0.100*	181.34	*0.100*	98.68	*0.100*	--	--	127.00	*0.100*
1984	151.95	0.045	491.33	0.046	386.90	*0.100*	161.00	0.103	316.00	0.035
1985	161.59	0.051	535.06	0.039	456.18	0.099	234.00	0.160	352.00	0.034
1986	137.26	0.035	506.00	0.042	308.70	0.062	238.00	0.372	315.00	0.041
1987	135.53	0.027	490.38	0.036	360.93	0.159	220.00	0.111	316.00	0.038
1988	168.40	0.054	560.55	0.042	405.68	0.105	224.00	0.122	363.00	0.036
1989	154.92	0.042	507.69	0.031	387.41	0.078	268.00	0.094	353.00	0.025
1990	194.64	0.043	403.54	0.036	370.26	0.095	209.00	0.103	315.00	0.029
1991	170.62	0.039	375.02	0.041	367.06	0.157	329.00	0.085	314.00	0.038

Table 4. Commercial fishery Weight-Per-Unit-Effort (WPUE) 1992-2021 and estimated log(SE).

	Region 2		Region 3		Region 4		Region 4B		Coastwide	
Year	Index	log(SE)	Index	log(SE)	Index	log(SE)	Index	log(SE)	Index	log(SE)
1992	167.66	0.040	413.39	0.048	324.01	0.117	280.00	0.095	315.00	0.035
1993	200.04	0.031	439.11	0.096	399.87	0.448	218.00	0.220	369.00	0.100
1994	175.74	0.027	362.77	0.049	343.14	0.333	197.00	0.101	302.00	0.069
1995	190.73	0.025	439.48	0.043	330.22	0.100	189.00	0.336	326.00	0.037
1996	208.81	0.042	505.01	0.046	427.58	0.138	269.00	0.185	387.00	0.039
1997	237.52	0.035	498.02	0.026	417.44	0.107	275.00	0.064	400.00	0.025
1998	221.23	0.029	512.59	0.036	411.86	0.089	287.00	0.058	402.00	0.025
1999	249.48	0.079	475.49	0.024	385.64	0.061	310.00	0.045	390.00	0.023
2000	227.94	0.036	492.21	0.025	403.74	0.082	318.00	0.046	396.00	0.020
2001	202.84	0.039	454.52	0.029	363.00	0.213	270.00	0.076	358.00	0.042
2002	214.81	0.032	466.46	0.025	296.56	0.082	245.00	0.081	356.00	0.020
2003	208.95	0.018	439.27	0.024	251.12	0.072	196.00	0.068	325.00	0.018
2004	192.88	0.028	425.79	0.026	235.23	0.072	202.00	0.061	315.00	0.019
2005	178.98	0.024	387.69	0.023	219.59	0.063	238.00	0.093	293.00	0.017
2006	180.22	0.024	360.70	0.022	178.26	0.064	218.00	0.111	268.00	0.019
2007	158.14	0.023	344.27	0.026	154.65	0.055	230.00	0.108	249.00	0.020
2008	138.83	0.020	318.17	0.024	162.55	0.071	193.00	0.069	229.00	0.017
2009	152.95	0.020	277.22	0.020	174.43	0.055	189.00	0.097	220.00	0.018
2010	185.21	0.037	242.32	0.024	143.97	0.080	142.00	0.063	202.00	0.020
2011	179.95	0.019	226.65	0.025	143.25	0.056	165.00	0.103	196.00	0.015
2012	193.96	0.020	213.46	0.032	139.17	0.080	149.00	0.066	193.00	0.021
2013	192.78	0.026	189.98	0.033	122.70	0.072	127.00	0.064	178.00	0.017
2014	210.44	0.026	182.93	0.039	116.04	0.092	146.00	0.070	183.00	0.022
2015	217.37	0.024	224.46	0.045	136.04	0.065	149.00	0.076	202.00	0.025
2016	212.66	0.019	216.22	0.044	128.30	0.066	123.00	0.083	196.00	0.020
2017	213.02	0.020	219.60	0.037	126.95	0.079	120.00	0.082	202.00	0.020
2018	197.07	0.026	191.12	0.056	115.12	0.058	134.00	0.071	178.00	0.028
2019	186.60	0.030	213.51	0.038	101.85	0.100	115.00	0.084	180.00	0.022
2020	175.93	0.025	216.61	0.041	100.27	0.084	105.00	0.059	178.00	0.022
2021	197.63	*0.055*	206.85	*0.090*	120.82	*0.164*	94.00	*0.152*	182.00	*0.049*

Age data

At each FISS station, otoliths are sampled randomly at rates selected to generate 1500 per IPHC Regulatory Area per year. The number of stations contributing to the annual age information varies considerably over the time-series, with Biological Region 3 the most heavily sampled, followed by Region 2, Region 4 and far fewer samples collected in Region 4B (Table 5). There are also a small number of geographically limited surveys from the period 1963-1966 for which there are age samples, but no corresponding index. Otoliths from the commercial fishery landings are also sampled in proportion to the weight of the catch with different rates by IPHC Regulatory Area (Kong et al. 2022). This has led to a relatively larger number of commercial trips sampled in Biological Region 2 over most of the historical period, with Region 3, Region 4, and Region 4B each contributing fewer samples (Table 6-7).

Table 5. Number of stations contributing to FISS age data (1963-2021).

Year	Region 2	Region 3	Region 4	Region 4B	Coastwide
1963	--	236	--	--	236
1964	--	305	--	--	305
1965	121	146	--	--	267
1966	66	--	--	--	66
1977	58	100	--	--	158
1978	62	98	--	--	160
1979	--	104	--	--	104
1980	80	101	--	--	181
1981	72	102	--	--	174
1982	154	148	--	--	302
1983	192	101	--	--	293
1984	241	198	--	--	439
1985	166	103	--	--	269
1986	178	97	--	--	275
1988	72	--	--	--	72
1989	--	33	--	--	33
1993	66	70	--	--	136
1994	14	147	--	--	161
1995	103	120	--	--	223
1996	198	424	--	--	622
1997	211	424	220	74	929
1998	228	507	100	42	877
1999	332	554	61	82	1029
2000	239	548	149	83	1019
2001	330	520	146	83	1079
2002	313	555	154	82	1104
2003	323	516	153	82	1074
2004	327	523	145	70	1065
2005	340	507	144	81	1072
2006	317	526	240	84	1167
2007	330	538	176	73	1117
2008	338	549	166	76	1129
2009	333	537	171	84	1125
2010	333	521	172	76	1102
2011	358	549	166	79	1152
2012	354	522	168	71	1115
2013	364	528	167	78	1137
2014	381	556	227	76	1240
2015	352	529	239	81	1201
2016	350	538	220	72	1180
2017	371	521	166	118	1176
2018	466	537	167	77	1247
2019	482	560	167	81	1290
2020	370	494	--	--	864
2021	393	550	77	37	1057

Table 6. Number of commercial fishing trips contributing to fishery age data (1935-1982); historical values in italics are assumed.

Year	Region 2	Region 3	Region 4	Region 4B	Coastwide
1935	*50*	*50*	--	--	*100*
1936	*50*	*50*	--	--	*100*
1937	*50*	*50*	--	--	*100*
1938	*50*	*50*	--	--	*100*
1939	*50*	*50*	--	--	*100*
1940	*50*	*50*	--	--	*100*
1941	*50*	*50*	--	--	*100*
1942	*50*	*50*	--	--	*100*
1943	*50*	*50*	--	--	*100*
1944	*50*	*50*	--	--	*100*
1945	*50*	*50*	*5*	--	*100*
1946	*50*	*50*	*5*	--	*100*
1947	*50*	*50*	*5*	--	*100*
1948	*50*	*50*	*5*	--	*100*
1949	*50*	*50*	*5*	--	*100*
1950	*50*	*50*	*5*	--	*100*
1951	*50*	*50*	*5*	--	*100*
1952	*50*	*50*	*5*	--	*100*
1953	*50*	*50*	*5*	--	*100*
1954	*50*	*50*	*5*	--	*100*
1955	*50*	*50*	*5*	--	*100*
1956	*50*	*50*	*5*	--	*100*
1957	*50*	*50*	*5*	--	*100*
1958	*50*	*50*	*5*	--	*100*
1959	*50*	*50*	*5*	--	*100*
1960	*50*	*50*	*5*	--	*100*
1961	*50*	*50*	*5*	--	*100*
1962	*50*	*50*	*5*	--	*100*
1963	*50*	*50*	*5*	--	*100*
1964	116	100	14	--	230
1965	118	106	12	--	238
1966	102	113	12	--	228
1967	125	133	20	--	278
1968	135	132	14	--	282
1969	113	102	12	--	227
1970	97	125	18	--	241
1971	82	77	9	--	168
1972	552	196	3	--	752
1973	311	262	5	--	578
1974	153	68	3	--	226
1975	234	76	7	--	320
1976	332	135	7	--	476
1977	247	138	7	--	401
1978	241	120	4	--	377
1979	125	101	6	--	244
1980	140	113	1	--	262
1981	146	90	7	--	248
1982	168	137	11	--	316

Table 7. Number of commercial fishing trips contributing to fishery age data (1983-2021).

Year	Region 2	Region 3	Region 4	Region 4B	Coastwide
1983	133	106	23	6	268
1984	170	90	9	13	282
1985	171	99	14	2	286
1986	158	152	34	1	345
1987	531	498	76	12	1117
1988	278	258	19	16	571
1989	318	371	39	24	752
1990	491	560	50	3	1104
1991	718	496	62	12	1288
1992	1027	478	61	20	1586
1993	959	471	65	11	1506
1994	896	474	89	31	1490
1995	887	468	72	37	1464
1996	859	437	76	27	1399
1997	676	429	183	58	1346
1998	515	277	127	47	966
1999	454	303	118	24	899
2000	512	358	119	27	1016
2001	505	233	117	13	868
2002	561	284	163	53	1061
2003	545	266	118	49	978
2004	491	200	75	9	775
2005	461	193	125	13	792
2006	483	256	81	22	842
2007	429	218	95	12	754
2008	385	221	98	11	715
2009	432	240	68	14	754
2010	354	260	97	25	736
2011	383	224	83	14	704
2012	421	217	81	13	732
2013	455	196	73	14	738
2014	426	221	64	8	719
2015	476	192	119	15	802
2016	466	164	112	15	757
2017	410	175	106	17	708
2018	337	178	105	17	637
2019	409	199	116	10	734
2020	406	176	47	12	641
2021	272	126	30	7	435

As has been the case since the 2015 stock assessment (Stewart and Martell 2016), all age data used in the stock assessment is aggregated into bins of ages from age-2 to age-25, with age 2 representing a ‘minus’ group including all fish of age 2 and younger, and age 25 representing a ‘plus’ group including all fish age 25 and older. For years prior to 2002 (except the survey ages from 1998 which were re-aged in 2013), surface ages were the standard method, replaced by break-and-bake in recent years. Because surface ages are known to be biased at older ages (Forsberg and Stewart 2015), the age data are aggregated at a lower ‘plus’ group, age 20+, for all years where this was the primary method.

Beginning with the 2019 stock assessment, sex-specific fishery age data has been available via the collection of fin clips and subsequent genetic assay based on sampling begun in 2017. The processing of these samples lags one-year, thus for the 2021 stock assessment there were four years of sex-specific fishery age compositions used (2017-2020). They are compiled in an identical manner to the standard fishery age data, but delineating males and females through the weighting and aggregation up to Biological Regions and coastwide.

Other biological and fishery information

There are several other sources of information contributing to the stock assessment models. These include:

1) the time-series of the Pacific Decadal Oscillation (PDO) index
2) the maturity ogive
3) fecundity information
4) weight-at-age
5) length-weight relationship
6) ageing error (bias and imprecision)
7) data based ‘priors’ on bycatch, discard, and recreational selectivity

The only significant changes to the treatment of these sources of information since the 2015 stock assessment (Stewart and Martell 2016), is the introduction of a revised length-weight relationship in 2021 (Webster and Stewart 2022). Because the directly measured weights collected during the FISS (since 2019) and the commercial sampling (2015) have been used directly in the stock assessment data preparation, the updated length-weight relationship has little effect on the assessment, except through potentially more accurate calculations by domestic agencies of mortality in weight from piece counts (this is relevant to non-directed discard mortality, recreational mortality and subsistence mortality). These effects will be realized gradually as calculation routines are updated and data sources are reported to the IPHC.

All other sources of information are updated (where appropriate) and described each year in the annual overview of data sources (Stewart and Webster 2022). For convenience, the treatment of each is briefly summarized in Table 8.

Table 8. Summary of other information sources contributing directly to stock assessment input files (Stewart and Webster 2022).

Input	Summary	Key assumptions
Pacific Decadal Oscillation index[1]	Monthly values averaged and compiled into a binary index for each year based on assignment to 'positive' and 'negative' phases	Used as a binary indicator rather than annually varying values (but see sensitivity analyses below).
Maturity	Trimmed logistic from Clark and Hare (2006); 50% female maturity at 11.6 years old.	Based on visual assessments, treated as age-based and time-invariant.
Fecundity	Assumed to be proportional to body weight.	Temporal variability is included via changes in weight-at-age.
Weight-at-age	Reconstructed from survey and fishery information by Biological Region.	Historical variability has been similar for female and male Pacific halibut.
Length-weight relationship	Not used directly in the assessment, most of the historical data relies on a constant average length-weight relationship.	Measured weights are used preferentially where available.
Ageing error	Pacific halibut are relatively easy to age accurately and with a high degree of precision using the break-and-bake method (Clark 2004a, 2004b; Clark and Hare 2006; Piner and Wischnioski 2004). Surface ages are biased and less precise (Stewart 2014).	Multi-decadal comparison suggest that accuracy and precision have not changed appreciably over the entire historical record (Forsberg and Stewart 2015).
Bycatch selectivity prior	Age-distributions are created from weighted and aggregated length frequencies from a variety of sources and age-length keys from trawl surveys.	Due to incomplete sampling, poor data quality in many years, and other uncertainties, data are considered unreliable for estimation of recruitment.
Discard selectivity prior	Age-distributions of sub-legal (<32 inch) Pacific Halibut captured by the FISS are used as a proxy for poorly sampled directed commercial fishery discards.	Survey data may not be representative of commercial fishing behavior but are currently the only source of information on the age range of discarded fish.
Recreational selectivity prior	Weighted age-frequency data from the IPHC Regulatory Area 3A recreational fishery are the only comprehensive source available.	These data may not be representative of all recreational mortality but provide the best information currently available.

External information on M

In 2021 a CAPAM workshop on natural mortality (formal report still pending) was held with the objective of developing best practices for the treatment of *M* in stock assessment modelling. Two primary conclusions were evident from the discussions at the workshop:

1) Although results are varied, simulations have generally indicated that estimation of *M* is preferable to the use of fixed values, where this is possible. The use of informative priors is frequently necessary, with the most common prior based on longevity.
2) Elevated *M* at the youngest ages/smallest sizes should be expected due to increased size-dependent predation mortality.

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[1] Data can be accessed at: https://oceanview.pfeg.noaa.gov/erddap/tabledap/cciea_OC_PDO.htmlTable?time,PDO

For the 2022 Pacific halibut assessment, both of these conclusions were evaluated for inclusion into the four stock assessment models. First, an age-independent prior on *M* for Pacific halibut was developed based on the meta-analysis of Hamel (2014; and subsequently updated, Hamel pers. comm.), which uses the prediction interval based on a meta-analysis of the maximum observed age for a wide range of species. Both male and female Pacific halibut have been observed to age-55 (with multiple fish of both sexes exceeding age-50 indicating that this is likely to be an accurate estimate of longevity, and not an artifact of a single case of ageing imprecision). The prior median is given by:

$$M = \frac{5.4}{Age_{max}}$$

which results in a value of 0.0982, and a log(SD) of 0.438. With such a large variance, this prior is only weakly informative (Figure 4), but still may provide additional stability for estimation of *M*.

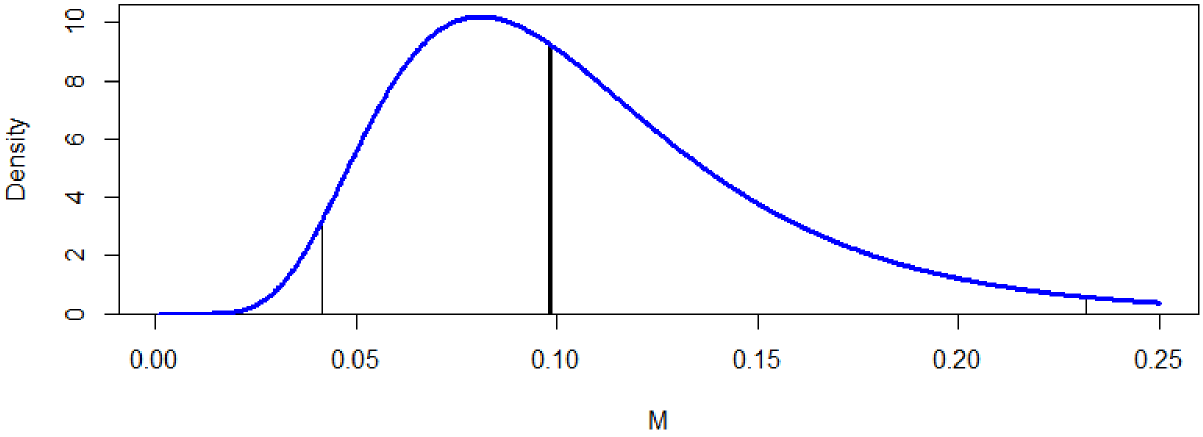


Figure 4. Informative prior for *M*. Thick vertical line denotes the median, thin lines the 2.5 and 97.5 percentiles of the distribution.

To explore the potential that *M* for Pacific halibut should be size-dependent, the average size at age was described from trawl survey data, which provides the best source of information on fish that are too small to be reliably captured with commercial or FISS longline gear. Sexual dimorphism is relatively small at the youngest ages, and rapid growth of both males and females proceeds at approximately 10 cm per year for the first 5-6 years of life (Figure 5).

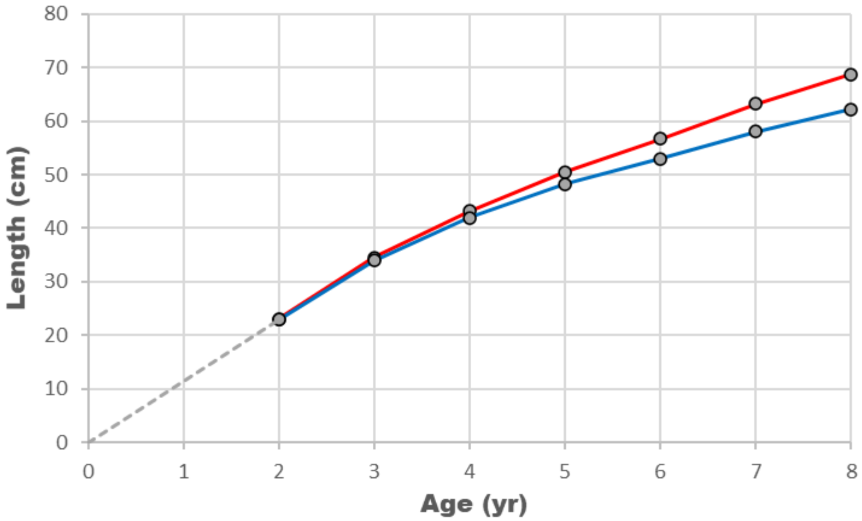


Figure 5. Average Pacific halibut length-at-age based on recent trawl survey data; the red line denotes females, and the blue line denotes males. The dashed line is a simple extrapolation for unobserved ages 0-1, assuming zero length at age-0.

Because of their very rapid growth, it might be expected that Pacific halibut would endure a lower *M* at age than other flatfish congeners, and so any meaningful comparison might be best summarized in terms of size. To explore how Pacific halibut size-at-age and *M* compare to other flatfish species, a summary of all available Northeast Pacific flatfish stock assessments was conducted. For each assessment, the estimate or fixed value of *M* and the average asymptotic size (either L_{inf} or L_{old}, depending on the parameterization) was recorded, separated by males and females where possible, as dimorphic growth is relatively common among flatfish. Complete data were available for 26 stocks spread over four geographical regions comprising the U.S. West Coast, British Columbia, Gulf of Alaska, and the Bering Sea (Table 8, Figure 6). These stocks represented 14 individual species, of which all but 5 reported sex-specific *M* and maximum size. There was no clear pattern of higher *M* for smaller flatfish, although the highest *M* values all occurred for flatfish with asymptotic size of approximately 60 cm (Figure 6) and for every stock with separate *M* values by sex, the higher *M* was associated with a smaller maximum size. A key result of this comparison is that flatfish with maximum sizes of >35 cm had natural mortality values both above and below those used for Pacific halibut. As Pacific halibut reach this size by age-3, this suggests that strongly elevated natural mortality due to predation common across flatfish species is likely to occur primarily below this age. Also of note is that the Hamel prior for Pacific halibut derived above contains the majority of the flatfish species examined within the 95% prediction interval.

Table 9. Summary of M and L_{inf} values from all available Northeast Pacific flatfish stocks. Where sex-specific values were not reported the combined value is included in the female column; in some cases only females were modelled and male values are missing. Region abbreviations: C GOA indicates the central Gulf of Alaska, W GOA the Western Gulf and E Goa the Eastern Gulf; BSAI indicates the Bering Sea and Aleutian Islands, BC the waters off British Columbia and WC the waters off the west coast of the continental United States.

		M		L_{inf}		
Species	Region	female	male	female	male	Reference
Northern rock sole	C GOA	0.200	0.232	50.29	41.92	Bryan and Palsson (2021)
Northern rock sole	W GOA	0.200	0.254	45.47	37.72	
Southern rock sole	C GOA	0.200	0.253	51.43	39.86	
Southern rock sole	W GOA	0.200	0.271	48.67	39.15	
Flathead sole	GOA	0.200	--	44.40	--	Turnock et al. (2017)
Arrowtooth flounder	GOA	0.200	0.350	83.76	52.41	Shotwell et al. (2021)
Rex sole	W GOA	0.170	0.170	46.83	41.02	McGilliard and Palsson (2021)
Rex sole	E GOA	0.170	0.170	36.73	34.64	
Dover sole	GOA	0.113	0.119	50.75	43.44	McGilliard et al. (2019)
Yellowfin sole	GOA	0.200	--	34.00	--	Bryan and Ferriss (2021)
Alaska plaice	BSAI	0.130	0.130	50.10	49.90	Ormseth (2021)
Flathead sole	BSAI	0.200	0.200	44.88	37.57	Monnahan and Haehn (2020)
Kamchatka flounder	BSAI	0.110	0.110	79.60	60.73	Bryan et al. (2020a)
Arrowtooth flounder	BSAI	0.200	0.350	84.83	52.70	Shotwell et al. (2020)
Greenland turbot	BSAI	0.112	0.112	90.29	71.99	Bryan et al. (2020b)
Yellowfin sole	BSAI	0.120	0.135	38.03	34.03	Spies et al. (2021)
Rock sole	BC	0.200	--	50.50	--	Holt et al. (2016)
English sole	BC	0.200	--	49.40	--	Starr (2009b)
Petrale sole	BC	0.210	0.210	56.30	45.80	Starr (2009a)
Arrowtooth flounder	BC	0.328	--	60.90	47.80	Grandin and Forrest (2017)
Dover sole	WC	0.108	0.114	48.05	41.98	Wetzel and Berger (2021)
Petrale sole	WC	0.159	0.164	53.12	40.83	Wetzel (2019)
Arrowtooth flounder	WC	0.216	0.300	69.77	44.40	Sampson et al. (2017)
Pacific sanddab	WC	0.459	0.566	30.33	26.47	He et al. (2013)
English sole	WC	0.260	0.260	40.56	23.99	Stewart (2007)
Starry flounder	WC	0.500	0.750	59.10	49.70	Ralston (2005)

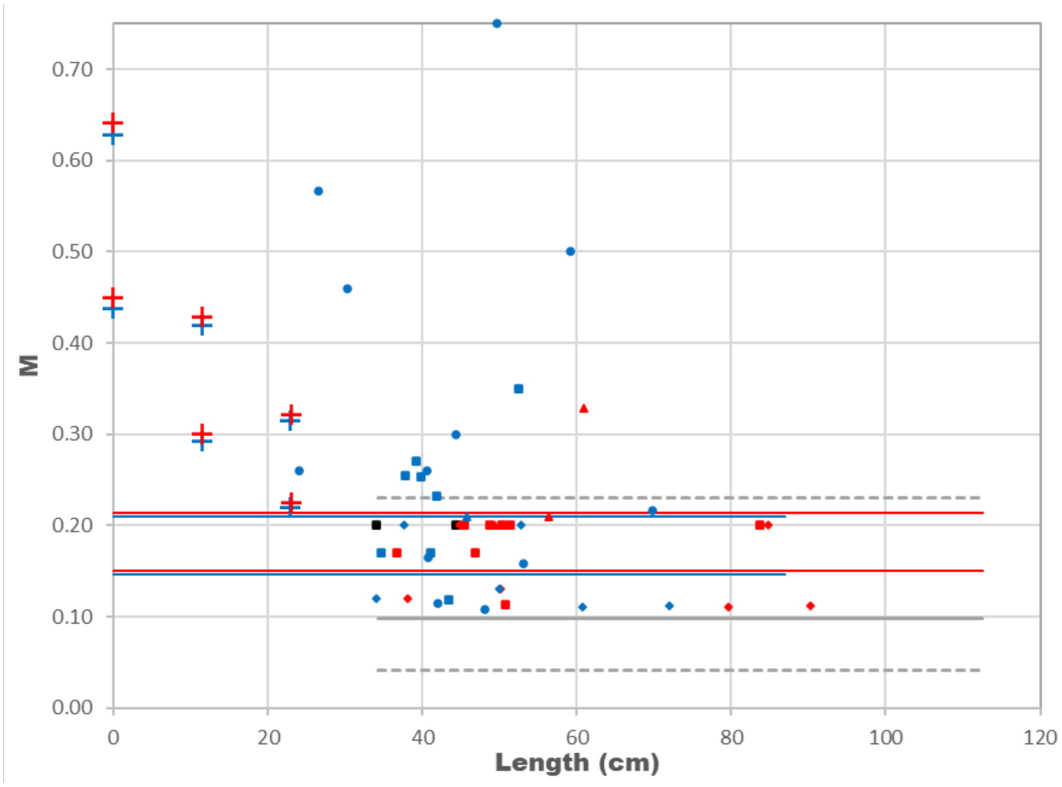


Figure 6. Average natural *M* for 26 Northeast Pacific flatfish stocks: males denoted by blue symbols, females by red symbols, combined sexes by black symbols. Regions are indicated by the point type: diamonds are the Bering Sea, squares are the Gulf of Alaska, triangles are British Columbia, and circles are the U.S. West Coast. The Hamel prior for Pacific halibut is shown as the grey line, with the dashed grey lines representing the 95% prediction interval. Solid red and blue lines denote the highest and lowest 2021 stock assessment estimates of *M* for ages 0-8, females in red, males in blue. Crosses denote the *M* at the average size for Pacific halibut ages 0-2 proposed for use in the 2022 stock assessment.

With very little data to inform a consistent level of *M* for Pacific halibut less than 35 cm (corresponding to ages 0-2) it was necessary to consider other sources of information. Ecosystem models that include predator-prey dynamics generally suggest much higher *M* for the youngest age classes of NE Pacific groundfish (Adams et al. 2022). Where this information has been applied in other assessments used for management advice somewhat arbitrary scalars such as 1.5 x *M* for age 2, 2 x *M* for age-1 and *3* x *M* for age-0 are generally consistent with ecosystem models (e.g., Ianelli et al. 2021). Applying this general approach to Pacific halibut would allow for size-dependent *M* that is consistent with theoretical concepts (Figure 6) but does not appreciably change the natural mortality used for ages represented in observed fishery and survey data (exclusively age 2+). With little to no data at these youngest ages, any effect is likely to ‘scale out’ in the absolute estimates of recruitment deviations; however, when an index of recruitment is evaluated (i.e., the PDO in this assessment; see sensitivity analyses below) it may be important to include elevated *M* at these ages.

Bootstrapping input sample sizes for age compositions

Data weighting in the Pacific halibut stock assessment has historically relied on the number of sampled FISS stations and number of sampled commercial fishery trips as a starting point for all models. Investigation of alternative tuning procedures and likelihoods has been necessarily conditioned on these starting values, yet they had not been evaluated specifically. Following the method developed in Stewart and Hamel (2014) effective sample sizes based on the actual distribution and weighting of both the samples and the fish within samples were bootstrapped for use as inputs to the 2022 stock assessment. Briefly, this method randomly resamples FISS stations (or commercial trips) with replacement from each stratum (IPHC Regulatory Areas for FISS data), then randomly resamples fish within those samples with replacement. Each bootstrapped data set is then used to construct a new age composition. The new age composition is then compared to the actual, and the effective sample size (McAllister and Ianelli 1997; Stewart and Hamel 2014) is calculated. From a set of bootstraps, the harmonic mean of the effective sample size provides an unbiased estimate of the central tendency, provided that sufficient bootstraps have been conducted to avoid appreciable Monte-Carlo error (in this case 10,000 was found to produce <0.5% variability in replicate data sets).

The effective sample size calculated in this manner is analogous to a minimum variance estimate – the actual effective sample size may be lower than calculated if not all strata are fully sampled (measurement error), of the source of the data differs from that assumed in the assessment (structural or process error). However, the effective sample size cannot be larger than the bootstrapped value simply due to the among and within sample variability and the sample sizes achieved. Thus, although time-consuming to produce, the approach provides an objective starting point for data weighting, and a logical upper bound on sample sizes used in the stock assessment models.

For Pacific halibut, the results of this bootstrapping analysis indicated that the effective sample size across all composition data was approximately four times the raw number of samples collected, albeit with considerable interannual variability (Figure 7). Important differences were evident between the fishery data and the FISS data and among geographical aggregations (Table 10). FISS age compositions tended to have slightly lower effective sample sizes per sample than the commercial fishery, consistent with fishery samples representing entire trips, potentially fishing several locations with the fish mixed before sampling occurs at the dock. To the degree that fish school by size and age, it is expected that all fish in each sample will not be independent (e.g., Pennington and Volstad 1994) and thus the effective sample size will tend to be less than the nominal sample size but still increase as additional fish are added to the sample over some range, until the clustering of fish makes additional samples necessary to increase the effective sample size further. In some cases where clustering occurs at a broader scale than the sampling (e.g., young/small fish in one area, old/large fish in another, even samples are not independent and thus the effective sample size can be less than the number of samples. This was observed for Biological Region 4B and was particularly pronounced for the FISS data (Table 10, Figure 8-9).

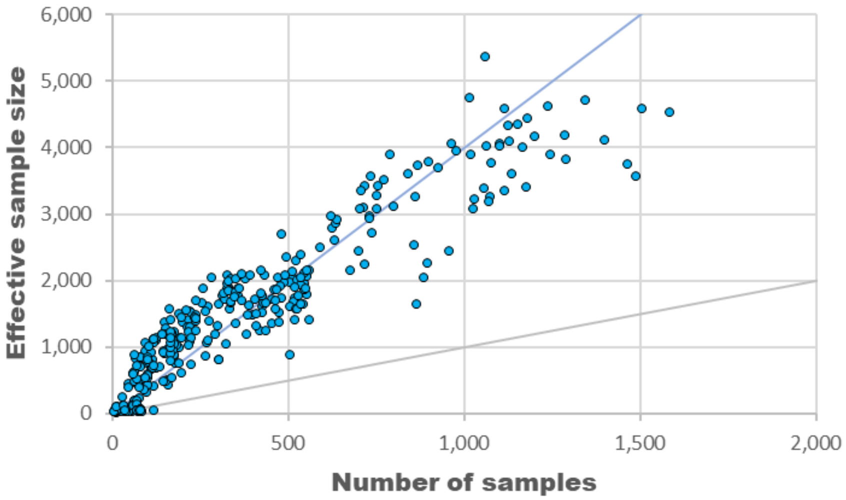


Figure 7. Number of samples vs. bootstrapped effective sample size for all FISS and fishery age compositions data. Grey line indicates a 1:1 relationship, blue line indicates a 4:1 relationship.

Table 10. Summary of bootstrapping results by data type and spatial aggregation.

Data type	Aggregation	Mean effective N per sample
FISS	Coastwide	3.7
FISS	Region 2	5.1
FISS	Region 3	4.1
FISS	Region 4	6.5
FISS	Region 4B	0.6
All fishery	Coastwide	4.1
All fishery	Region 2	3.6
All fishery	Region 3	5.6
All fishery	Region 4	8.8
All fishery	Region 4B	2.6
Sexed fishery	Coastwide	4.1
Sexed fishery	Region 2	3.9
Sexed fishery	Region 3	5.5
Sexed fishery	Region 4	7.9
Sexed fishery	Region 4B	4.4
Unsexed fishery	Coastwide	4.1
Unsexed fishery	Region 2	3.6
Unsexed fishery	Region 3	5.7
Unsexed fishery	Region 4	8.9
Unsexed fishery	Region 4B	2.3

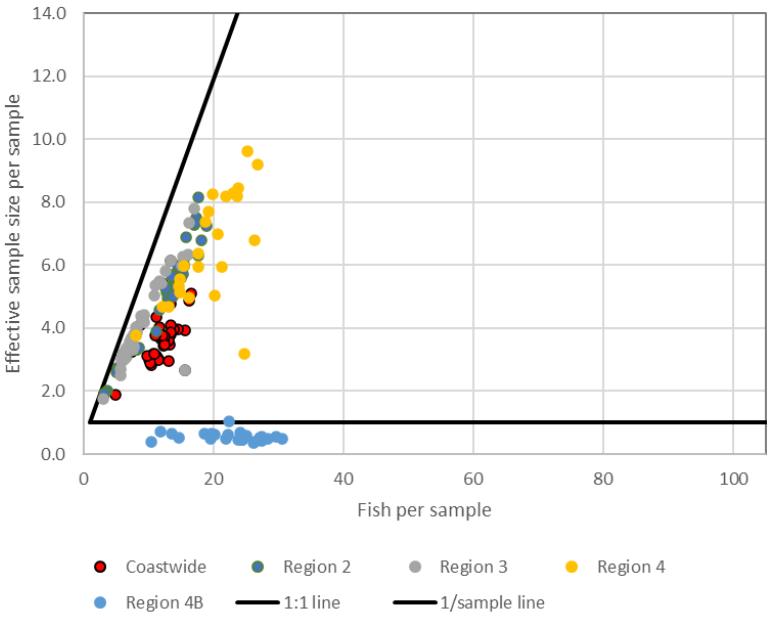


Figure 8. Effective sample size per FISS station sampled for age data as a function of the number of fish sampled by Biological region and coastwide. Diagonal line indicates complete independence among fish within a sample, horizontal line indicates clustering such that fish within samples are not independent. See Stewart and Hamel (2014) for more information.

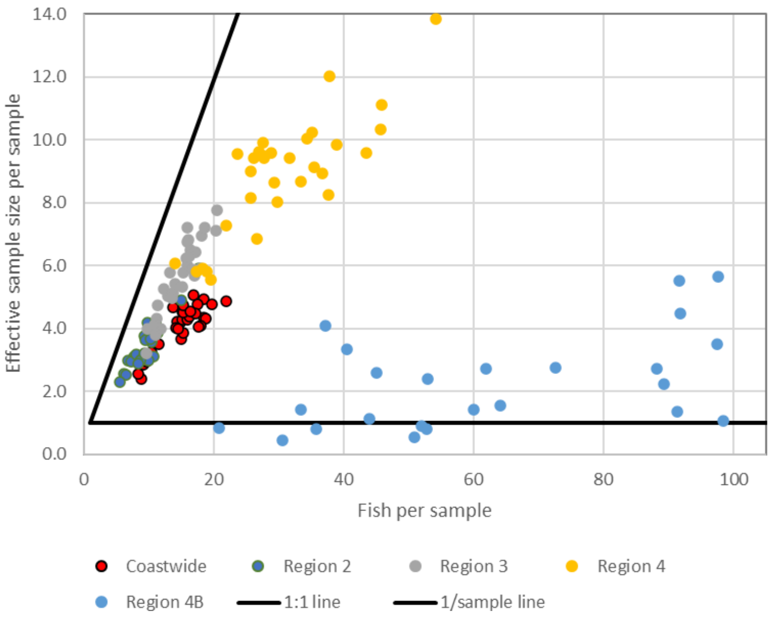


Figure 9. Effective sample size per commercial trip sampled for sexes-aggregated age data as a function of the number of fish sampled by Biological region and coastwide. Diagonal line indicates complete independence among fish within a sample, horizontal line indicates clustering such that fish within samples are not independent. See Stewart and Hamel (2014) for more information.

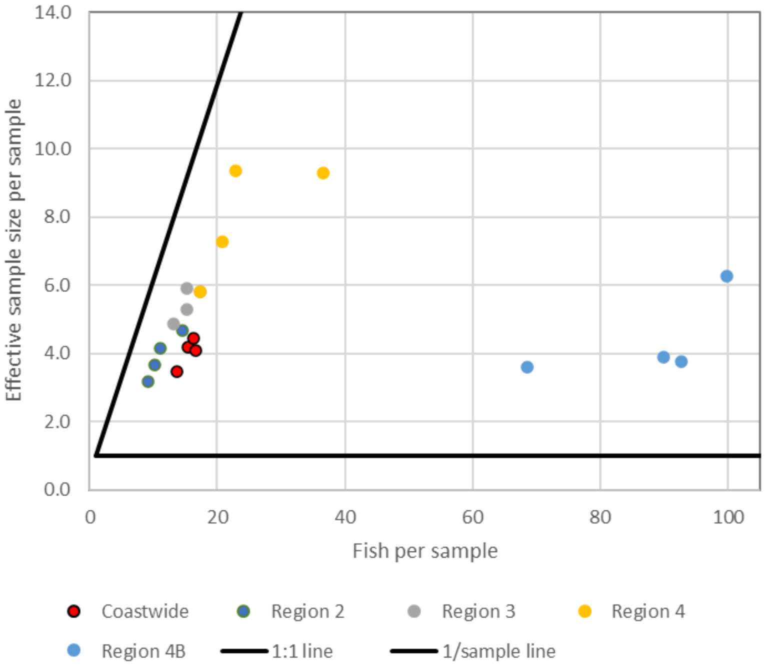


Figure 10. Effective sample size per commercial trip sampled for sex-specific ages as a function of the number of fish sampled by Biological region and coastwide. Diagonal line indicates complete independence among fish within a sample, horizontal line indicates clustering such that fish within samples are not independent. See Stewart and Hamel (2014) for more information.

Because early fishery data are unavailable in current IPHC data bases, age compositions prior to 1991 were unable to be bootstrapped. Instead, the average relationship between the number of samples and the bootstrapped effective sample size (Table 10) was used to approximate effective sample sizes for use as starting values in the assessment models. Bootstrapped FISS (Table 11) and fishery (Table 12-13) effective sample sizes are provided below.

Table 11. Bootstrapped effective sample size for FISS age data (1963-2021).

Year	Region 2	Region 3	Region 4	Region 4B	Coastwide
1963	--	1,448	--	--	1,448
1964	--	814	--	--	814
1965	403	479	--	--	866
1966	180	--	--	--	180
1977	117	403	--	--	506
1978	121	309	--	--	433
1979	--	418	--	--	418
1980	216	541	--	--	744
1981	186	797	--	--	946
1982	480	938	--	--	1,313
1983	746	589	--	--	1,181
1984	1,384	599	--	--	1,239
1985	1,127	567	--	--	1,057
1986	1,229	525	--	--	1,091
1988	139	--	--	--	139
1989	--	121	--	--	121
1993	481	514	--	--	692
1994	105	921	--	--	962
1995	839	716	--	--	1,086
1996	1,434	2,141	--	--	2,970
1997	1,548	1,796	1,226	42	3,685
1998	729	882	347	29	1,640
1999	1,903	1,779	586	50	3,225
2000	1,484	1,942	1,370	49	3,888
2001	2,082	1,725	1,194	54	3,769
2002	1,776	2,049	1,275	53	4,056
2003	1,721	1,683	1,180	39	3,253
2004	1,877	2,297	1,189	46	4,025
2005	1,676	1,595	1,187	54	3,190
2006	1,805	2,000	1,233	34	4,002
2007	1,943	2,386	1,047	41	4,575
2008	2,027	1,862	1,401	31	4,084
2009	1,989	1,927	542	31	4,335
2010	1,831	1,886	1,200	37	4,019
2011	1,765	2,107	1,224	37	4,353
2012	1,819	1,568	897	36	3,348
2013	1,868	1,560	782	37	3,605
2014	2,018	2,145	1,126	47	4,620
2015	2,015	1,761	1,431	36	4,170
2016	1,751	2,036	1,030	35	4,429
2017	1,696	1,399	985	47	3,405
2018	1,572	1,637	1,064	36	3,899
2019	2,692	1,403	1,132	41	3,819
2020	2,098	2,070	--	--	3,247
2021	2,068	1,885	387	39	3,382

Table 12. Bootstrapped effective sample size for commercial fishery age data (1964-2011).

Year	Region 2	Region 3	Region 4	Region 4B	Coastwide
1964	*412*	*565*	*124*	--	*935*
1965	*419*	*599*	*107*	--	*968*
1966	*362*	*639*	*107*	--	*927*
1967	*444*	*752*	*178*	--	*1,130*
1968	*480*	*746*	*124*	--	*1,146*
1969	*402*	*577*	*107*	--	*923*
1970	*345*	*707*	*160*	--	*980*
1971	*291*	*435*	*80*	--	*683*
1972	*1,961*	*1,108*	*27*	--	*3,057*
1973	*1,105*	*1,481*	*44*	--	*2,350*
1974	*544*	*384*	*27*	--	*919*
1975	*831*	*430*	*62*	--	*1,301*
1976	*1,180*	*763*	*62*	--	*1,935*
1977	*878*	*780*	*62*	--	*1,630*
1978	*856*	*678*	*36*	--	*1,533*
1979	*444*	*571*	*53*	--	*992*
1980	*497*	*639*	*9*	--	*1,065*
1981	*519*	*509*	*62*	--	*1,008*
1982	*597*	*775*	*98*	--	*1,285*
1983	*473*	*599*	*204*	--	*1,090*
1984	*604*	*509*	*80*	--	*1,146*
1985	*608*	*560*	*124*	--	*1,163*
1986	*561*	*859*	*302*	--	*1,403*
1987	*1,887*	*2,816*	*675*	--	*4,541*
1988	*988*	*1,459*	*169*	--	*2,321*
1989	*1,130*	*2,098*	*346*	--	*3,057*
1990	*1,745*	*3,166*	*444*	--	*4,488*
1991	2,242	2,350	593	49	4,181
1992	3,069	1,907	604	48	4,519
1993	2,446	2,031	617	30	4,575
1994	2,258	1,521	516	80	3,560
1995	2,032	1,861	436	31	3,744
1996	2,532	1,660	448	38	4,116
1997	2,148	1,770	1,017	26	4,700
1998	2,035	1,391	1,096	38	4,054
1999	1,713	1,637	1,110	27	3,776
2000	2,133	1,878	1,122	24	4,741
2001	1,967	1,454	802	14	3,727
2002	2,155	2,042	1,569	43	5,359
2003	1,645	1,540	1,061	26	3,944
2004	1,975	1,364	766	30	3,512
2005	1,862	1,497	1,141	29	3,892
2006	1,737	1,661	703	34	3,595
2007	1,607	1,400	1,054	27	3,280
2008	1,486	1,536	876	32	3,086
2009	1,651	1,702	818	19	3,078
2010	1,349	1,875	928	17	3,569
2011	1,190	1,510	833	20	3,072

Table 13. Bootstrapped effective sample size for commercial fishery age data (2012-2021). 2017-2020 represent bootstrapping of the sex-specific age data.

Year	Region 2	Region 3	Region 4	Region 4B	Coastwide
2012	1,248	1,300	837	19	2,970
2013	1,353	1,129	719	38	2,712
2014	1,514	1,297	885	27	3,416
2015	1,373	987	1,120	43	3,105
2016	1,689	966	912	67	3,414
2017	1,316	1,100	1,013	96	3,342
2018	1,655	883	763	47	2,860
2019	1,500	1,127	673	55	2,936
2020	1,713	1,031	388	42	2,917
2021	1,605	672	241	31	2,076

Mortality due to marine mammal depredation

Recent stock assessments have investigated the sensitivity to additional mortality due to marine mammal depredation. Adding mortality generally results in an increase in the scale of the estimated population size: unmodelled whale depredation effectively represents unobserved productivity (Figure 19 in Stewart and Hicks 2022). However, if trending rapidly, this unobserved mortality could also result in bias in the estimated population trend.

The sablefish stock assessment in Alaska (Goethel et al. 2021) accounts for marine mammal depredation by first estimating the effect on catch rates based on the difference in catch rates for depredated compared to non-depredated commercial fishing activity within spatial strata (Peterson et al. 2017; Peterson and Carothers 2013; Peterson et al. 2014). This approach implicitly assumes that depredation is independent of underlying population density and subsequent catch rates. These estimates are then combined with a frequency of interaction estimated from observer data and result in a relatively small positive adjustment to total expected mortality (1.5% for 2020-2021, Goethel et al. 2021).

Analysis of FISS marine mammal interactions indicates that the most important marine mammal depredation for Pacific halibut occurs due to sperm whales in IPHC Regulatory Area 3A and orca whales in IPHC Regulatory Area 4A (Webster 2021). When orca whales are present in IPHC Regulatory Area 4A FISS catch rates were estimated to be reduced to 51% of those when whales were not present, and 84%/86% for orca whales and sperm whales in IPHC Regulatory Area 3A. Because this approach is based on the space-time modelling and informed by the full FISS data set, it implicitly accounts for differences in the underlying biomass distribution. One possible path forward to estimating whale depredation in the Pacific halibut fishery would be to use these estimates of catch-rate reduction along with observations of whale interactions from the commercial fishery in order to estimate additional mortality due to marine mammal depredation associated with commercial fishing.

The IPHC added fields to the commercial fishery logbooks in 2017 for reporting of damage to fishing gear/catch (found to be indicative of marine mammal depredation from FISS observations) as well as the number and species of whales if any were observed. Informal results suggest incomplete participation in completing these fields in the logs –because they are still relatively new, because of the potential sensitivity of marine mammal interactions and because harvesters may not perceive a benefit to accurate reporting of this information. Further, there have been challenges in the collection of these data (e.g., consistent use of reporting codes) as well as processing this information in IPHC databases (e.g., accurate delineation of missing data vs. no marine mammal observations). For these reasons, the summaries provided in this section should be considered highly preliminary and will likely be revised in the future.

Preliminary evaluation of logbooks corresponding to commercial fishing sets targeting Pacific halibut suggest that for most IPHC Regulatory Areas a majority of sets have some information recorded and that completeness may be increasing slightly since the fields were added in 2017 (Figure 11). Using a relatively strict criteria that both some gear damage and at least one marine mammal must have been observed, the reported rate of depredation appears to be around 1% (Figure 12). Further delineating by marine mammal species supports FISS observations of orca activity being most important in IPHC Regulatory Area 4A, sperm whale activity being most important in IPHC Regulatory Area 3A and only a small fraction of interactions with pinnipeds (Figure 13). Raw average WPUE for sets identified as depredated vs. those that were not depredated suggests a similar reduction in catch rates to those estimated for FISS data when orcas were the source of depredation (Figure 14). For sperm whale and pinniped depredation, there was no clear reduction in catch rates; this could be explained by these species depredating in areas with higher catch rates than average, issues with categorizing depredation or other factors. are currently suggestive of trends observed in the FISS but appear to be inadequate. Published observer data on marine mammal interactions with commercial longline fisheries targeting Pacific halibut suggests a slightly higher rate than currently reported in logbooks, but considerable variability among years, either actual or due to relatively low observer coverage rates (supplementary table 3 in Dahlheim et al. 2022).

In aggregate, this preliminary evaluation of depredation suggests that there is some mortality occurring that is not modelled in the current stock assessment, but that it is relatively low, and that the effect is likely to create a slight underestimate of the stock size and productivity. More work is being conducted to determine necessary steps to improve reporting rates, data collection protocols and database issues. Pending these efforts, no formal correction to the mortality time-series is proposed for 2022.

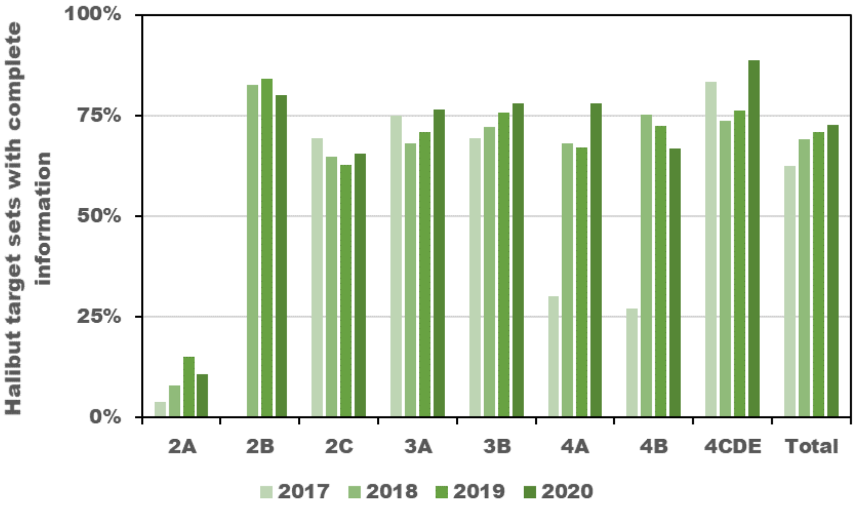


Figure 11. Percent of logbook-recorded sets with apparently complete information by IPHC Regulatory Area and year.

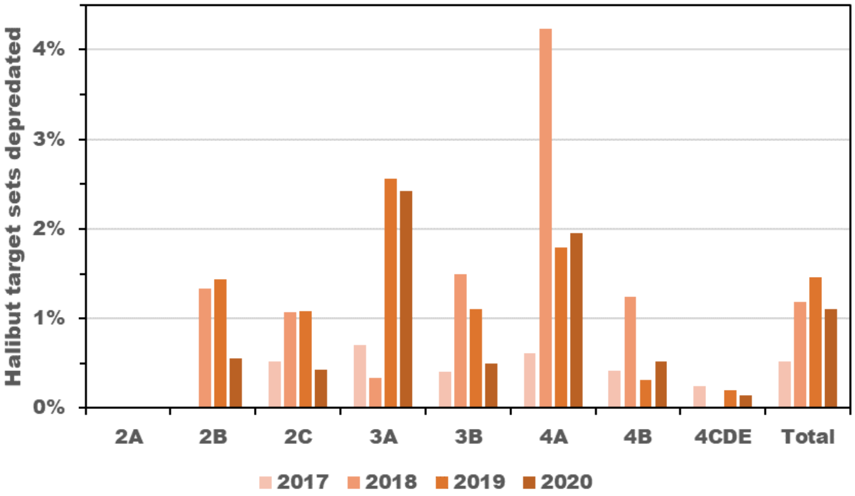


Figure 12. Percent of logbook-recorded sets with reported marine mammal depredation by IPHC Regulatory Area and year.

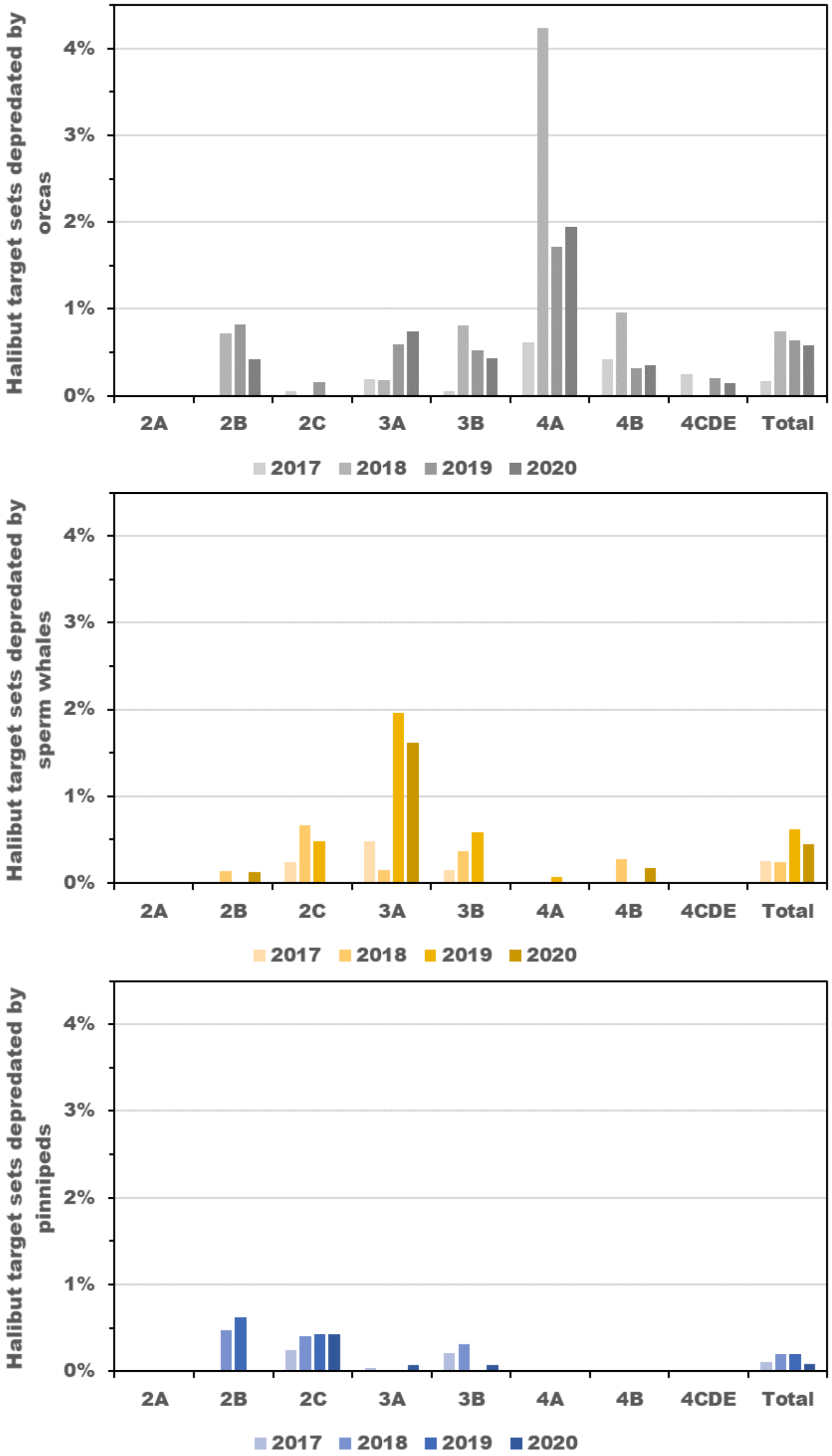


Figure 13. Percent of logbook-recorded sets with reported marine mammal depredation for orcas (upper panel), sperm whales (middle panel) and pinnipeds (lower panel) by IPHC Regulatory Area and year.

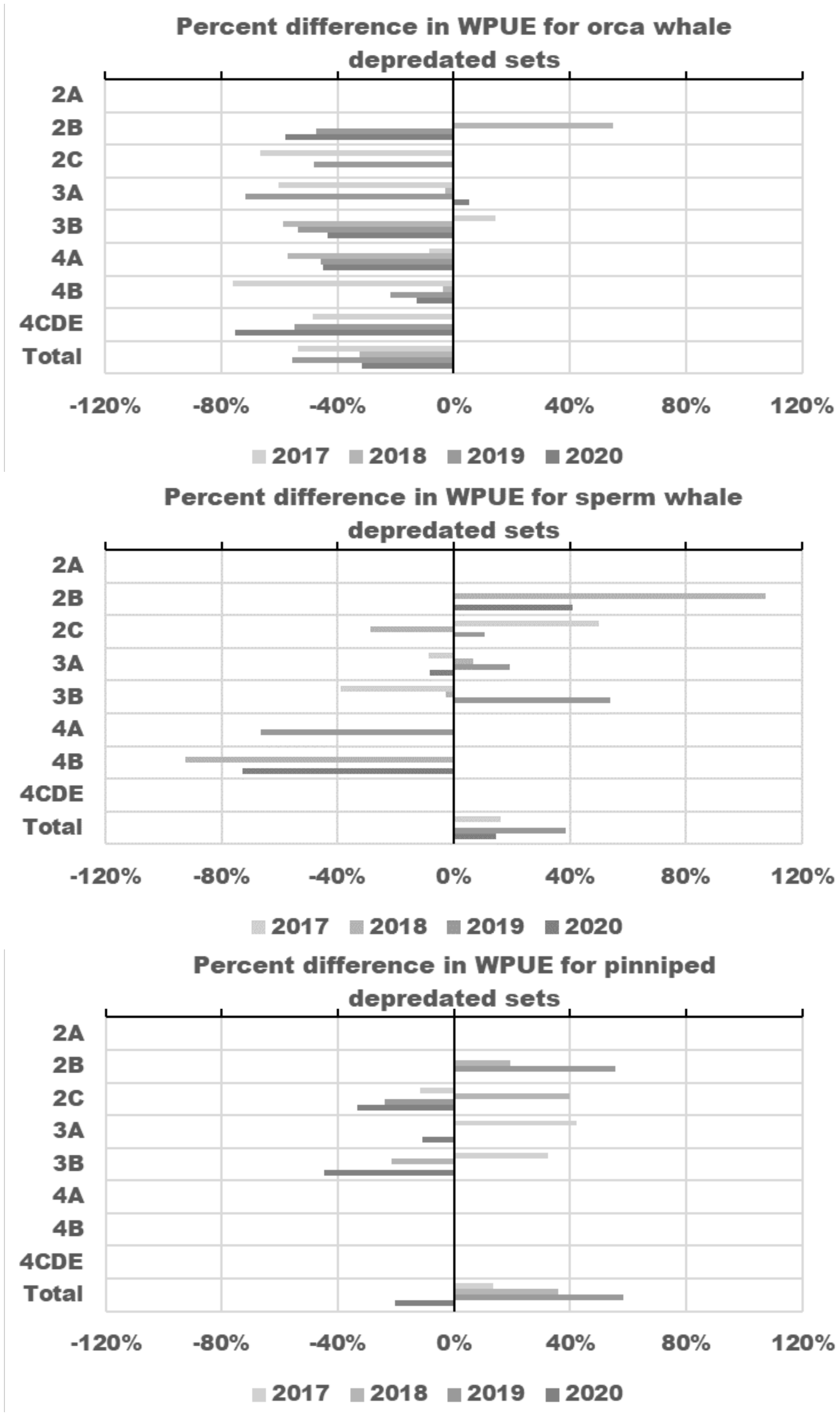


Figure 14. Percent difference in WPUE for logbook-recorded sets with reported marine mammal depredation for orcas (upper panel), sperm whales (middle panel) and pinnipeds (lower panel) compared to those with no reported depredation by IPHC Regulatory Area and year.

Model development

Multimodel approach

Creating robust, stable, and well-performing stock assessment models for the Pacific halibut stock has proven extremely challenging 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; Clark and Hare 2006). These changes have reflected improvements in fisheries analysis methods, changes in model assumptions, and responses to recurrent retrospective biases and other evidence of model mis-specification and concurrent degradation of model performance (Stewart and Martell 2014). Perhaps the most influential of these changes was the transition from separate IPHC Regulatory Area-specific assessment models to a coastwide model in 2006, as the understanding of adult movement among areas was substantially updated by the results of the IPHC's extensive PIT-tagging experiment in 2003-2009 (Clark and Hare 2006; Webster et al. 2013). Some simulation studies have found that dividing a migratory population into several discrete assessment units tends to overestimate the total biomass (e.g., Li et al. 2014; McGilliard et al. 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, the current ensemble of four stock assessment models, representing a two-way cross of short vs. long time series', and aggregated coastwide vs. AAF models was developed for the full assessment analysis and review in 2015 (Stewart and Martell 2016) and further improved in 2019 to accommodate sex-specific age composition data from the commercial fishery (Stewart and Hicks 2019b). AAF models are commonly applied when biological or sampling differences among geographical areas 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, 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 aggregate coastwide level. Both aggregating the data into a single series and approximating spatial dynamics via AAF approaches may be useful under some circumstances; however, there is no clear best-performing configuration under all conditions. Not surprisingly, models that most closely match the biology, which is only known under simulated conditions, tend to perform the best (Punt et al. 2015).

To capture the structural uncertainty inherent among the Pacific halibut stock assessment models, it is necessary to use multi-model inference, here referred to as an 'ensemble' of models (e.g., Ianelli et al. 2016; Karp et al. 2018; Stewart and Martell 2015). The ensemble approach, applied in many fields in addition to fisheries (Du 2014; Hamill et al. 2012), recognizes that there is no "perfect" or "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 2015). 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 (Stewart and Hicks 2018), and provides a more realistic perception of uncertainty than any single model, and therefore a stronger basis for risk assessment.

The current ensemble explicitly captures two critically important dimensions of uncertainty: how the time-series data are used via short and long models, and how the spatial information is treated in the models via data aggregation to the level of Biological Regions treated as separate fleets (AAF) or to the coastwide level. Inclusion of these sources of structural uncertainty results in wider confidence intervals than are commonly seen in single-model stock assessments (Stewart and Hicks 2019a). More detail on how the models are weighted and integrated can be found in the Ensemble section below.

Structural rationale

Consistent with analyses since 2015, this stock assessment is implemented using the generalized software stock synthesis (Methot and Wetzel 2013a), a widely used modeling platform developed at the National Marine Fisheries Service. This platform allows for a wide range of structural choices with regard to biology and growth, catchability, selectivity, spatial processes, stock-recruitment dynamics as well as error distributions and integrated projections. A benefit of using this code is that it is well documented, and the inputs and output formats are standardized (Methot Jr et al. 2021a), regardless of model configuration, allowing easy interpretation of model files and rapid evaluation of the results without re-running the fitting algorithm using the r4ss package (Taylor et al. 2021) implemented in the R programming language (https://cran.r-project.org/).

A primary structural stock assessment model choice is whether or not to model growth explicitly (and often parametrically) or empirically. Many stock assessments assert/estimate a growth function of some type and rely on this growth function to translate between numbers and biomass for model calculations. This approach has the benefits of allowing direct fitting to observed length observations, interpolating and/or extrapolating predictions for years where direct observations may be missing, as well as direct inclusion of the potential effects of selectivity at length on the observed data. The cost of such an approach is that growth can be an extremely complex process, varying over time, space and by cohort (via density dependence). When there is appreciable growth variability, a great deal of complexity may be required to adequately model this population process, even before sampling and selectivity issues have been addressed. Failure to account for this type of variability can lead to poor fits to composition data, potentially biasing the assessment results (Maunder et al. 2015, and subsequent special issue papers).

The Pacific halibut stock assessment models, like many other stock assessments with relatively complete age and size information, take a simpler approach to growth by using empirically derived weights-at-age. The empirical weight-at-age approach has the benefit of reducing complexity with regard to growth modelling but has several costs in other modelling areas. These include the need for more complexity in modelling selectivity, particularly where some of the selectivity process may be a function of size rather than age alone. This is the case for Pacific halibut, where the interaction of changes in size-at-age, gear selectivity that is likely at least partially a function of fish size, and a minimum size limit thus requires the treatment of selectivity-at-age as a time-varying process (Stewart and Martell 2014). However, the treatment of selectivity as time-varying appears to be a necessity for Pacific halibut even if treated as a function of size; static selectivity for a spatially aggregated model in the face of changes in availability was identified as a primary contributor to severe historical retrospective patterns (Stewart and Martell 2014).

There are relatively few examples of stock assessments used for management purposes that are explicitly spatial: modelling movement among areas, distributing recruitment events, and tracking spatial variability in biological characteristics (e.g., McGilliard and Palsson 2021; Stewart et al. 2009). Most such cases rely on low rates of movement to allow for estimation of recruitment distribution among areas. More frequently assessments either aggregate the available data across spatial heterogeneity (preferably weighting appropriately such that the aggregate information reflects the underlying distribution), or retain separate data series representing spatial areas, but fit to them in the context of a single instantaneously mixing population model (the AAF approach). These methods for dealing implicitly with spatial dynamics are by necessity gross approximations, with performance properties specific to a particular application that are unknown, and almost certainly depend on the true underlying processes. Some simulation studies have shown that fisheries operating in different areas with differing selectivity schedules can be reasonably approximated by an AAF approach (e.g., Waterhouse 2014). Other studies have found acceptable performance of AAFs when simulating actual spatial variability (e.g., Hurtado et al. 2014, McGilliard et al. 2014); however additional studies have found that combining spatial data into weighted aggregates also performs acceptably and may be more stable than more complex AAF approaches (Punt et al. 2015, Li et al. 2015). A primary conclusion from simulation-based studies is that if the true underlying process is well-represented, then models reflecting these dynamics tend to perform well (Goethel and Berger 2017). Unfortunately, in the case of Pacific halibut it is not clear whether aggregated or AAF models might be the best choice as neither approach accurately represents the complex spatial dynamics.

The choice of how long a time-series to model generally represents a compromise among: data availability, data quality, model complexity, and technical convenience (e.g., data preparation and model convergence times). As assessment model time series' are extended to include more historical data, commonly the quality of those data becomes increasingly lower as standardization of sampling programs has a greater likelihood of having changed appreciably. In the case of Pacific halibut, fishery-independent survey information has been reasonably comprehensive since approximately 1997, and sufficient to support the recently developed geostatistical model since 1993 (Webster 2018). Current fishery sampling approaches have also not changed dramatically over the same period. The completeness of this time period with regard to data availability was one of the primary incentives for stock assessment models used by the IPHC since 2006 to begin the modelled period in 1996. Notable differences prior to that period included the transition in the survey and fishery from “J” to circle hooks, variable and much less comprehensive survey coverage, lack of access to raw historical fishery data (ages, catch rates, etc.), and many others. The costs of using only a relatively short time-series include a lack of integration between harvest strategy calculations derived from full historical period, a lack of perspective on recent trends, the need for careful treatment of initial model conditions, inability to estimate some parameters, and increased sensitivity to additional data, as each year represents a greater fraction of the total information available in the model. These trade-offs prompted the development of the first long time-series model in 2013, with the recognition that neither the short or long time-series approach was clearly superior, and that differences in the results reflected a meaningful source of uncertainty in the assessment results.

All of the halibut models considered here treat male and female halibut separately. Like many broadcast spawning fishes, there is a basic assumption that spawning is likely to be limited primarily by female spawning output and not by male abundance (at least over a reasonable range of sex-ratios; this is generally not a concern except for cases such as some crab stocks where fishery mortality may operate primarily on males). If the sex-ratio could be expected to be stable over time, it might be reasonable to structure assessment models without regard to sex and/or just assume half of the mature biomass represented females. However, for Pacific halibut, highly dimorphic growth interacting with gear selectivity for larger fish, and a fishery in which there are strong incentives to target the larger females (due to the minimum size limit and graduated price structure) results in sex-ratios of the catch and of the landings skewed largely toward females. Historical modelling suggested that the potential for a static assumption regarding sex-ratio could lead to a highly biased interpretation of stock status and that females and males are best modelled separately.

In aggregate, these considerations led to the choice of four stock assessment models during the 2014 assessment process: a two-way cross of: coastwide vs. AAF data structuring, and long vs. short time-series. Each of these models explicitly treated male and female halibut separately and employed empirical weight-at-age rather than an explicit growth function. All models fit to both fishery and survey index trends and age compositions and allowed for temporal variability in selectivity and catchability. Additional alternative modelling approaches were considered, including a simple surplus production model and a Virtual Population Analysis model. Both of these approaches suggested that recent removals and stock trends were on a similar scale to the four models included in that assessment (Stewart and Martell 2015) but presented sufficiently substantial issues in interpretation or application to the management process that they were not formally included in the final stock assessment.

General model configuration

There are a number of basic technical settings and features that are common to all four stock assessment models described here. This section provides an overview, which is supplemented by a description of specific individual model details below.

The stock synthesis software separates inputs into several files read in prior to model estimation including the primary data file, the primary control file (including parameter setup and estimation switches), the weight-at-age file, the forecast file (including settings for reference point calculations), and the starter file (including some general estimation and reporting switches and settings). Each of these input files for each of the four stock assessment models described here are included in the background documents, along with the primary report file of estimated and derived quantities and the directory of summary and diagnostic figures created by r4ss (see Appendix A). Note that not all automatically created diagnostic material is relevant to the model configurations employed here.

These models were configured to make use of relatively standard population structuring. There were no seasonal dynamics, and catches were assumed to be removed halfway through the year via Pope's approximation. This approach does not require iterative estimation of fleet- and year-specific fishing mortality rate parameters (often reducing model run times) and should reasonably approximate the dynamics unless fishing mortality rates are extremely high. Catches were input in thousands of pounds (net weight; head-off and gutted, approximately 75% of round weight), so that the mean weight-at-age inputs were in net pounds and the numbers-at-age are tracked in thousands of individuals. Population dynamics contain ages 0-30, and female and male halibut are modelled separately in the underlying dynamics.

The input data were partitioned via a fleet structure of: the directed fishery (by area in the AAF models), discard mortality from the directed fishery, non-directed discard mortality ('bycatch'), recreational, subsistence, and survey (FISS; by area in the AAF models). Table 14 summarizes the data and key features of each model (note that all changes from the 2021 model are described in greater detail below). Age data were partitioned by sex (the vectors for each year contain females, then males, such that the sex-ratio is inherently included in the age compositions), where this information was available and assigned the appropriate ageing method in the data file (see section above). Where few fish contribute to the 'tails' of the age distributions for each fleet and year combination, the model was set to automatically aggregate observations and predictions at each of the low and high ages with proportions less than 0.1%. This choice avoids large vectors of zeroes in the multinomial calculations. The model was also set up to add a very small constant (0.0001) to all age proportions in order to stabilize the computation.

Table 14. Comparison of structural assumptions among models.

	Model			
	Coastwide Short	Coastwide Long	AAF Short	AAF Long
Modelled period[1]	1992+	1888+	1992+	1888+
Data partitions	N/A	N/A	Regions 2, 3, 4, 4B	Regions 2, 3, 4, 4B
Directed Fishery fleets	1	1	4	4
Other fishing fleets	4	4	4	4
Survey fleets	1	1	4	4
Fishery CPUE (weight)	1992+	1907+	1992+	1907+, 1915+, 1981+, 1981+
Fishery age data years	1992+	1935+	1992+	1935+, 1935+, 1945+, 1991+
Survey CPUE (numbers)	1993+	1977+	1993+, 1993+, 1997+, 1997+	1977+, 1977+, 1997+, 1997+
Survey age data years	1993+	1963+	1993+, 1993+, 1997+, 1997+	1965+, 1963+, 1997+, 1997+
Weight-at-age	Aggregate	Aggregate	Areas 2, 3, 4	Areas 2, 3, 4
Female *M*	Fixed at 0.15	Estimated	Estimated	Estimated
Male *M*	Estimated	Estimated	Estimated	Estimated
Stock-recruit relationship	B-H	B-H	B-H	B-H
Initial conditions estimated	R_{init} *N*-at-age: 1-19	R_0, *N*-at-age: 1-29	R_{init}, *N*-at-age: 1-19	R_0, *N*-at-age: 1-29
Environmental regime effects on recruitment	No	Estimated	No	Estimated
Steepness (*h*)	0.75	0.75	0.75	0.75
$\sigma_{\text{recruitment deviations}}$	1.0	0.54	0.80	0.5
Survey selectivity	Asymptotic, by sex	Asymptotic, by sex	Domed, by sex (R2, R3) Asymptotic, by sex (R4, R4B)	Domed (R2, R3), Asymptotic (R4, R4B)
Fishery selectivity	Asymptotic, by sex	Asymptotic, by sex	Domed, by sex (R2, R3) Asymptotic, by sex (R4, R4B)	Domed, by sex (R2, R3) Asymptotic, by sex (R4, R4B)
Scale of male fishery selectivity	Estimated, time-varying	Estimated, time-varying	Estimated, time-varying	Estimated, time-varying
Non-directed discard selectivity	Domed	Asymptotic	Domed	Domed
Recreational selectivity	Asymptotic	Domed	Domed	Domed
Discard selectivity	Domed, by sex	Domed, by sex	Domed, by sex	Domed, by sex
Subsistence selectivity	Mirrored to recreational	Mirrored to recreational	Mirrored to recreational	Mirrored to recreational

[1] Mortality estimates for 2022 were projected based on adopted IPHC limits.

All growth specifications in the control file were bypassed in order to use the empirical weight-at-age approach; therefore, the settings in the control file and the results included in model outputs related to these settings are not meaningful (this includes length-at-age, weight-at-length, and maturity-at-length; these are all integrated directly in the weight-at-age inputs). The weight-at-age file also included a matrix of spawning output-at-age representing the product of annual weight-at-age (a matrix) and the static vector of maturity-at-age (Stewart and Webster 2022).

For all estimated parameters (except temporal deviations), uniform priors were implemented, with bounds sufficiently wide to avoid maximum likelihood estimates falling on or very near a bound, unless the bound was structurally logical. Table 15 summarizes the counts of estimated parameters in each model. Natural mortality was allowed to differ by sex, with the value for male halibut estimated in all four models, and the value for females in all but the short coastwide model. Treatment of both the stock-recruitment relationship and the initial conditions at the start of the modelled time-series differed among the four models and are described below.

The double-normal selectivity parameterization is used in all four models, as it represents a flexible, but still parametric approach that can easily be made time-varying via just one or two parameters with annual deviations. There are more flexible nonparametric selectivity options, but these generally require all the parameters to vary over time, creating a substantial increase in complexity. The double-normal selectivity can be easily configured to be either asymptotic or dome-shaped, by adjusting the width of the peak and/or descending slope and final selectivity parameters. It also includes an option for male selectivity to be offset from female selectivity, based directly on the parameters of the selectivity curve (females from males), such that time-varying selectivity for one sex can be mapped into variability for both sexes without estimating a second set of parameters. The double-normal was implemented for all model fleets, with at least the ascending limb of selectivity (ascending width and peak parameters) allowed to vary over time for all four models (described further below).

As has been the case in all recent halibut models, the catch-per-unit-effort index derived from the directed halibut fishery is included in each of the models, but the catchability is allowed to vary over time, except in a few cases where there was no improvement in model fit by allowing temporal variability or where iterative tuning of the degree of interannual change suggested no meaningful variation. In principle, there are many factors which can create changes in the proportionality of the catch-rate in a fishery with the underlying population. The most obvious of these are abrupt changes in fishing methods, such as the change from “J” to circle-hooks in 1984. This type of change was accommodated (in the long time-series models) via an unconstrained deviation on catchability in that year (effectively a separate *q* for the two parts of the time series). Beyond abrupt changes, there are many factors that can ‘drift’ over time, but may not be so obvious, including technological improvements, changes in spatial areas or times of year being fished, etc. This type of change suggests a random walk in catchability, which was the approach taken in all four models here. To implement this, a catchability parameter was estimated for the first year for which index data were available, and then a deviation (from the previous year’s value, not the mean) was estimated for each subsequent year of the time-series.

The annual catchability deviations were constrained by a single σ for each fleet. The iterative tuning algorithm for identifying the internally consistent values for each σ is described below along with other changes for 2021.

Table 15. Comparison of estimated parameter counts among models.

	Model			
	Coastwide Short	Coastwide Long	AAF Short	AAF Long
Static				
Female *M*	--	1	1	1
Male *M*	1	1	1	1
Log(R_0)	1	1	1	1
Initial R_0 offset	1	--	1	--
Environmental link coefficient	--	1	--	1
Fishery catchability	1	1	4	4
Survey catchability	1	4	--[1]	4
Fishery selectivity	5	5	21	20
Discard selectivity	8	7	5	5
Non-directed discard selectivity	4	2	3	3
Recreational selectivity	5	6	5	6
Survey selectivity	5	5	21	18
Total static	32	34	63	64
Time-varying				
Recruitment deviations[2]	54	168	54	168
Fishery catchability deviations	--	111	116	218
Fishery selectivity deviations	78	175	244	568
Survey selectivity deviations	84	90	206	260
Total deviations	216	544	620	1,214
Total	248	578	683	1,278

[1] The analytic solution is used for these catchability parameters.

[2] Includes initial age structure and five uninformed forecast years (the latter only included here such that counts will match that reported in model output).

In all models, fit to the age data used a multinomial likelihood with initial input sample sizes based on the bootstrap results described above, subsequently adjusted down via a multiplicative scalar for each fleet in the control file (more discussion below). Indices of abundance from both the FISS and commercial fishery (by area in the AAF models) were fit using a log-normal likelihood and input log(*SE*)s based on the space-time modelling. Survey indices were fit in numbers of fish to avoid converting numbers to weights in the data and then weights back to numbers in the model predictions (as informally recommended by the Scientific Review Board in 2014). Weight-per-unit-effort is the native scale for the fishery indices based on logbook records.

Using the method first developed for the 2015 assessment, discard mortality, bycatch and recreational selectivity are estimated, but the age composition data are down-weighted to avoid imparting any significant information on recruitment strengths from these uncertain and potentially non-representative data sets. In this way, the data that are available serve as an informative 'prior' on the selectivity for each of these fleets, and therefore propagate some uncertainty associated with selectivity estimation, but do not strongly inform other model parameters and population dynamics estimates.

Discards in the directed commercial fishery are treated as a separate fleet in each model. This approach was taken for several reasons: discard rates may be a function of spatial fishing effort and not simply contact selectivity as is often assumed in stock assessments - there has been little relationship between the magnitude of discards and the magnitude of commercial landings when this has been evaluated for previous reviews. Further, modelling discards with a retention curve in the empirical weight-at-age approach within SS does not allow for separate mean weight-at-age vectors to be applied to landings and discards (which may differ significantly for younger ages due to the size limit). Sex-specific selectivity curves were estimated in each model informed by the observations from the sublegal fish captured by the setline survey. The selectivity was configured to be a double normal, with female halibut offset from male halibut to account for the dimorphic growth (the opposite of all other fleets), and the relative scale of females to males estimated directly. Both sexes were allowed to be dome-shaped, with differing descending limbs. Because the sublegal survey age data were already included in the likelihood as part of the survey age compositions, it would be a misrepresentation of the uncertainty to naively fit them again equally as part of the discard data set. Instead, previous analyses showed that down-weighting these data such that they had a very small input sample size had no appreciable effect on the model results but still allowed for the direct estimation of selectivity. This approach lends itself to direct inclusion of observer data on discarded halibut when sampling/expansion methods that are representative of the entire fleet become available.

Bycatch and recreational selectivity curves were also allowed to be dome-shaped given the relative frequency of younger halibut in the observed distributions. Where descending limb parameters were estimated to be at the upper bounds, these parameters were fixed (making the curves asymptotic) to avoid any negative behavior during minimization and approximation of the variance in model quantities via the Hessian matrix. Since the 2019 assessment, sex-specific age composition data for the recreational fishery has become available (Stewart and Webster 2022), and so additional offset parameters were added to allow for sex-specific selectivity as in the treatment of the discards. Because of the down-weighting of the data for these series, and the unknown or potentially poorly spatially representative nature of the data themselves, no attempt was made to allow these selectivity curves to vary over time.

The presence of both observation error (in the indices and age composition data) and process error (in fishery catchability and selectivity for the survey and fishery) creates a challenge for standard weighting and tuning practices employed in many assessment models. Specifically, if process error is not modelled (and/or a fixed value is asserted), the input sample sizes (and sometimes index variances) can be relatively easily iteratively tuned or estimated (Maunder

2011). This approach is useful for reducing the potential effects of outliers, lack-of-fit, or model misspecification with regard to composition data (Francis 2011). At the other extreme, if the observation error is assumed to be known (and assigned a fixed value), then the degree process error can be estimated via random effects, or iteratively tuned using a maximum likelihood-based approximation (the 'Thompson and Lauth method'; Annex 2.1.1 in Thompson and Lauth 2012). When data are sufficient, both components can be iteratively or by more statistically rigorous means estimated simultaneously (Thorson 2019; Thorson et al. 2016).

The general goal for the treatment of process error in selectivity and catchability and observation error in the data is to first reduce clear signs of bias to the degree possible and then to achieve internal consistency among error distributions and sample sizes/variances. In all four models developed here, the initial input sample sizes, for 2022 derived from the bootstrapping analysis described above were considerably larger than commonly applied weighting for stock assessment models would suggest (Table 11-13). These values were iteratively reduced based on evaluation of three considerations: the relative magnitude of the standardized Pearson residuals, comparison of the input value for each fleet with the harmonic mean effective sample size which is an unbiased estimator for a set of independent multinomial samples (Stewart and Hamel 2014), and the scaling suggested by the Francis (2011) method (as implemented in the r4ss package). For almost all fleets and all models, this approach led to a substantial reduction from initial sample sizes. In no cases were the input values increased from the maximum values derived via bootstrapping.

Starting from a small value for the input σ for each fleet and parameter combination where temporal variability was allowed, process error was increased until the tuned value was consistent with the degree of variability observed among the deviations (SE_{devs}^2) and the average uncertainty of the deviations themselves $\bar{\sigma}_{dev}{}^2$. This approach is very close to that outlined by Thompson and Lauth (2012) and is consistent with the preferred method for tuning this and other types of process error (such as recruitment deviations) in stock synthesis (Methot and Taylor 2011; Methot et al. 2019):

$$\sigma_{tuned} \sim \sqrt{SE_{devs}^2 + \bar{\sigma}_{dev}{}^2}$$

In addition to providing internal consistency, this approach makes intuitive sense: under perfect information the average variance of the deviations will be zero and the variability among the deviations will exactly match the process error, conversely under no information the variance of the deviations will be the input constraint. After initial process error tuning, the input sample sizes were adjusted downward until the weights suggested by the fit to the mean age over the time series were approximately equivalent to the input values (the "Francis method'; Francis 2011). There were only minor changes to the tuned σ values required after iteration of the input sample sizes, suggesting the two processes were relatively separable and stable; further there were only minor changes in the process error variances in this assessment relative to the 2019 assessment despite the revised input sample sizes.

As a final model-building step, models were regularized via adjusting parameterizations through removing and/or fixing selectivity parameters that consistently remain stuck to bounds or are not contributing to the likelihood in a meaningful way (<1% correlation with other model parameters). This regularization does not include forecast recruitment deviations, which are expected to be uncorrelated with other model parameters (and the objective function), but are 'estimated' in order to appropriately propagate the uncertainty in recent recruitments into forecasts.

The tuning approach for the stock-recruitment relationship was very similar, ensuring that the input σ governing recruitment variability was consistent with the observed variability and variance estimates; the calculation for this tuning is automated in the r4ss package, and the output was used as a guide for the scale of the bias correction, including ramps to and from the peak value consistent with the information content of the data and variability in the deviations observed in the output. This step is important for recruitment variability as it also provides for a better approximation for the bias correction in recruitment deviations (Methot and Taylor 2011) in the 'main' or best informed period of the time-series of recruitments. Again here, after initial tuning, little change was observed across alternative models (or from the 2019 results).

In the end, this tuning process provides a model that is internally consistent: the error distributions are commensurate with the fit to the data and the degree of process error is consistent with the signal (information content) in the data. Importantly, accounting for process error in selectivity was the primary solution for historically observed retrospective patterns in the Pacific halibut stock assessment models (Stewart and Martell 2014). Tuning diagnostics and results specific to each model are provided below.

Coastwide short

The initial conditions for a model starting after an extensive historical fishery and appreciable recruitment variability must be structured to avoid simple assumptions that may have strong effects on the subsequent time-series. For the coastwide short model the initial conditions included estimating the population numbers at age 1-19 in the first year of the model (1992 after extension of the time-series; see below). Since the age data available for the initial year were aggregated at age-20 (due to the historical use of the surface ageing method), there was no specific information on additional individual year-classes. To accommodate a non-equilibrium value in the plus group, an offset to initial equilibrium recruitment (via a single time 'block') was also estimated. The effect of these two approaches was to essentially decouple the numbers-at-age at the beginning of the time-series from any equilibrium assumptions.

As in previous assessments, the coastwide short model employed a Beverton-Holt stock recruitment relationship with estimated equilibrium recruitment level (R_0) setting the scale of the stock-recruit relationship. Steepness (h) was fixed at a value of 0.75 for this and all other models, an assumption that has been explored extensively in previous assessments. Fixing steepness, but iteratively solving for the internally consistent level of recruitment variability generally does not have a large effect on year-class strengths where data are informative, but does have very strong effects on direct estimates of Maximum Sustainable Yield (Mangel et al. 2013); however, this quantity is not of specific interest for the Pacific halibut assessment. A summary of the number of estimated parameters contributing to each aspect of the model is provided in Table 15.

Age-based selectivity for female halibut for both the FISS and commercial fishery was estimated using the double normal, forced to be asymptotic once it reached peak selectivity. This required two parameters: the ascending width of the curve and the age at which the peak selectivity is reached. Both parameters are allowed to vary over time with a random walk of annual deviations. These deviations were initiated in the first year for which age composition data were available, and no deviation was estimated for the terminal year (2022), because there were no data yet in the model to inform that deviation (it will be estimable when the 2022 data are added for the final assessment). This means that the actual mortality in 2022, when available, may have a different effect than initial projections. Male selectivity for the survey was estimated via offsets to the female ascending width and peak parameters, and a third parameter defining the scale of male selectivity relative to that for females. In the coastwide short model, with fixed female natural mortality and direct overlap between all years of fishery and survey age data, the male offset parameters for the fishery have been estimated in recent assessments. These parameters have been informed by the weak information on sex-ratio included the sex-aggregated age data. In aggregate, there were five estimated base parameters each for the survey and fishery and annual deviations on the ascending limb parameters (Table 15).

As in the 2015 and 2019 assessments, the scale of male selectivity for both the survey and fishery were allowed to vary over time as a random walk. With only sex-aggregated commercial fishery age compositions prior to 2017, it is not clear how strongly the temporal variability in the scale of male selectivity is informed (and potentially how correlated it would be with female natural mortality, which is fixed in this model). However, the addition of time-varying deviations on the scale parameters was found to improve the residual patterns in previous assessments for the fit to the fishery age-data and has not shown signs of unreliable estimation over sensitivity and alternative model runs.

Coastwide long

Initial conditions for the coastwide long time-series model include the initial age structure and a long period of uninformed recruitments with the model period beginning in 1888 and the first age data available for 1935 (Table 14); therefore, there was a substantial ‘burn in’ for recruitment variability prior to any data. The treatment of the stock-recruitment function in the coastwide long model was substantially different from that of the coastwide short model. Consistent with historical IPHC analyses (Clark and Hare 2002a, 2006) and previous stock assessments, the coastwide long model allowed for the possibility that recruitment variability is correlated with the regimes of the Pacific Decadal Oscillation (PDO; Mantua et al. 1997). To implement this approach, a Beverton-Holt relationship was used, parameterized with an estimated value for the equilibrium recruitment level (R_0) parameter, and a fixed value of steepness (h) of 0.75. The annual average of the PDO index was converted to a binary indicator (PDO_{regime}) where productive regimes (e.g., 1977-2006) were assigned a value of 1.0, and poor regimes (e.g., 1948-1976) a value of 0.0 (Stewart and Webster 2022). These regimes were linked to the scale of the stock-recruit function via an adjusted equilibrium level of recruits (R_0') based on an estimated coefficient (β) creating an offset to the unadjusted value:

$$R_0' = R_0 * e^{\beta * PDO_{regime}}$$

The adjusted equilibrium recruitment value was then used in the stock-recruit function with bias-corrected annual deviations:

$$R_y = f\left(SB_y, R_0', SB_0, h\right) * e^{r_y - \frac{\sigma^2}{2}}$$

This approach changed since 2015 (but see alternative sensitivity analyses below). This parameterization has the desirable property that if there is no correlation between the putative environmental index and underlying mean recruitment, the β parameter to be estimated at a value of 0.0 and the recruitment estimates will be unaffected. In that case R_0' is simply equal to R_0. As was the case for the coastwide short time-series model, fixing steepness precludes the naïve use of *MSY* estimates.

The approach to selectivity in the coastwide long model was identical to that in the coastwide short model, except that the annual scale of male selectivity was only estimable after adding the sex-ratio information beginning in 2017 (see changes from 2021 below) Selectivity deviations on the ascending limb parameters of the fishery and survey series were initiated in the first year for which age composition data were available for both the fishery (1935) and the survey (1963).

AAF short

The AAF short model was configured very similarly to the coastwide short model. The most notable difference was in the treatment of selectivity for the survey and fishery in Biological Regions 2 and 3: these were allowed to be dome-shaped relative to the coastwide population dynamics. Implementing dome-shaped selectivity for these four model fleets requires the addition of a third selectivity parameter defining the width of the descending limb. This additional parameter was not allowed to vary over time.

Another difference between the short time-series models was in the treatment of the scale of male selectivity for the fishing fleets in each of the four areas. Similar to the coastwide long model, the three parameters defining the annual male offset to female selectivity for the commercial fishery in each area were only estimable beginning with the 2017 sex-ratio data. Temporal variability in selectivity parameters occurred over a slightly longer range of years in the AAF short model, as there were Region-specific survey data available for the entire time-series from Biological Regions 2 and 3.

Finally, unlike in the 2021 and earlier assessments (as described below), the preliminary 2022 short AAF model estimates female *M*. Likelihood profiles (see below) suggested a defined and reasonable minima somewhat closer to the long coastwide and AAF models than the previously assumed value of 0.15.

AAF long

The only structural differences between the AAF long and AAF short models were the years over which deviations in recruitment, selectivity and catchability are estimated. The AAF long model treated the stock-recruitment function in the same manner as the coastwide long model, including the PDO as an estimated covariate to equilibrium recruitment.

Changes from 2021

In the intervening period between the last full stock assessment analysis and review in 2019 and this preliminary analysis for 2022, the length and information content of the data sets has grown, and new information, such as the bootstrapping results (described above) has become available. Changes to specific data sets have been documented in the recent assessments and their effects evaluated singly in each year (Stewart and Hicks 2021; Stewart and Hicks 2022). Key changes for 2021 included:

1) Extending the time series to include projected mortality based on limits adopted for 2022 (IPHC 2022),
2) updating to the newest stock synthesis software version (3.30.19; Methot Jr et al. 2021a),
3) expanding the treatment of natural mortality (*M*) to include an informative prior and increased values at the youngest ages based on meta-analyses,
4) improving the basis for data weighting via use of bootstrapped effective sample sizes based on the FISS and fishery sampling programs as model inputs (rather than the raw number of sets/trips),
5) re-tuning the process and observation error components of these models to achieve internal consistency within each,
6) allowing for interannual variability in the sex-ratio of the commercial fishery selectivity,
7) and exploring whether female *M* in the short models was estimable (male *M* and *M* for both sexes in the long models was already estimated).

The sequential effects on the model results of each of these changes are described below as a ‘bridging’ analysis from the 2021 stock assessment.

Extending the time-series

In order to provide for transparent comparisons from this preliminary stock assessment through the final results for 2022, the initial step in this analysis was to extend the modelled time-series to 2022, using the projected mortality associated with the limits set by the IPHC (IPHC 2022). Weight-at-age was assumed to remain constant from 2021 to 2022; however, it will be updated when new data become available. No other information was needed for this single year projection and all model results and parameter estimates remained unchanged relative to the final 2021 stock assessment.

Software version update

The Pacific halibut stock assessment has updated to newer versions of the stock synthesis software (Methot and Wetzel 2013a; Methot and Wetzel 2013b) as new features have been added, and in order to avoid major changes as input/output changes have evolved over time. The 2019 stock assessment was implemented in version 3.30.13 (Methot et al. 2019), which was updated to 3.30.15 (Methot Jr et al. 2020b) for the 2020 stock assessment in order to utilize the automatic calculation of variance and covariance for dynamic unfished stock size, a feature that was unavailable in previous years. For 2021, version 3.30.17 (Methot Jr et al. 2021b) was used, but the results were unaffected as there were no changes made that were related to any of the features used for Pacific halibut. Similarly, for 2022 the models were updated to version 3.30.19, but the results were identical to those produced under the previous version. For simplicity, this step has been omitted from the bridging figures below.

Treatment of M

As described above an informative prior was developed for use on both male and female Pacific halibut *M*. In addition, elevated *M* for ages 0-2 was also introduced to the assessment models in order to facilitate an in-depth exploration of the PDO as a covariate with recruitment strengths. The change did not affect the two short time-series models that had *M* fixed at 0.15 and had only a tiny effect on those models that estimated female *M*, slightly reducing the MLE for the long coastwide and long AAF models (Figure 15-17). This affect was consistent with the mode of the density for the informative prior slightly lower than the point estimates from the models, but with a large variance (Figure 19).

Addition of elevated *M* at ages 0-2 also had little effect on model estimates of spawning biomass (upper panels, Figure 15-17). The exception was the AAF long model (Figure 18), which was quite sensitive to any change affecting the historical time series (see discussion of convergence and likelihood profile sections below). In contrast to the spawning biomass time-series, the absolute estimates of recruitment increased substantially for all four models in order to generate numbers of fish at ages 3+ consistent with previous model fits (lower panels, Figure 15-17).

Data weighting

The next step in the bridging analysis was to replace the previously used input sample sizes (the number of samples contributing to the FISS and fishery age composition data) with the bootstrapped maximum effective sample sizes described above. The effective sample sizes were also tuned (as described above) during this step based on the calculated Francis weights and the magnitude of observed residuals. There were no clear directional patterns in the results of this change and changes to the estimated time-series were minor (Figure 15-17).

After revising and tuning the bootstrapped input sample sizes, process error variances were again iteratively tuned along with another iteration of the data weighting to ensure that all model configurations were internally consistent. Despite discovery and correction of an error in the implementation of time-varying catchability (leaving out several years from the block design) during this step changes were again relatively minor when compared to the uncertainty estimates and other bridging steps (Figure 15-17).

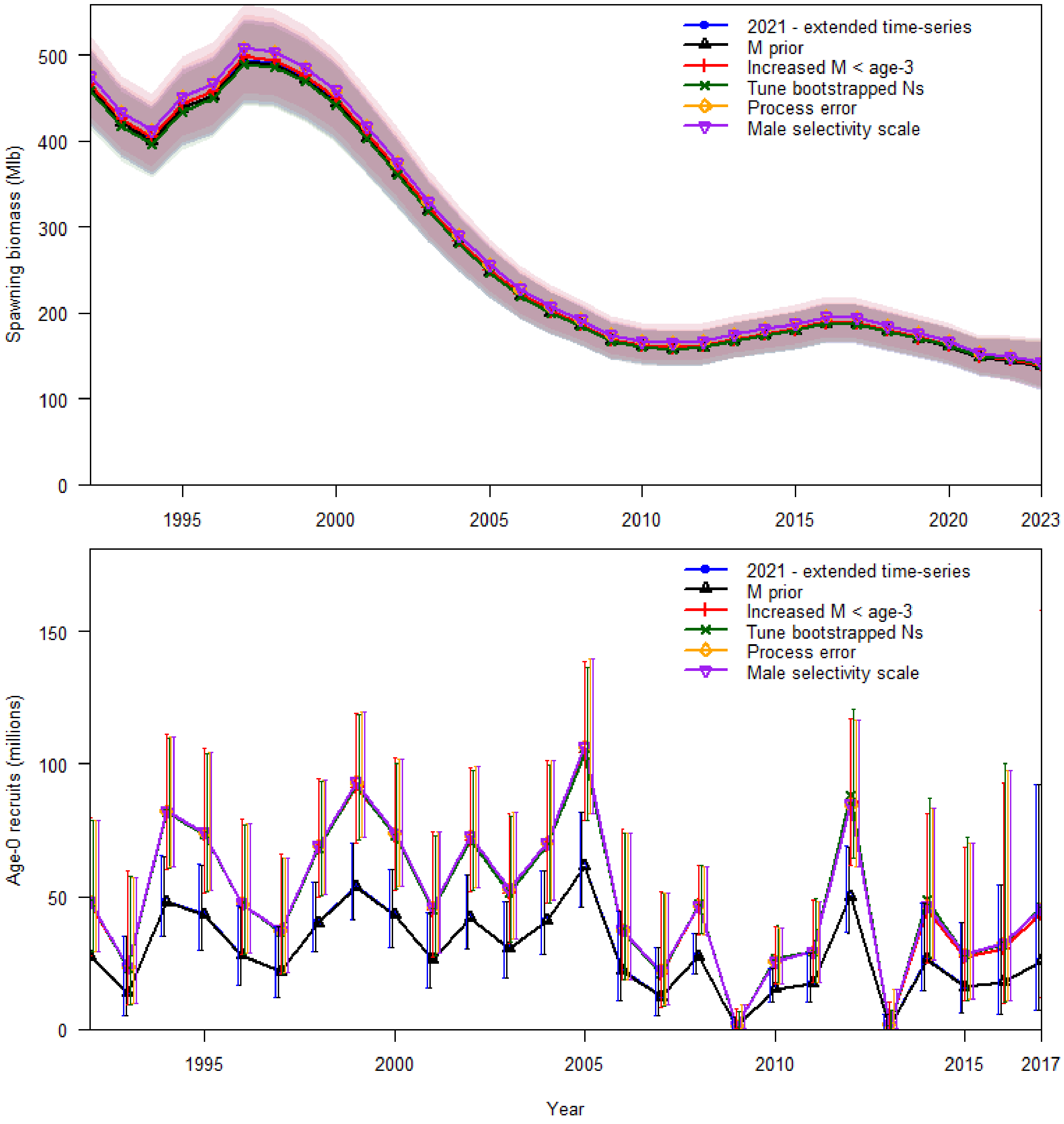


Figure 15. Comparison of estimated biomass (upper panel) and recruitment time series (lower panel) over sequential changes from the 2021 to preliminary 2022 coastwide short models.

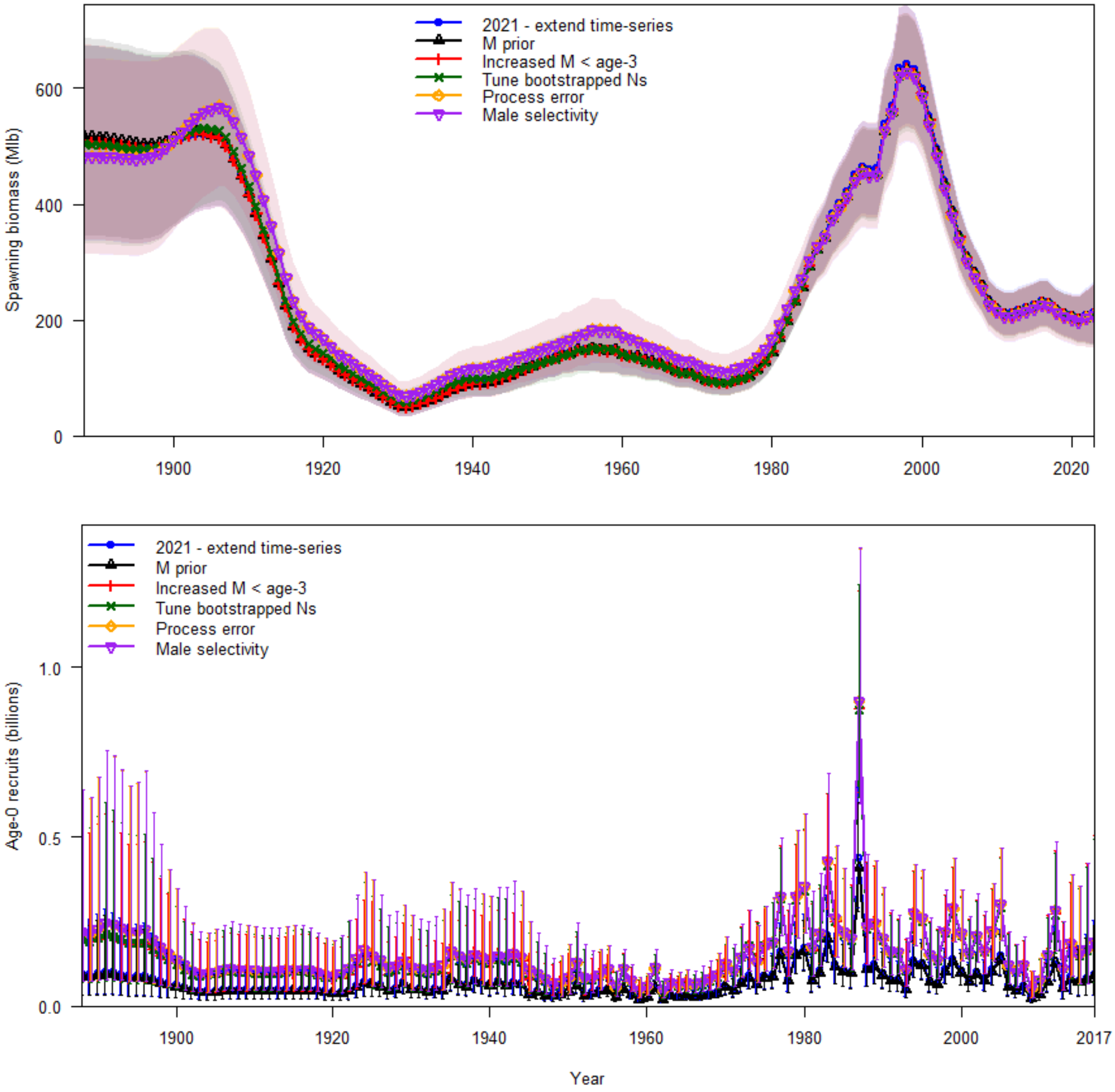


Figure 16. Comparison of estimated biomass (upper panel) and recruitment time series (lower panel) over sequential changes from the 2021 to preliminary 2022 coastwide long models.

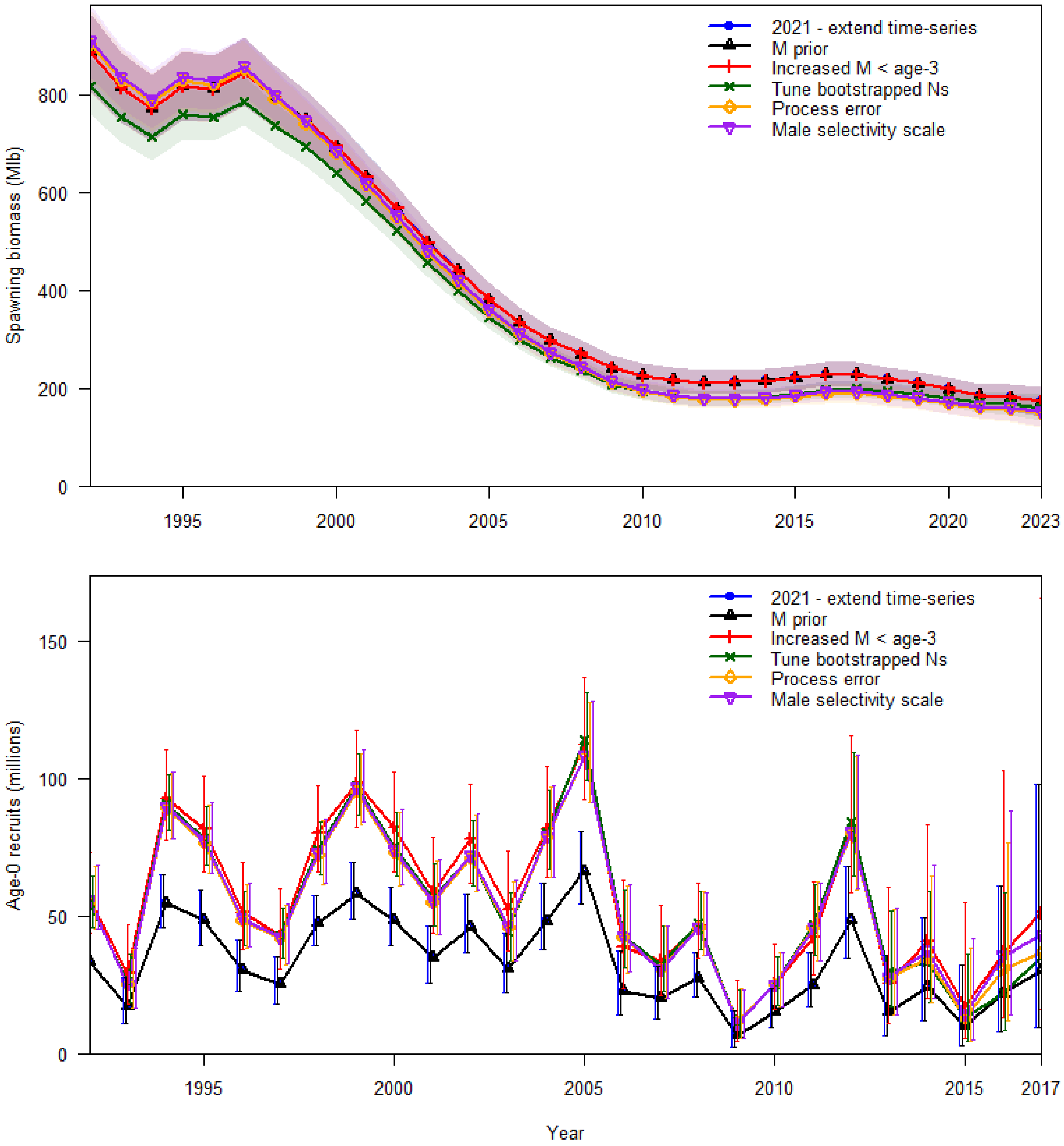


Figure 17. Comparison of estimated biomass (upper panel) and recruitment time series (lower panel) over sequential changes from the 2021 to preliminary 2022 AAF short models.

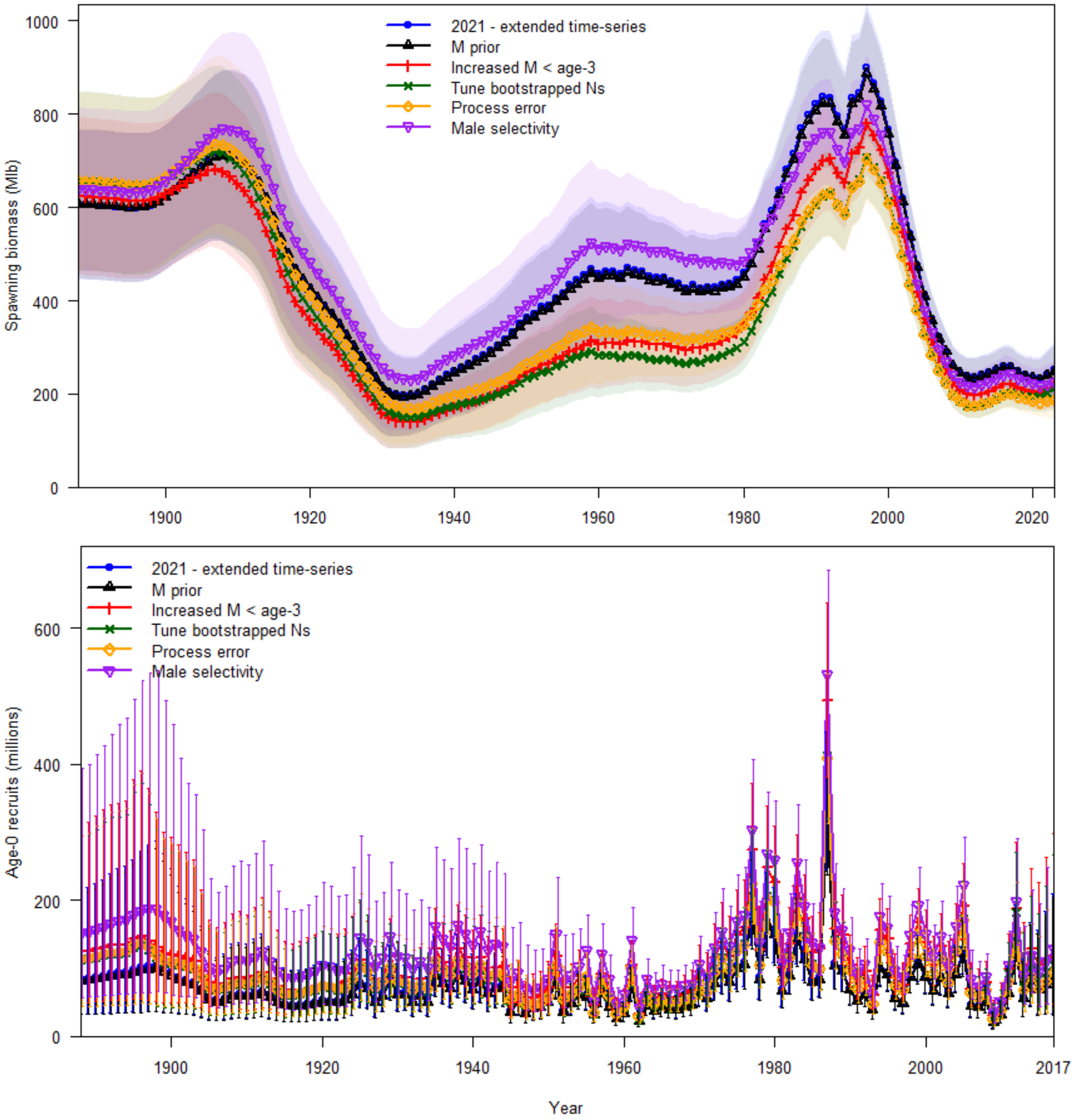


Figure 18. Comparison of estimated biomass (upper panel) and recruitment time series (lower panel) over sequential changes from the 2021 to preliminary 2022 AAF long models.

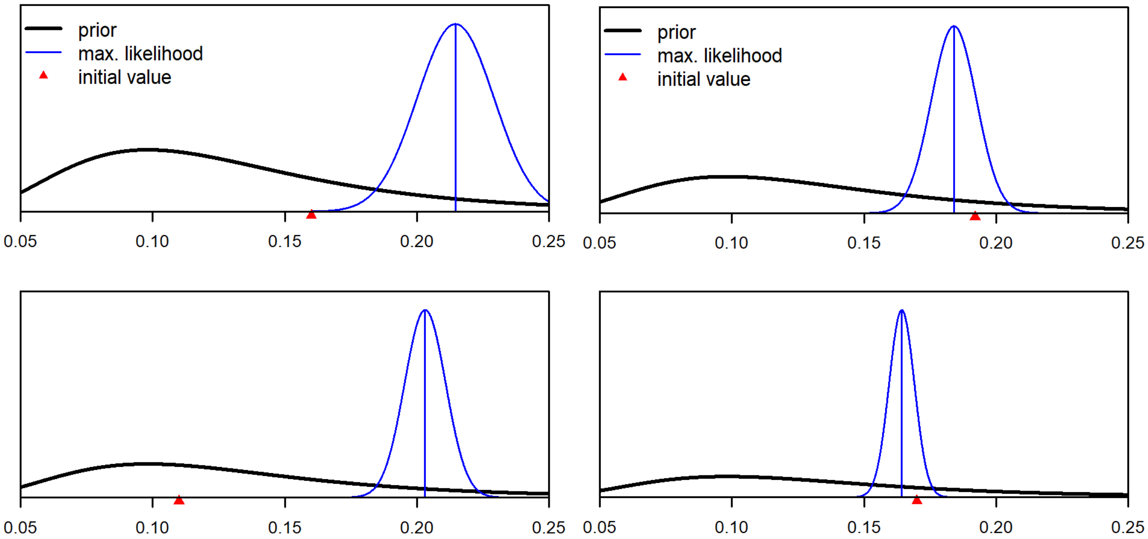


Figure 19. Prior and maximum likelihood estimates for female (upper panels) and male (lower panels) *M* in the coastwide long (left panels) and AAF long (right panels) assessment models.

Commercial fishery selectivity

In the 2019 stock assessment, the AAF short and the two long models did not allow the scale of the male fishery selectivity curve (which mainly determines the sex-ratio of the landings) to be time-varying. At the time of the preliminary assessment there were only 2 years of sex-specific age compositions available. As additional years of data have become available (now 2017-2020, with 2021 anticipated for the full 2022 stock assessment), it is now possible to allow the models to track the year-to-year variability, and more importantly, to disconnect the recent parameter estimates from the historical period. Again here, the results were generally insensitive to this change, with the exception being the most complicated of the models, the AAF long model (Figure 18). While not evident in the bridging analysis, this change created much more stable retrospective patterns than observed in previous assessments (see retrospective section below).

Estimation of female M in the two short models

The final change evaluated in the bridging analysis was the estimation of female *M* in the two short time-series models. For the short coastwide model, all efforts to estimate *M* resulted in the value going to the upper bound. As has been the case in previous assessments, the conclusion was reached that this value was not estimable, even with the informative prior now available. In contrast, the AAF short model produced an estimate of *M* consistent with the two long time-series models and the likelihood surface clearly indicated that the fixed value of 0.15 was much less plausible (0.21, see likelihood profile section below). This step in the bridging analysis is plotted separately along with the previous and initial step so that the results can be more clearly compared (Figure 20).

The choice to fix or estimate female *M* is an important one, which has clear implications for the scale of the estimated spawning biomass. Previous short time-series assessments, back at least to 2006, either assumed that female *M* was not estimable or did not find a clear minimum within the range of values considered plausible. There is no clear basis for the historically assumed value of 0.15, but the choice to fix female *M* has led to models with very tight uncertainty intervals, in contrast to the much broader intervals estimated here (Figure 20).

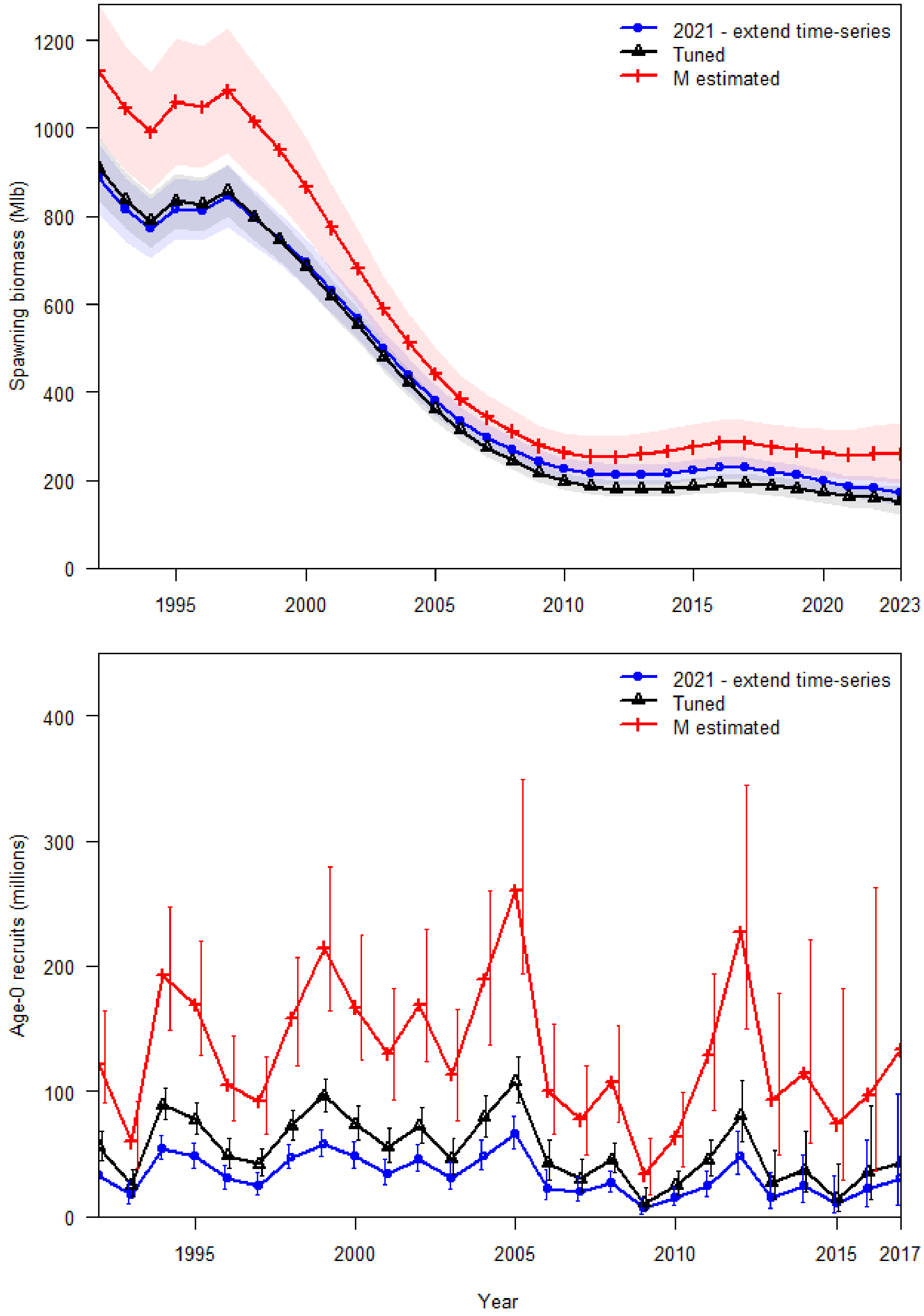


Figure 20. Comparison of estimated biomass (upper panel) and recruitment time series (lower panel) for AAF short models with and without female *M* estimated.

Convergence criteria

Standard tools for monitoring convergence criteria include assessing the maximum gradient component, sensitivity to alternative phasing and initial values, use of overdispersed starting points or 'jitter analyses', as well as likelihood profiles, and Bayesian integration.

For this preliminary 2022 assessment, all individual models all had a maximum gradient component < 0.004. A series of preliminary and intermediate runs did not indicate any signs that the estimates reported here represented local minima for all but the AAF long model, nor did the models have difficulty converging and producing a positive definite Hessian matrix under the range of alternative and sensitivity analyses (some presented in this document, but many used only for development).

Convergence was tested specifically through a 'jitter' analysis perturbing all parameter values simultaneously by 1% of the range between upper and lower bounds and repeating minimization. Initial testing revealed that the coastwide long model recovered the MLE 100% of the time. Similarly, the coastwide short model recovered the MLE 98% of the time and failed to converge to a solution 2% of the time. Being more complex, convergence success was lower for the AAF short model, recovering the MLE 68% of the time, failing to converge 21% and stopping short of the actual MLE 11%. The AAF long model, with considerably more process-error parameters than the others did show a greater sensitivity to all sensitivity and bridging analyses. Further, this model did occasionally get stuck at an alternate minimum that was 1% different in spawning biomass and 1.16 negative log likelihood units worse than the true minimum. The AAF long model required starting values much closer to the true MLE for a wide range of runs, and still converged to the MLE 44% of the jittered runs, 21% stopping short and 35% failing to converge. This indicates that, at least for the current configuration, use of good starting values and jitter analyses is most important for the long AAF model.

Wherever parameters were hitting bounds either the bounds were adjusted (if biologically plausible) or the parameters were fixed. For example, the descending limb of the 4B commercial fishery in the AAF models was estimated to be at the bound of 1.0 (as has been the case for all recent assessments), and so was fixed at this value. This approach reduces the likelihood that variances calculations will be (undesirably) effected by parameters stuck to bounds but does require periodic revisitation to ensure that the signal for parameters hitting bounds remains, and that fixing those parameters does not have an appreciable effect on the maximum likelihood solution.

Individual model diagnostics and results

This section provides more detail on the specific diagnostics and results of each of the four assessment models. It is not intended to provide the fit and residuals to every data component, but to summarize the basic performance of the model and specifically highlight areas of potential deficiency. Figures showing comprehensive diagnostics and results and the full report files, as output directly from stock synthesis, are provided electronically as described in Appendix A. Each model section finishes with a brief summary of the relative strengths and weaknesses of that model.

Coastwide short

Predictions of both the fishery and survey indices of abundance fit the observed data very well in the coastwide short model (Figure 21). In the 2018 assessment, a small amount of process error was allowed on fishery catchability. Since 2019, the iterative tuning of the annual catchability deviations suggested that process error was no longer needed. The predicted aggregate age distributions also matched the observed distributions well, for both the fishery and survey indicating that the selectivity parameterization was generally capturing differences in both the age-structure and the sex-ratio (Figure 22).

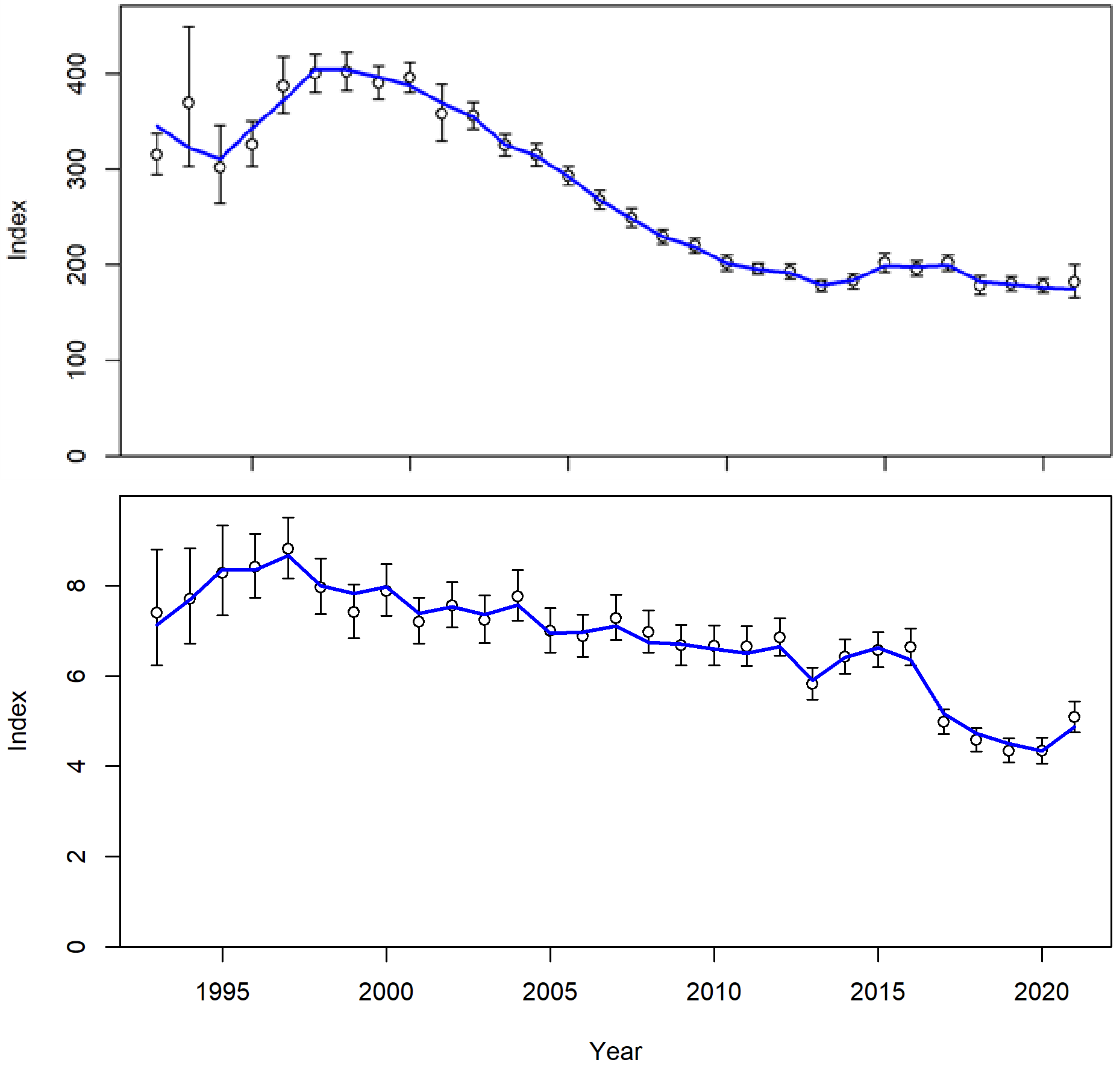


Figure 21. Fit to fishery (upper panel) and FISS (lower panel) indices of abundance in the coastwide short model; note that the scale of the y-axes differ.

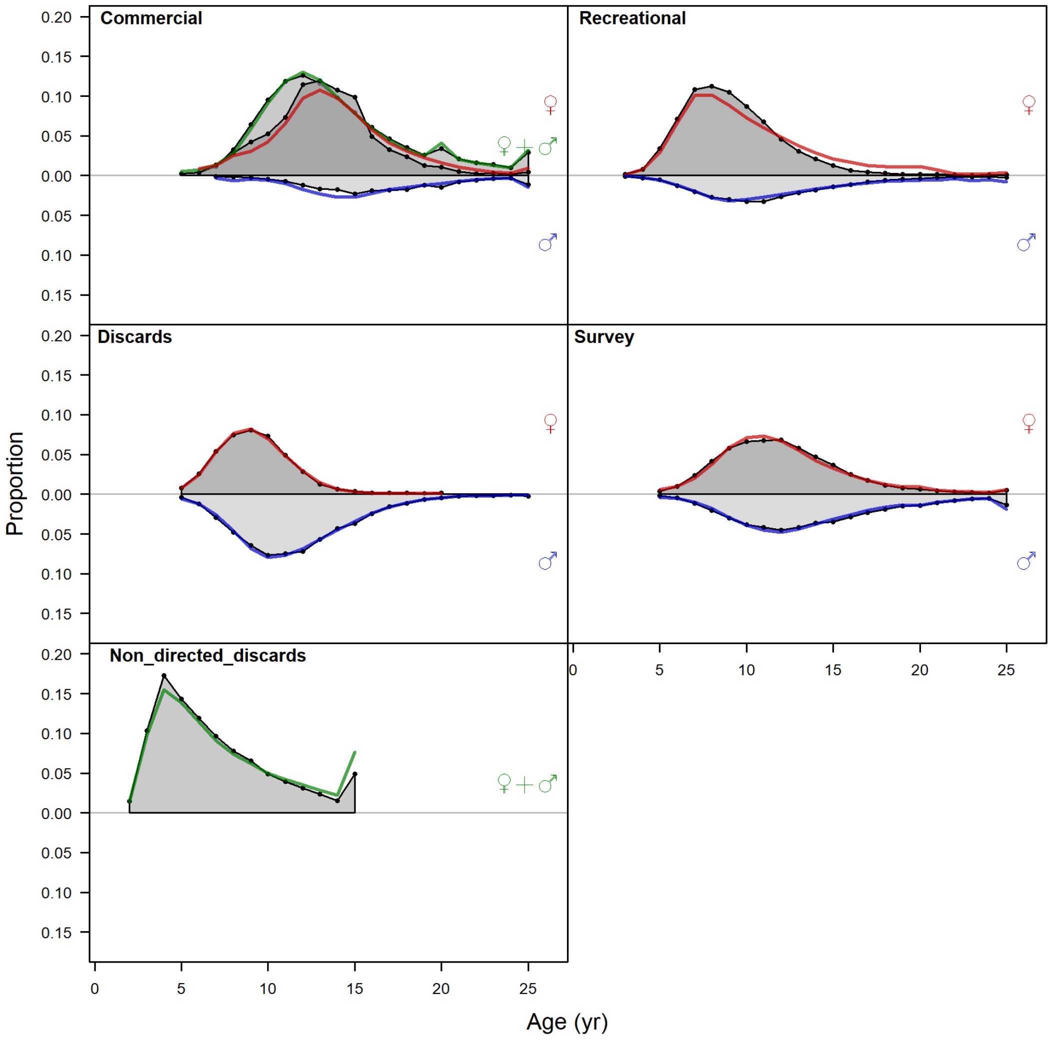


Figure 22. Aggregate fit to all age data by model fleet in the coastwide short model; sex-specific distributions for the commercial fishery represent only 2017-2020 and are plotted on top of sexes-aggregated distributions spanning 1992-2016 + 2021.

The coastwide short model tuning resulted in a higher weight on the coastwide FISS ages than for the commercial fishery age data (Table 16). The discard, non-directed discard and recreational age data were all heavily down-weighted (as described above) and so input sample sizes were not iterated to larger values, despite fits to the data that implied a higher weight. Fit to the annual FISS age compositions were generally good (Figure 23), although some patterning was visible in the standardized residuals (Figure 24). Specifically, there was a clear pattern of negative residuals in the plus group for male halibut; however, this was almost imperceptible in the fits themselves due to the very small observed and predicted values in this age bin. The fits to the annual fishery data were also acceptable (Figure 25-25). Similarly, the implied fit to the sex ratio information for the commercial fishery was somewhat more variable (Figure 27) than that for the FISS (Figure 28). Additional diagnostics and diagnostic figures (such as fits to the down-weighted annual compositions for the discard, bycatch, and recreational fleets) are included in the background materials.

Table 16. Post-iteration sample size diagnostics for age-composition data by model and fleet. Average iterated input denotes the value used for model runs reported here, after iterating the bootstrapped starting points.

	Average iterated input	Harmonic mean effective	Francis weight effective	Maximum Pearson residual
Coastwide short				
Fishery	62	294	62	2.45
Discards[1]	13	270	49	0.98
Non-directed discards[1]	5	47	39	2.25
Recreational[1]	5	114	27	0.88
FISS	242	668	242	2.06
Coastwide long				
Fishery	112	289	122	4.09
Discards[1]	6	210	90	0.78
Non-directed discards[1]	3	37	7	1.33
Recreational[1]	3	145	31	0.51
FISS	82	194	83	2.88
AAF short				
Region 2 fishery	723	676	1,078	4.47
Region 3 fishery	808	699	951	3.85
Region 4 fishery	23	78	36	3.54
Region 4B fishery[2]	36	138	81	1.82
Discards[1]	13	219	73	1.21
Non-directed discards[1]	5	58	22	1.12
Recreational[1]	5	143	20	0.85
Region 2 FISS	7	86	7	1.04
Region 3 FISS	18	262	18	1.25
Region 4 FISS	66	181	63	3.95
Region 4B FISS[2]	41	185	50	1.83
AAF long				
Region 2 fishery	322	304	651	4.31
Region 3 fishery	266	309	544	3.78
Region 4 fishery	18	60	28	4.36
Region 4B fishery[2]	37	129	80	1.90
Discards[1]	6	189	84	1.56
Non-directed discards[1]	3	43	8	1.12
Recreational[1]	8	151	23	0.91
Region 2 FISS	7	78	8	1.39
Region 3 FISS	12	101	13	1.26
Region 4 FISS	72	182	68	3.53
Region 4B FISS[2]	41	185	45	1.93

[1] Inputs down-weighted, and not iteratively reweighted – see text.

[2] Iterated sample size equal to maximum (bootstrapped input).

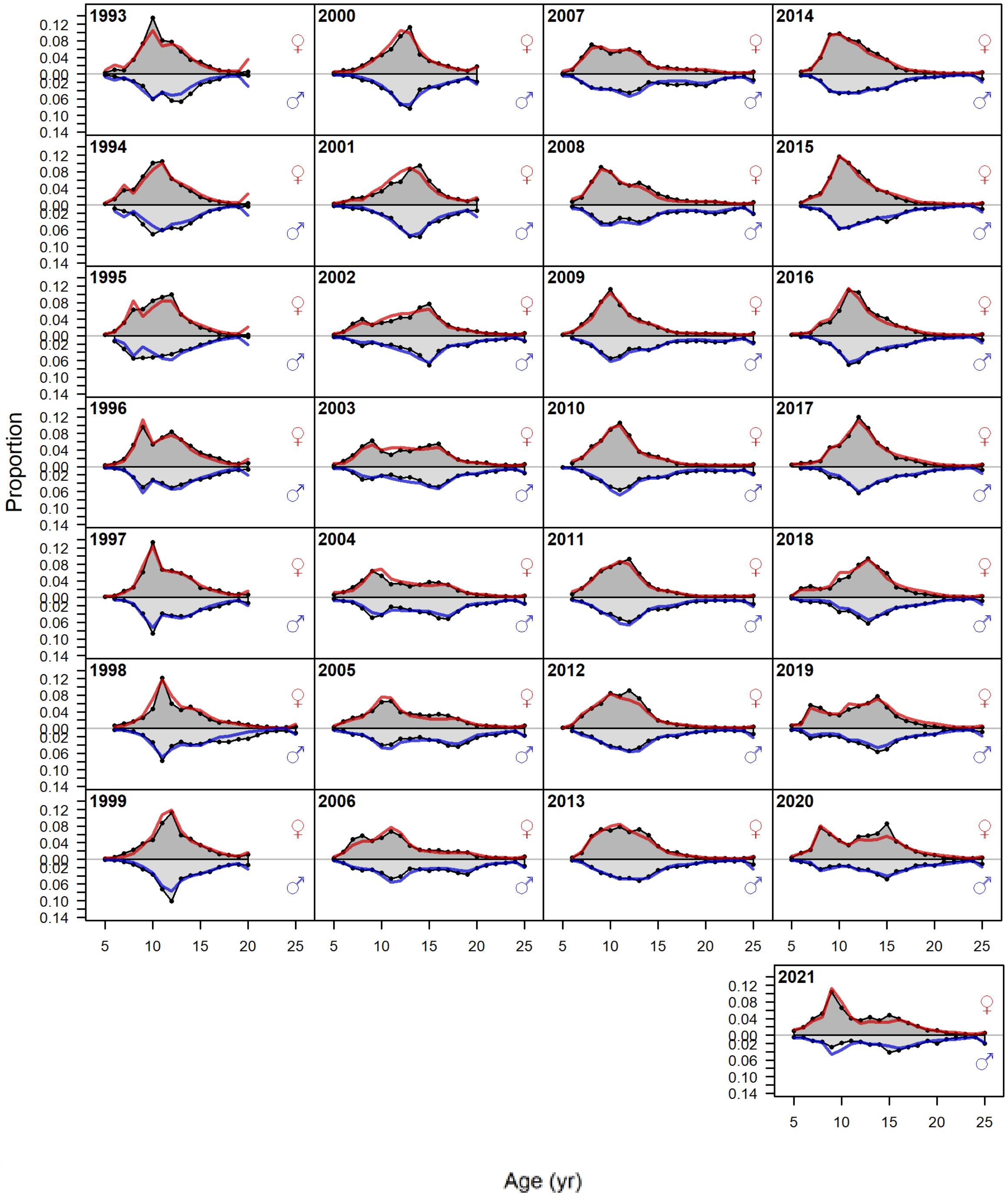


Figure 23. Fit to annual age data from the FISS survey in the coastwide short model.

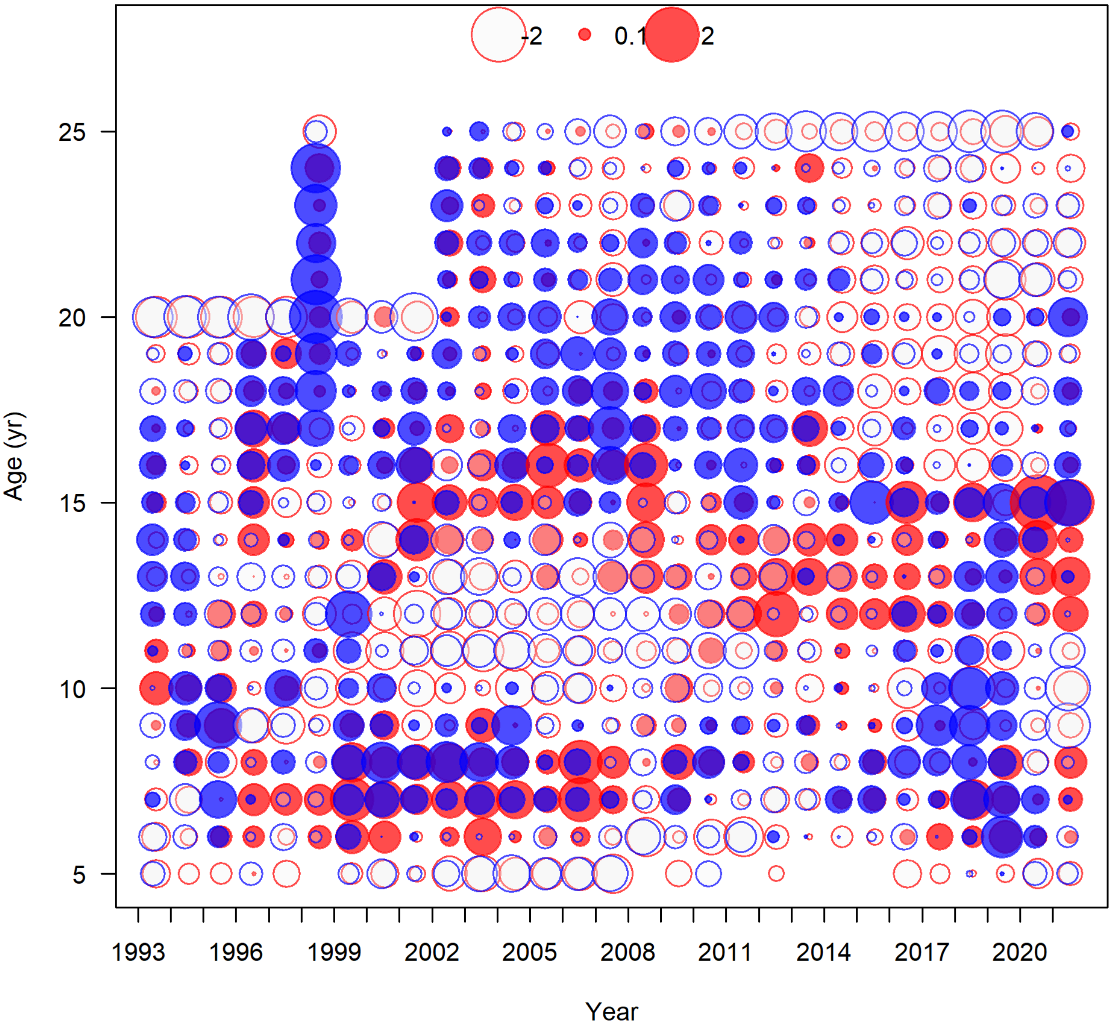


Figure 24. Pearson residuals for fit to annual age data from the FISS survey in the coastwide short model; red circles denote female residuals, and blue circles denote male residuals.

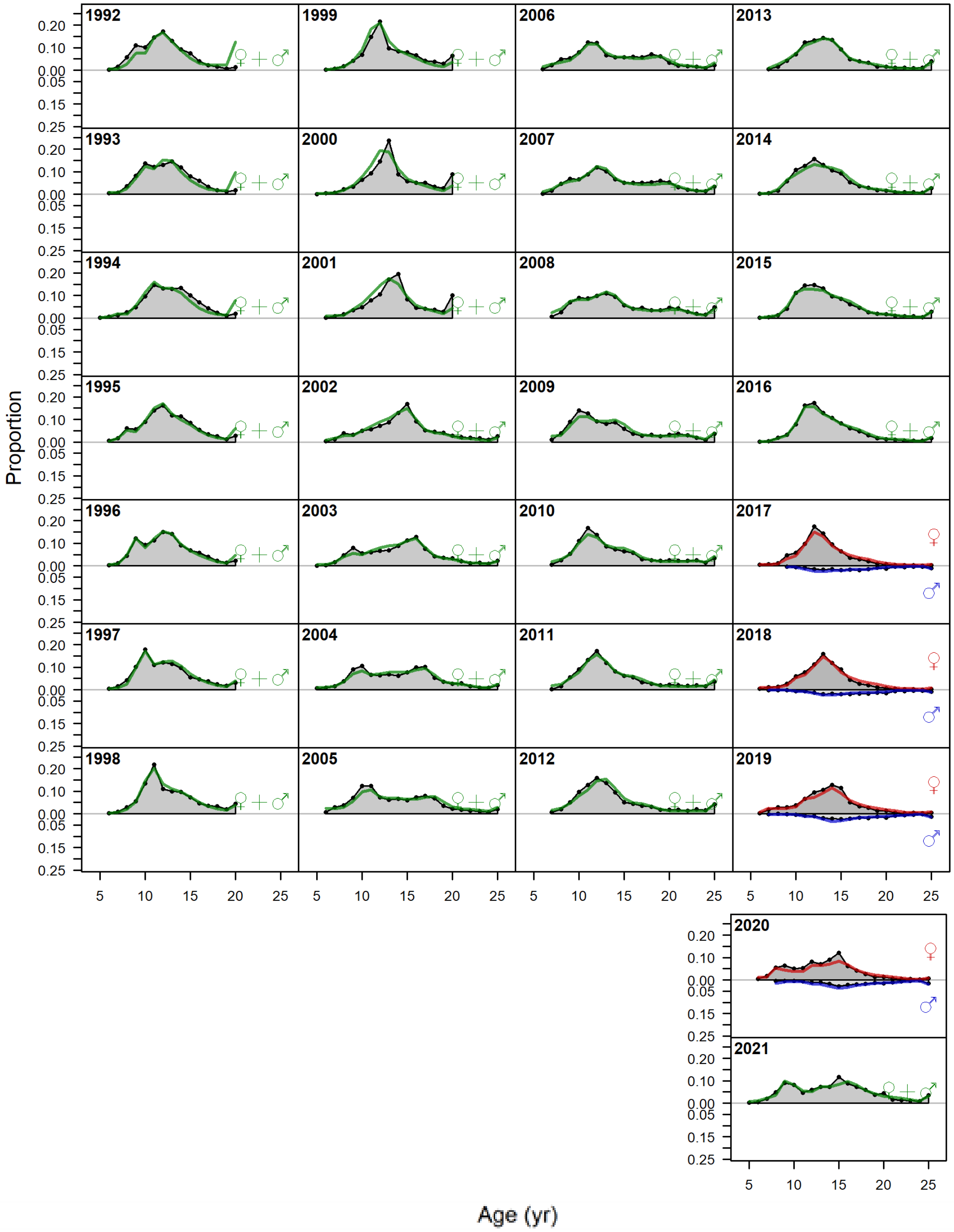


Figure 25. Fit to annual age data from the commercial fishery landings in the coastwide short model.

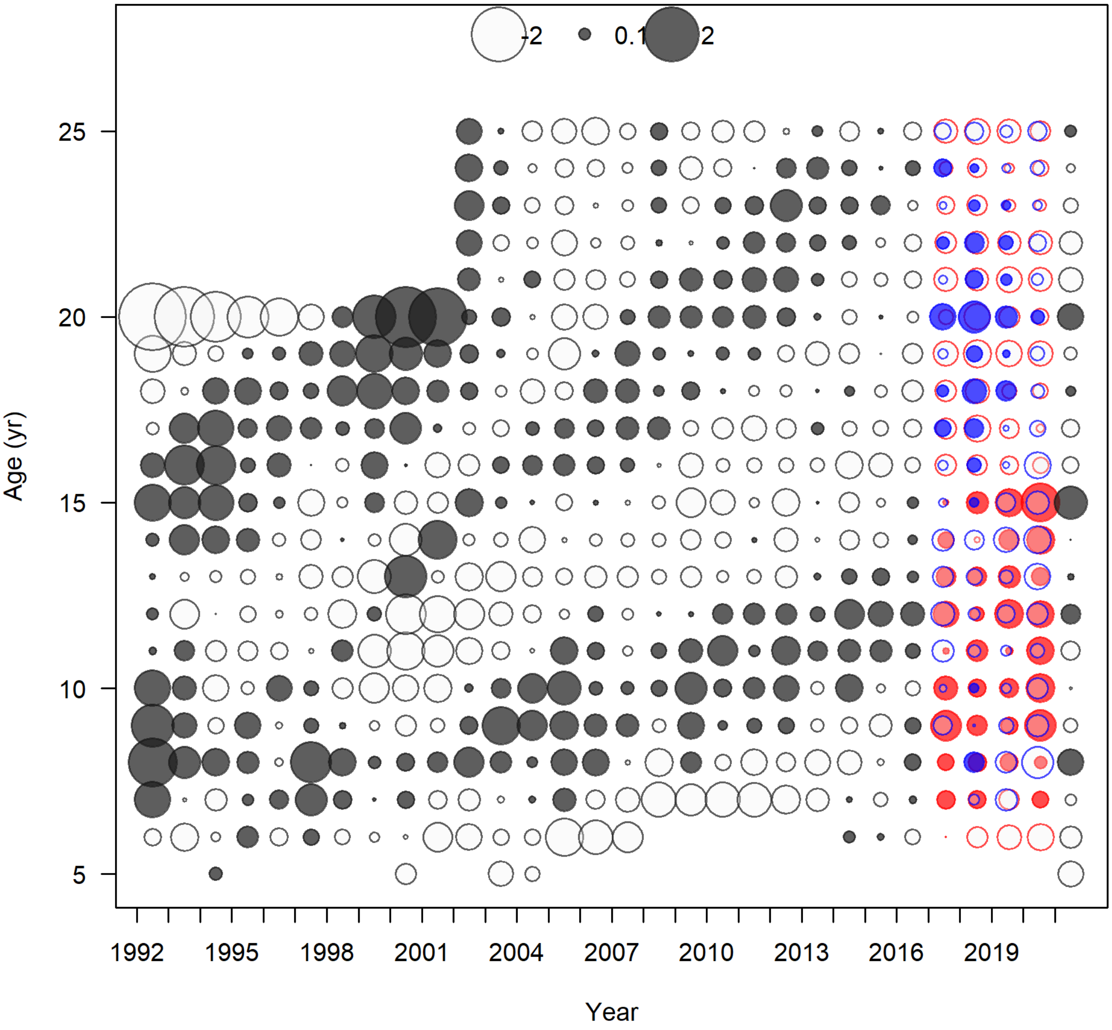


Figure 26. Pearson residuals for the fit to annual age data from the commercial fishery landings in the coastwide short model; grey circles denote unsexed residuals, red circles denote female residuals, and blue circles denote male residuals.

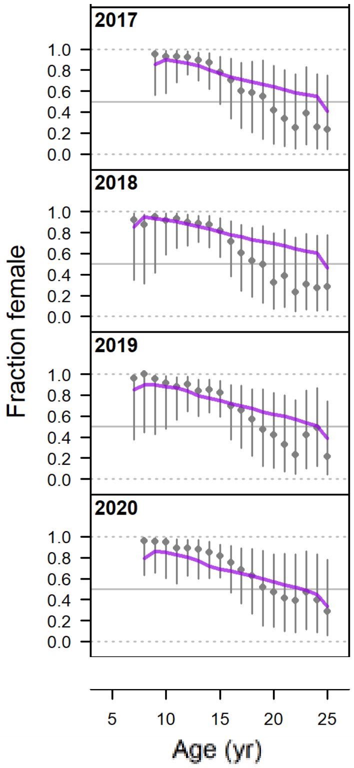


Figure 27. Observed and predicted sex-ratio in the commercial fishery landings from the coastwide short model.

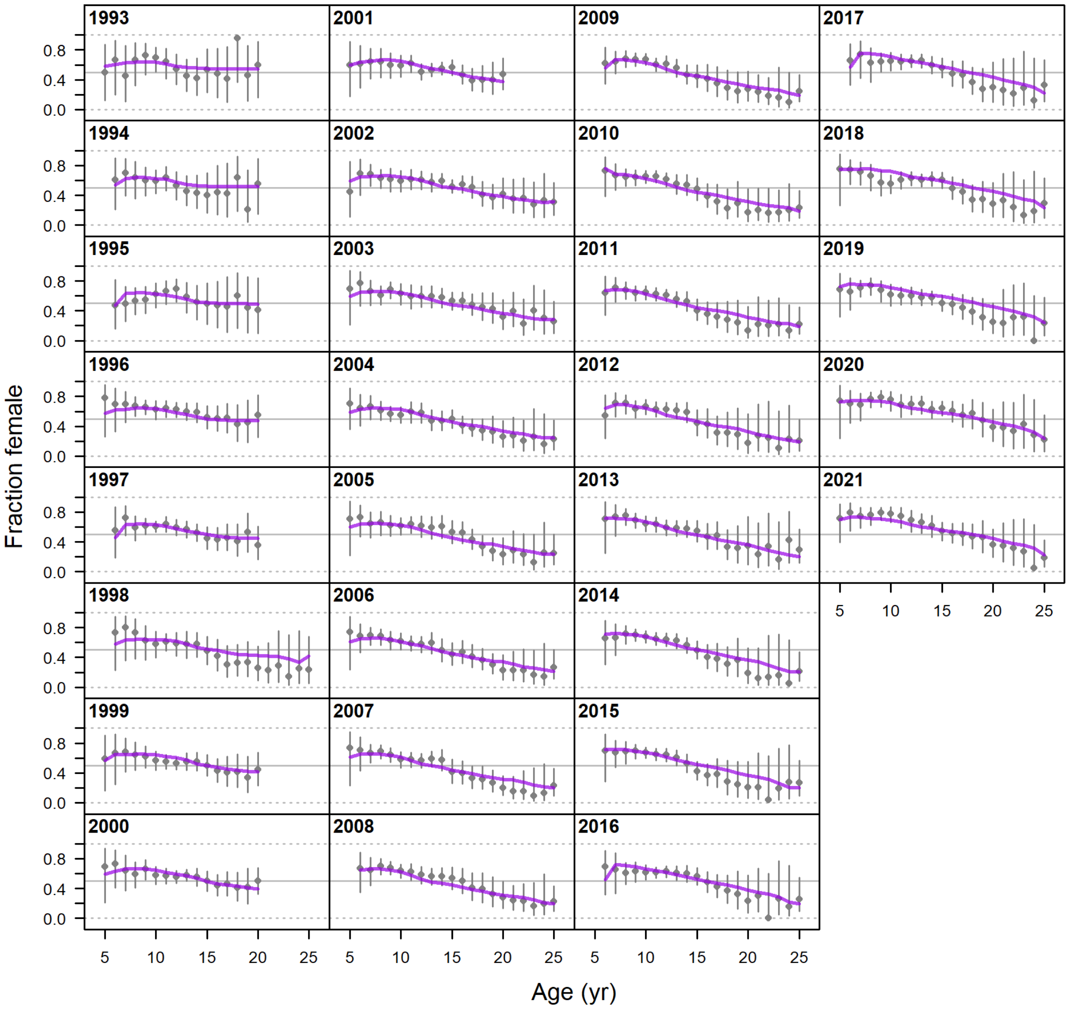


Figure 28. Observed and predicted sex-ratio in the FISS from the coastwide short model.

Neither the FISS nor the fishery selectivity was estimated to have a highly variable ascending limb over the short time-series (Figure 29). The estimated fishery selectivity showed a trend toward increasing selection of males in the middle of the time-series, more pronounced than that estimated for the FISS (Figure 30), perhaps a function of the catch distribution shifting toward the Eastern side of the stock where fast-growing males are much more common, as well as the decline in the strong cohorts from the 1980s which produced an abundance of older females. For the discard fleet, estimated selectivity included fewer males than females (Figure 31). Estimated selectivity for the non-directed discards fleet showed a peak at ages 4-5 and a slightly domed relationship. Recreational/subsistence selectivity was shifted to the left of the commercial fishery discards (and therefore the FISS).

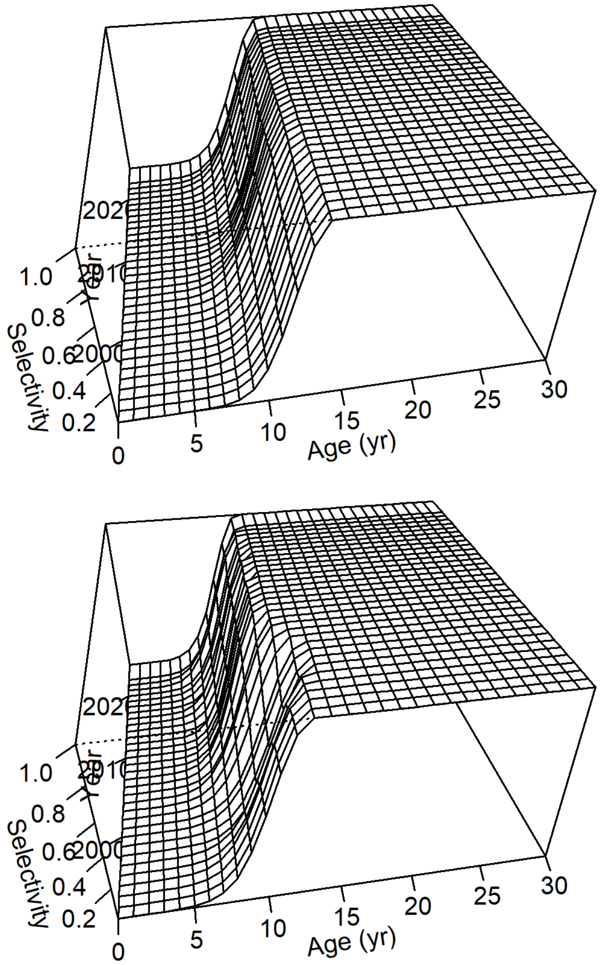


Figure 29. Estimated time-varying female selectivity curves for the commercial fishery landings (upper panel) and the FISS (lower panel).

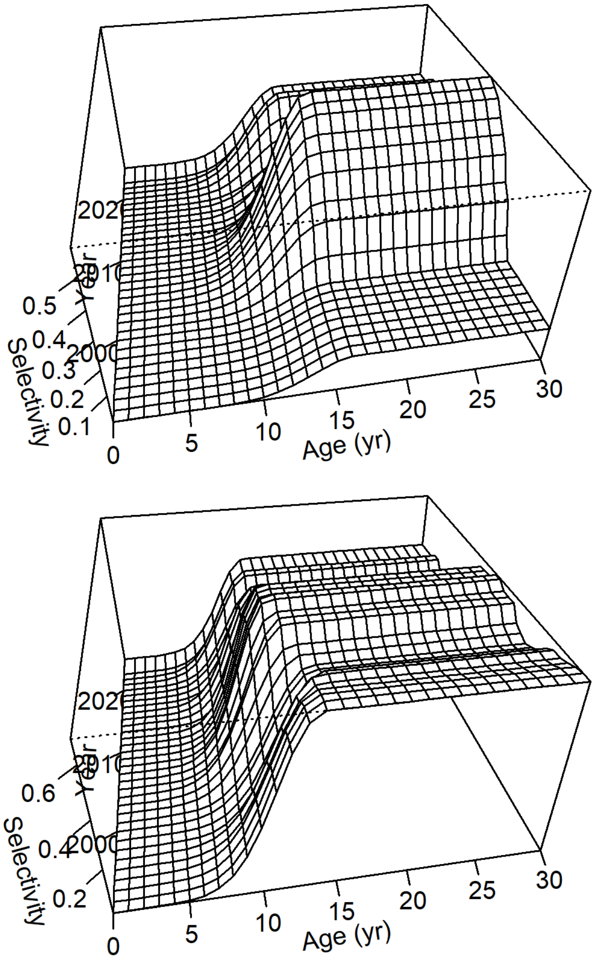


Figure 30. Estimated time-varying male selectivity curves for the commercial fishery landings (upper panel) and the FISS (lower panel).

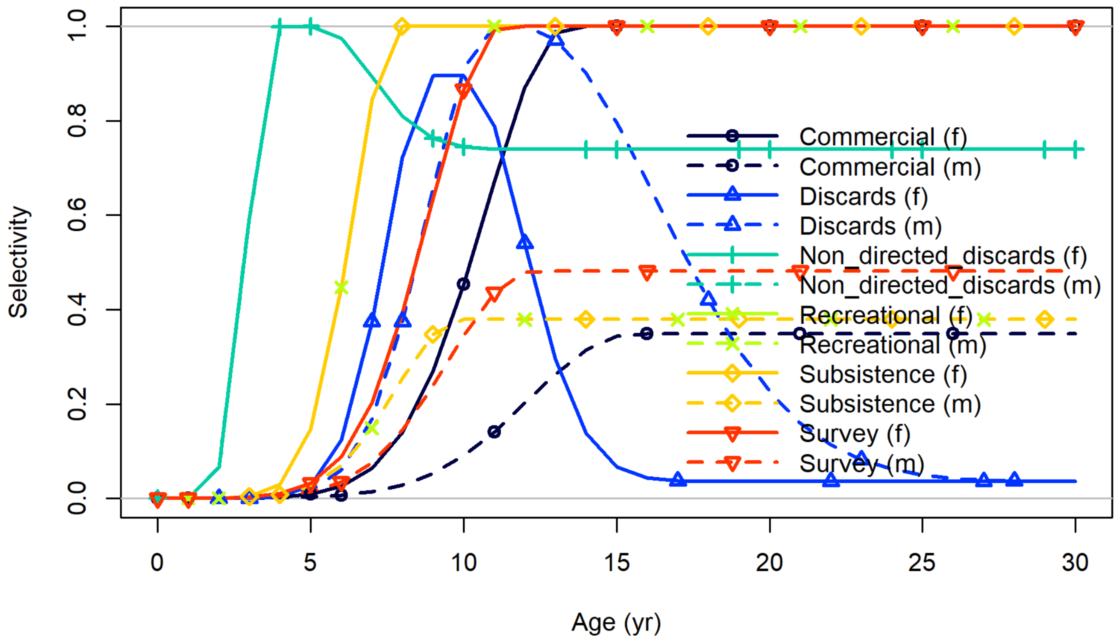


Figure 31. Estimated ending year selectivity curves by sex for the commercial fishery, discard, non-directed discard, recreational and FISS fleets in the coastwide short model.

Male *M* was estimated to be slightly lower (0.149) than the fixed value assumed for females of 0.15 (Table 17); this represented a slight increase from the value estimated in the 2019 and earlier assessments. The large negative estimated initial recruitment offset is consistent with the start year occurring after a very long time-series of fishing. The lower *M* fixed in the coastwide short model corresponded to much lower recruitment and female spawning biomass estimates (Table 17) than the other three models, as has been the case for all recent assessments.

Summary of strengths and weaknesses for the coastwide short model:

Strengths:

- Lowest technical overhead (complexity) of the four models in the ensemble
- Fit the fishery and FISS indices very well
- Fit the survey age data (males and females) relatively well
- Parameter estimates are derived from the most recent time period
- Internally consistent data weighting

Weaknesses:

- Basis for fixed female *M* is unclear
- Does not include uncertainty in female *M* (see likelihood profile evaluation below)
- Does not include extensive historical data
- May lose Region-specific trends and biological patterns due to aggregation

- Does not use environmental information to inform recruitment
- Commercial fishery age data is not heavily weighted and there are therefore residual patterns despite allowing for process error in selectivity

Table 17. Select parameter estimates (maximum likelihood value and approximate 95% confidence interval) and important recent population estimates by model and Biological Region (where applicable).

	Model			
	Coastwide Short	Coastwide Long	AAF Short	AAF Long
Biological				
Female M	0.150 (*Fixed*)	0.215 (0.186-0.243)	0.211 (0.195-0.227)	0.184 (0.167-0.200)
Male M	0.149 (0.138-0.159)	0.203 (0.188-0.218)	0.177 (0.167-0.187)	0.164 (0.154-0.173)
Log(R_0)	11.375 (11.167-11.582)	11.857 (11.546-12.168)	12.347 (12.115-12.579)	11.545 (11.262-11.829)
Initial log(R_0) offset	-1.469 (-1.685--1.253)	NA	-0.368 (-0.596-0.140)	NA
Environmental Link (β)	NA	0.372 (0.144-0.600)	NA	0.349 (0.129-0.569)
Survey Log(q) Δ1984 (transition to circle hooks)	NA	0.945 (0.592-1.299)	NA	R2: 1.222 (0.844-1.600) R3: 1.822 (1.553-2.092)
Fishery Log(q) Δ1984	NA	0.718 (0.541-0.895)	NA	R2: 0.586 (0.402-0.769) R3: 0.920 (0.724-1.115) R4: 0.858 (0.663-1.053) R4B: 0.529 (0.347-0.712)
2012 Recruitment (Millions)	85 (58-112)	283 (127-439)	278 (163-393)	195 (119-270)
2022 SB (Million lb)	150 (126-173)	202 (155-250)	259 (199-320)	218 (178-260)

Coastwide long

Both the fishery and FISS indices were fit well (Figure 32), with breaks in catchability to accommodate the change from “J” to circle hooks which were very large in both series (Table 17). In aggregate, the predicted age compositions matched the observed data well (Figure 33); however, there were notable differences among years within the time-series. Fits to the FISS were quite poor in the early portion of the time series (Figure 34), improving where the data became more spatially comprehensive in the mid-1990s, and quite good in the most recent years (Figure 35). Fishery data fit reasonably well for the entire time-series (Figure 36-36), with patterns in the residuals corresponding to relatively small differences with observed distributions.

The small contribution of males to the fishery landed catch is clear from the four years that have sex-specific information Figure 37. Harmonic mean effective sample sizes were much larger than adjusted inputs when Francis weights were close to 1.0 (Table 16).

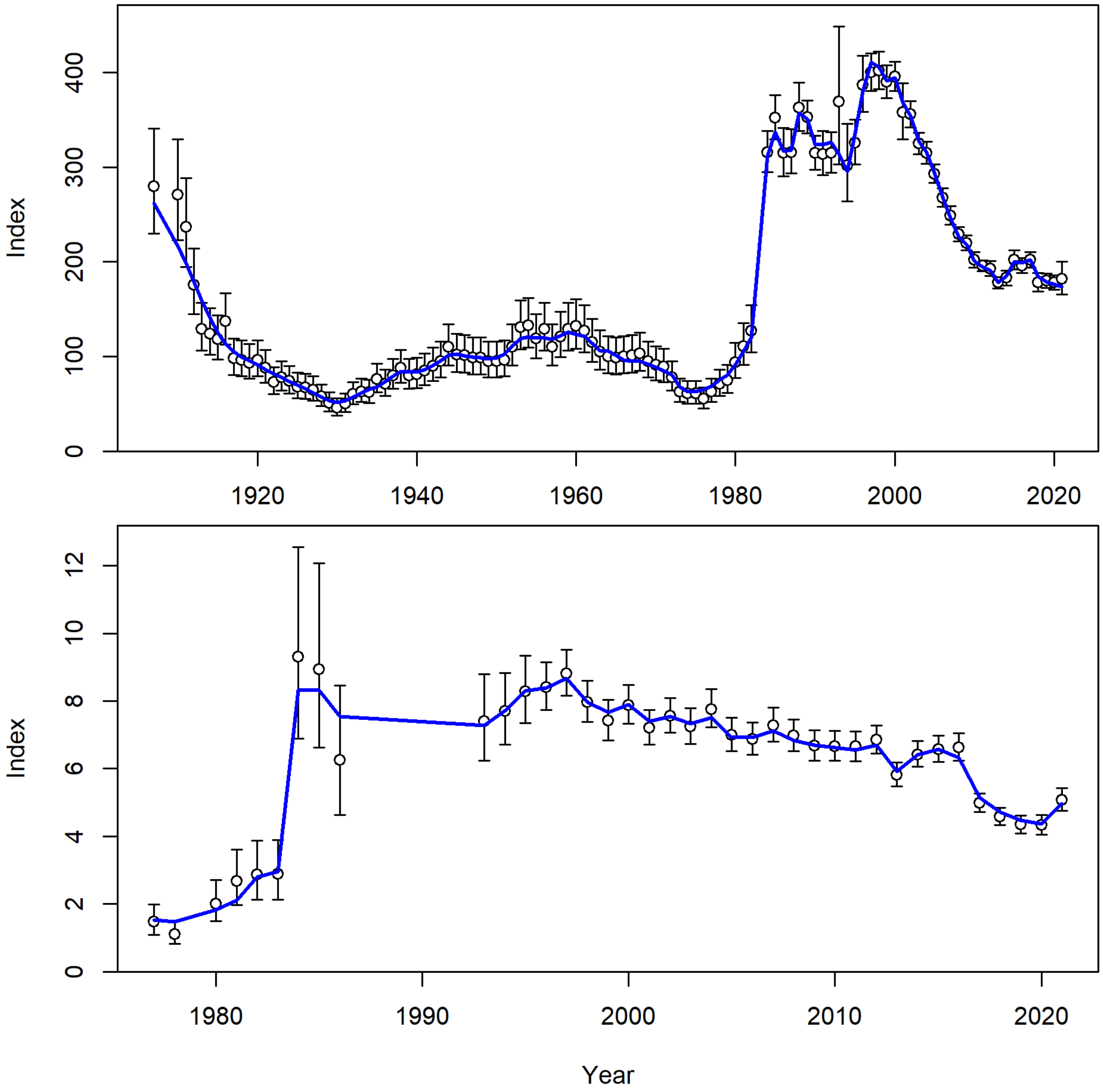


Figure 32. Fit to fishery (upper panel) and FISS (lower panel) indices in the coastwide long model.

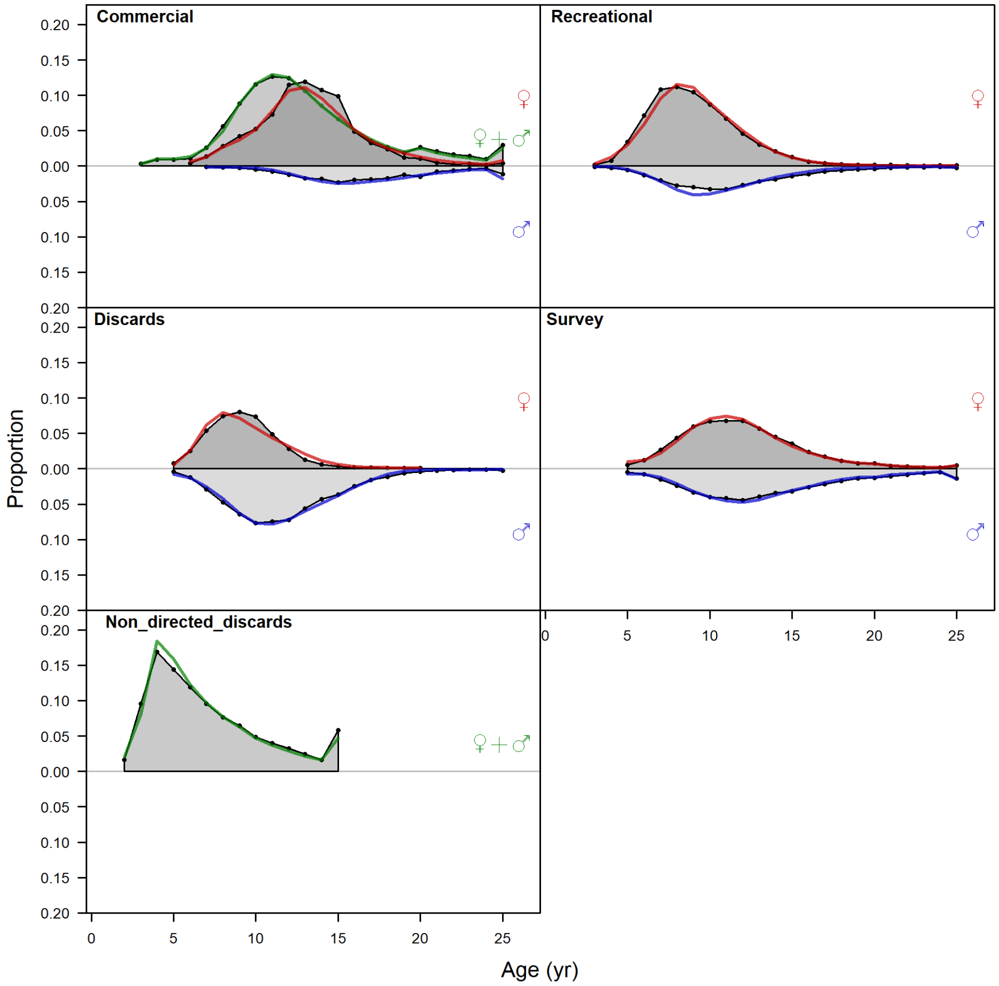


Figure 33. Aggregate fit to all age data by model fleet in the coastwide long model..

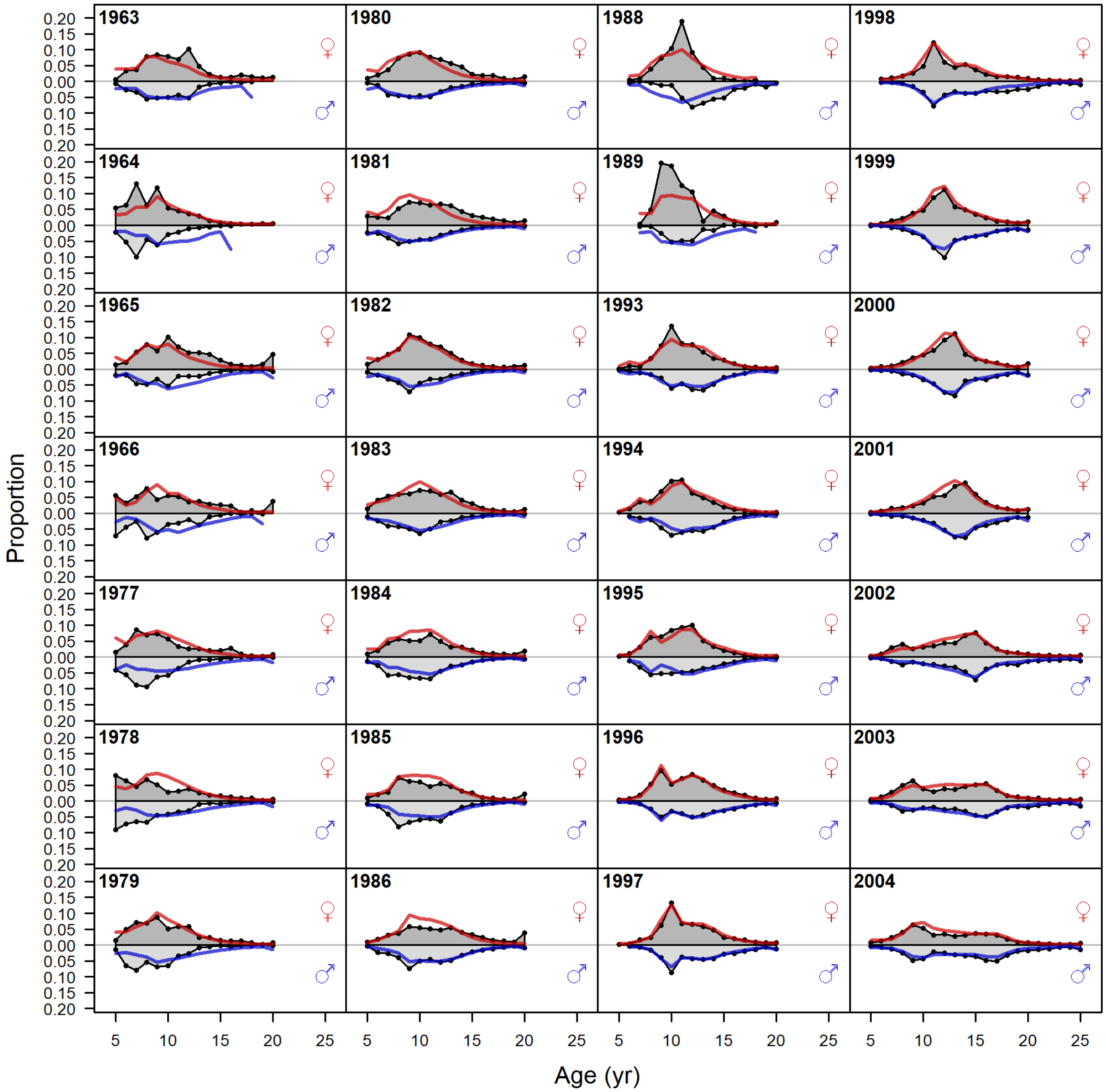


Figure 34. Fit to early years of FISS age data in the coastwide long model.

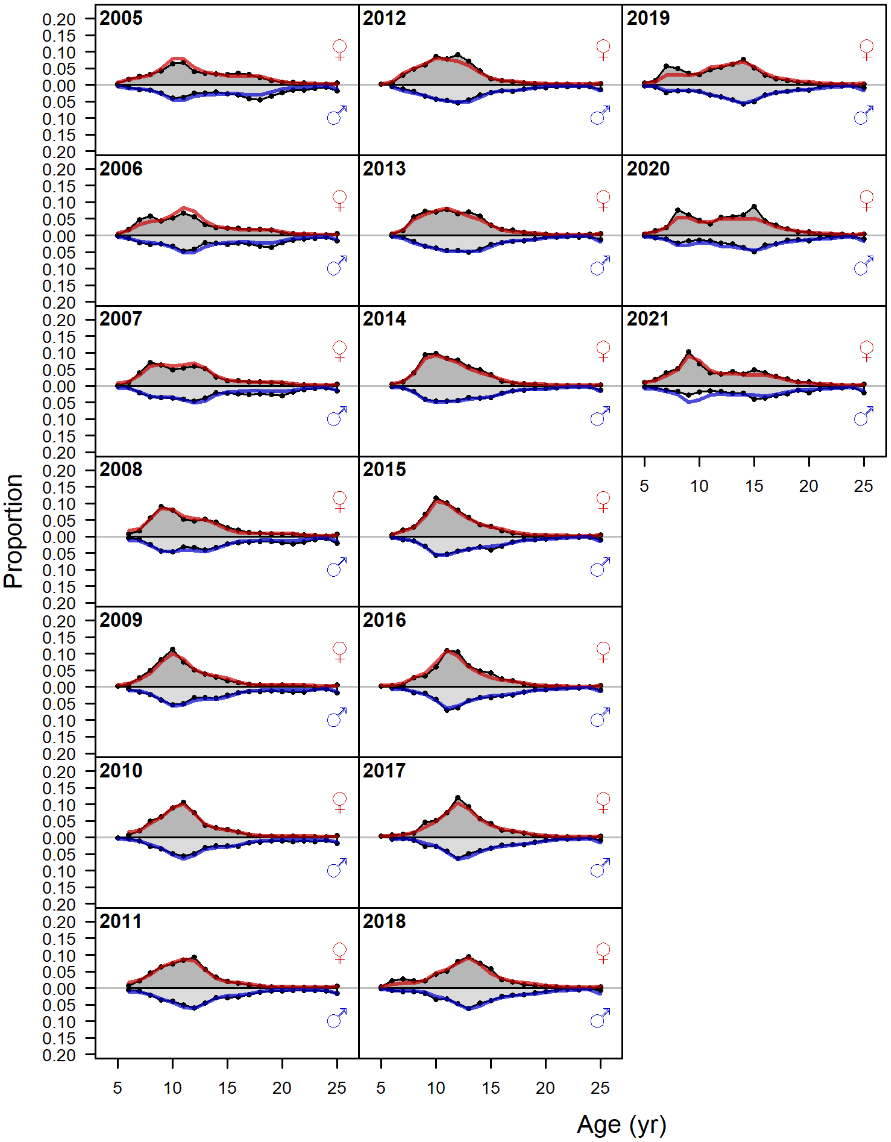


Figure 35. Fit to later years of FISS age data in the coastwide long model.

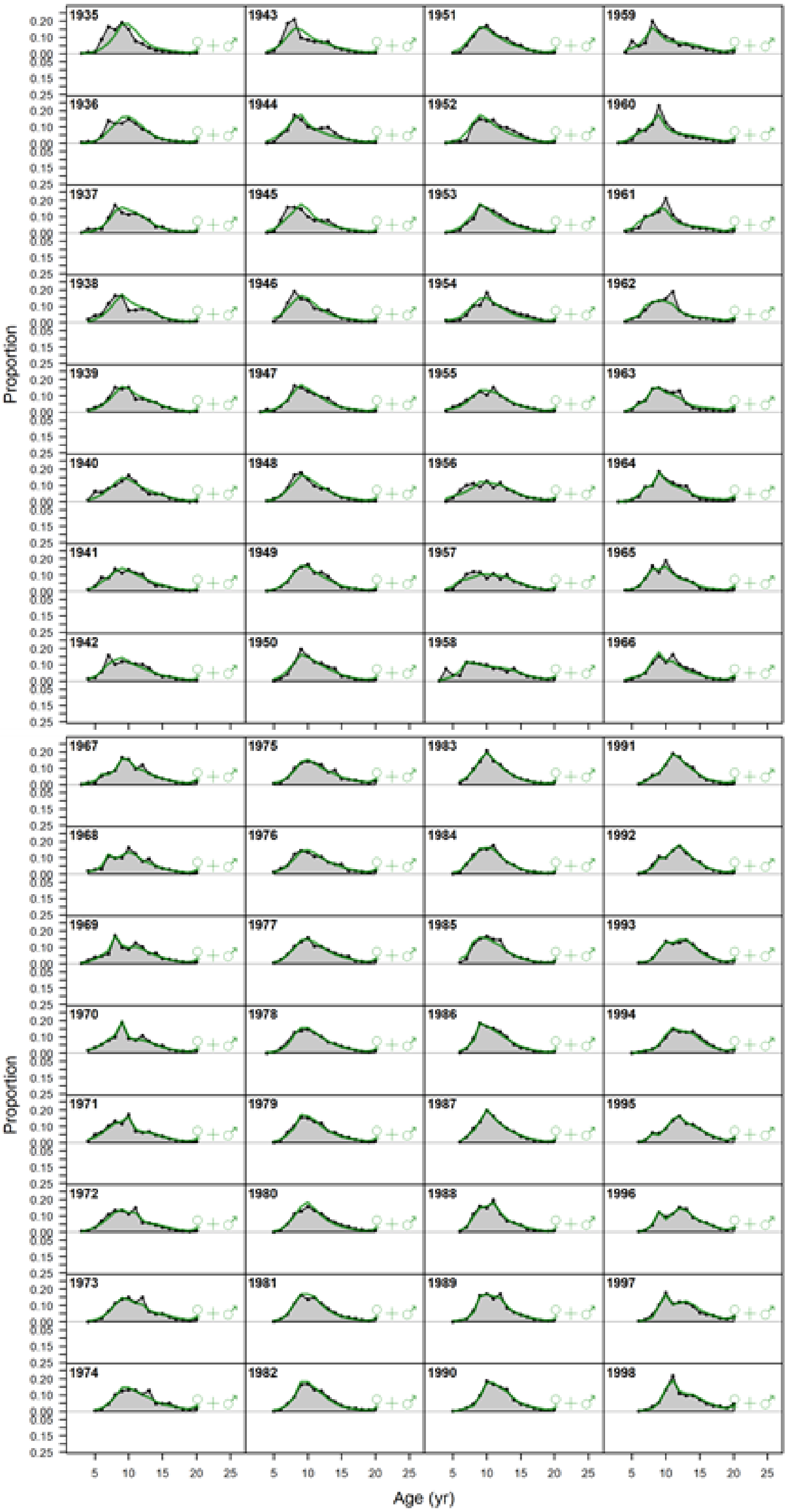


Figure 36. Fit to early years of fishery age data in the coastwide long model.

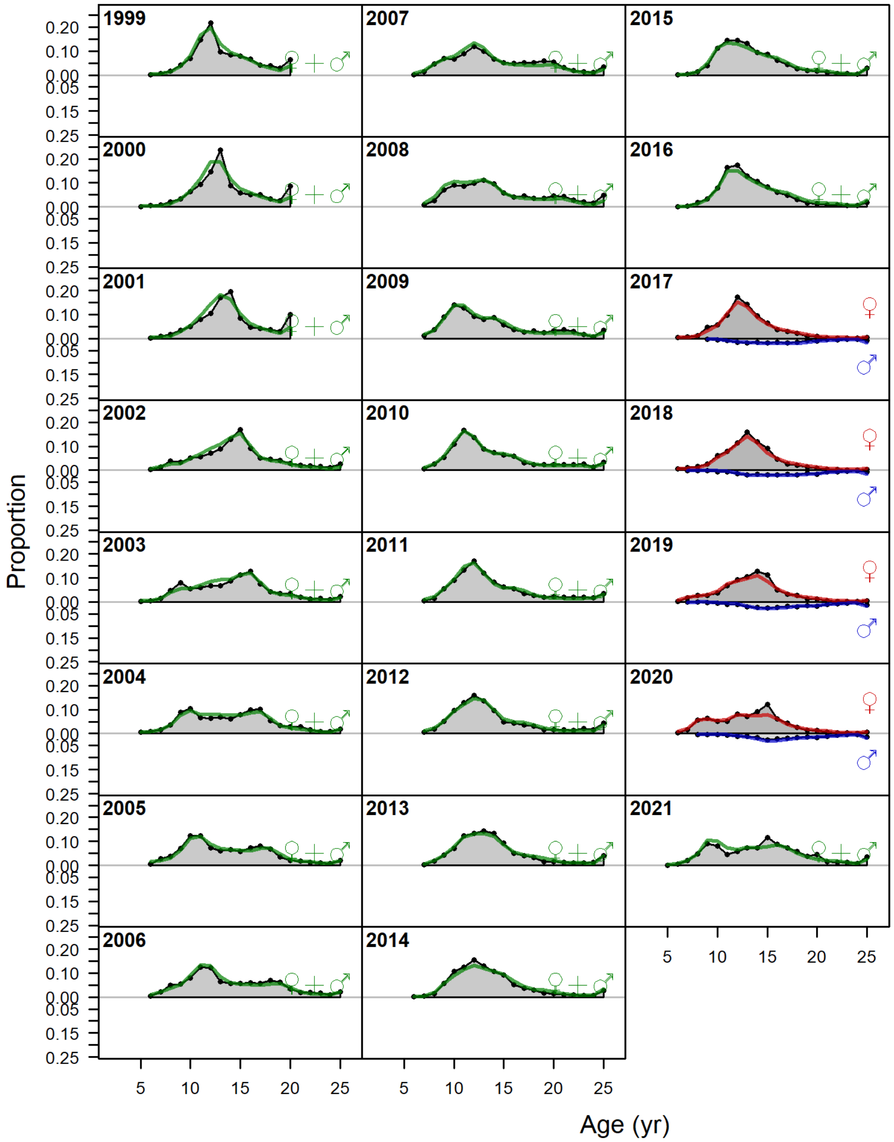


Figure 37. Fit to later years of fishery age data in the coastwide long model.

Fishery selectivity generally showed a pattern toward selecting fewer younger fish in the latter half of the time series, but a similar trend to the FISS in the most recent years (Figure 38). This may be consistent with changes in both the age-structure of the stock, the trends in size-at-age interacting with age-based selectivity and the spatial distribution creating changes in availability. Fishery catchability showed a very large (unconstrained) increase associated with the change from “J” to circle hooks (Table 17, Figure 39). Older halibut were more represented in the non-directed fishery discards age data prior to 1992, and therefore the estimated selectivity was nearly asymptotic. Recreational and discard selectivity estimates were relatively similar to those from the coastwide short model.

Female natural mortality in the coastwide long model was estimated to be higher (0.215) than for males (0.203) although the 95% intervals overlap broadly (Table 17, Figure 19). The environmental link parameter (β) was estimated to be positive (0.372), with no density below a value of 0.0, thus suggesting a strong and significant relationship between average recruitment and the phase of the PDO (Table 17). However, the time series of estimated recruitments (Figure 40) and deviates from the PDO-informed stock-recruitment relationship (Figure 41) suggested that some residual effect and/or mismatch in the relationship might still be present. Specifically, the poor PDO period from 1947-1977 and the positive phase from 1978-2006 generally correspond to negative and positive deviations even with the relationship included (Figure 41).

Summary of strengths and weaknesses for the coastwide long model:

Strengths:

- Includes uncertainty in female natural mortality
- Includes extensive historical data
- Uses environmental information to inform recruitment
- Modest technical overhead (complexity)
- Fits the fishery and survey indices well
- Fits both the survey and fishery age data well
- Internally consistent data weighting

Weaknesses:

- May lose Region-specific trends and biological patterns due to aggregation
- Relies heavily on only fishery trends over the historical period
- Implicitly assumes stationarity in some processes (e.g., the stock-recruitment function, *M*) over the long historical period
- Implicitly assumes that availability to the fishery did not change over the historical period, despite known patterns in geographical expansion prior to the 1960s

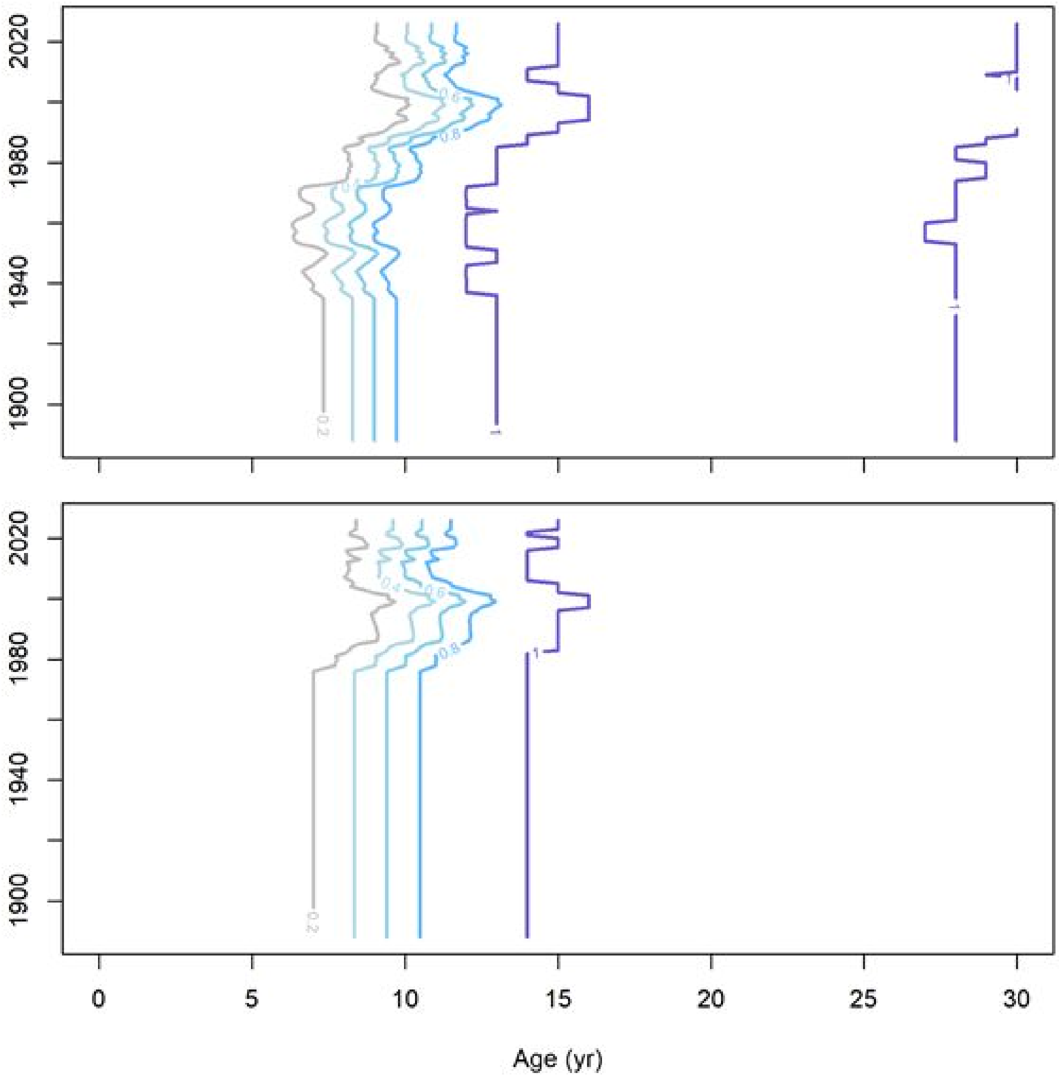


Figure 38. Estimated selectivity for females in the commercial fishery landings (upper panel) and survey (lower panel) in the coastwide long model.

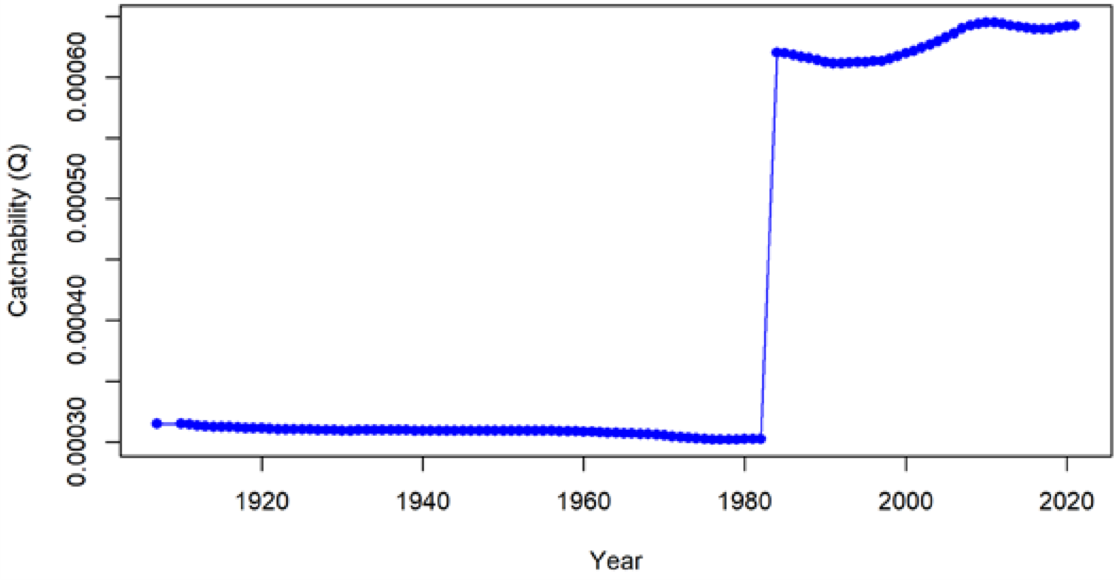


Figure 39. Time-varying fishery catchability in the coastwide long model. The change corresponding to the transition to circle hooks in 1984 is unconstrained.

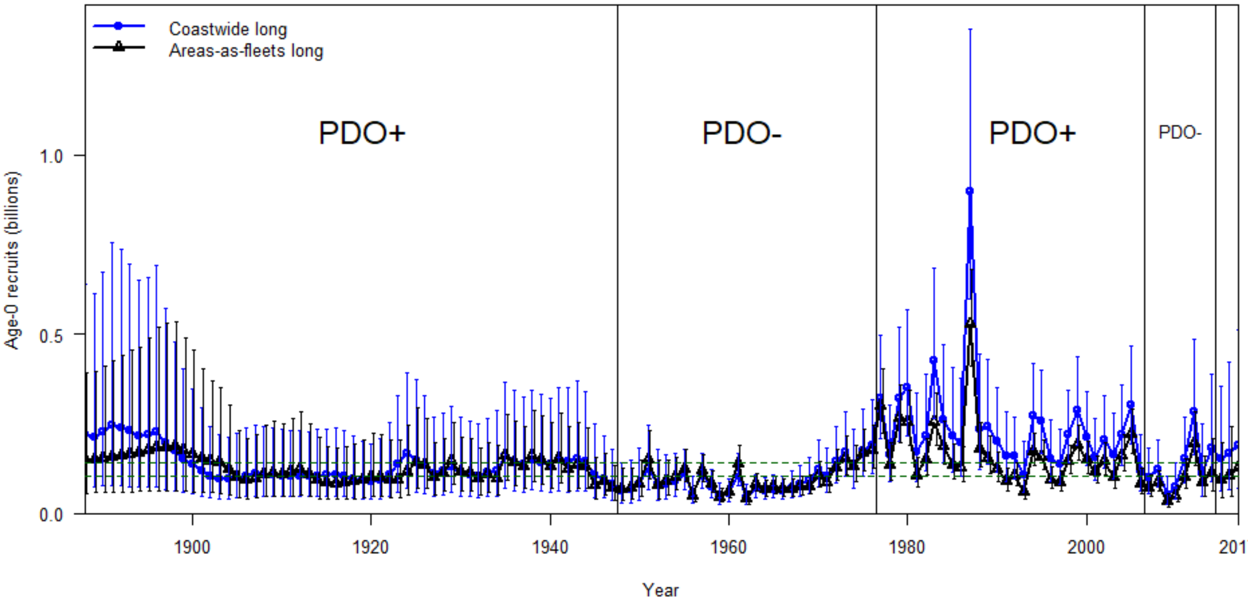


Figure 40. Estimated recruitments and assumed PDO regimes from the coastwide long and AAF long models (right panel); horizontal lines indicate equilibrium values in the absence of the PDO.

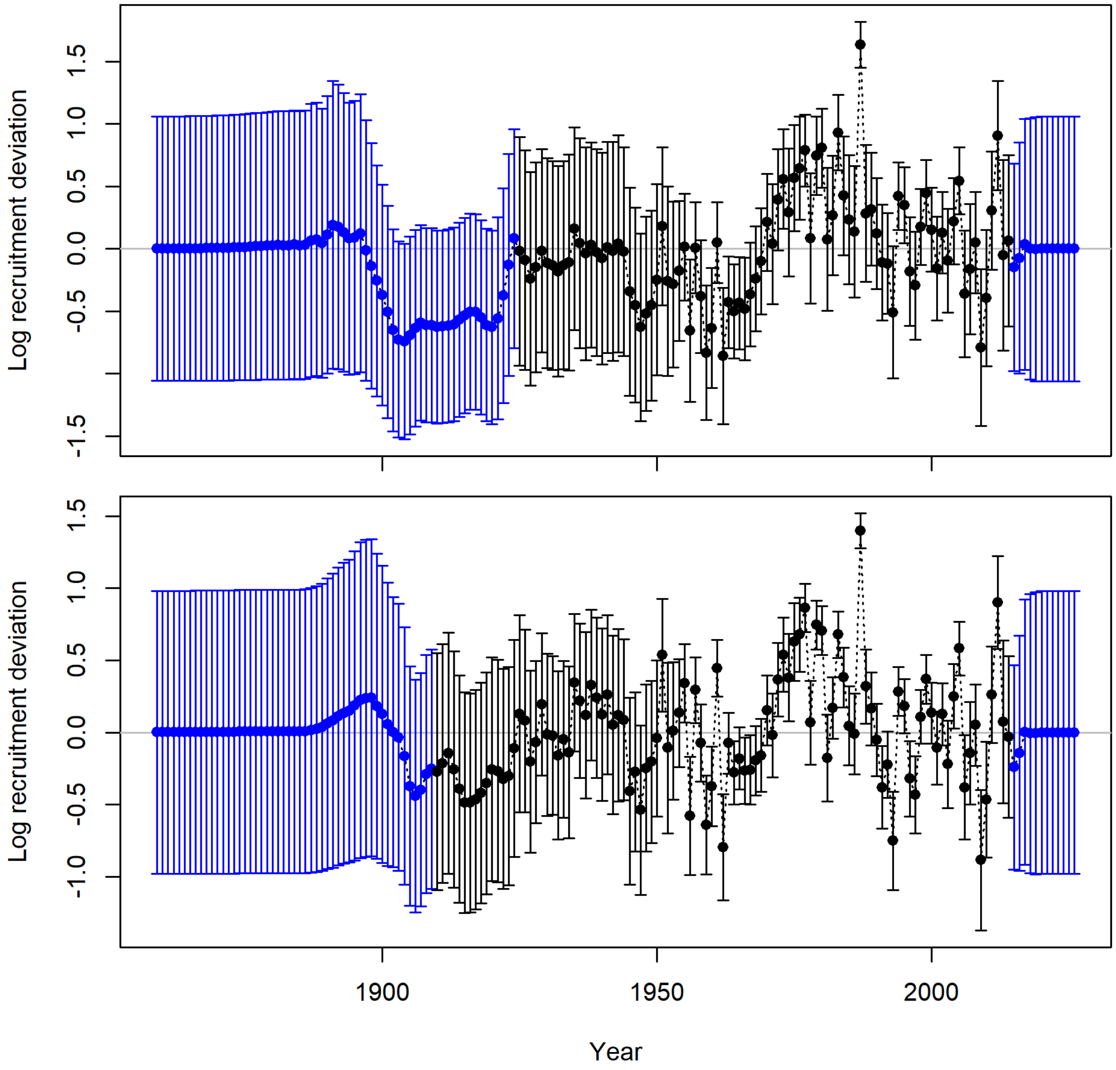


Figure 41. Estimated recruitment deviations in the coastwide long (upper panel) and AAF long (lower panel) models; horizontal lines indicate expected values based on the stock-recruitment functions as modified by the estimated PDO relationships.

AAF short

The AAF short model fit the observed trends in all fishery and FISS indices relatively well (Figure 42-42). Fit to the aggregate age data for each fleet clearly illustrated the differences in age structure (Figure 44). The biggest differences between female and male halibut observed from the FISS occurred in Region 3, and generally Regions 4 and 4B were predicted (and observed) to have the greatest fraction of older halibut, a majority of which were males. The fit to the annual FISS age data generally captured these patterns, with the worst fit occurring for the data from Region 2 (Figure 45); the Francis weight suggested a low weighting for the Region 2 FISS data consistent with these patterns (Table 16). Although showing a reasonably good aggregate fit, the fit to annual commercial fishery landings in Biological Regions 4 and 4B (Figure 46-46Figure 47) did not capture the strong peaks created by the 1987 year-class in the late 1990s and early 2000s; however of these fleets only the Region 4 data were down-weighted from the bootstrapped inputs based on the Francis weighting (Table 16). No model configurations evaluated during model development were able to fit the peak observations of this cohort observed in Regions 4 and 4B, which may be a reflection of the spatial nature of the dynamics not well approximated by an AAF approach.

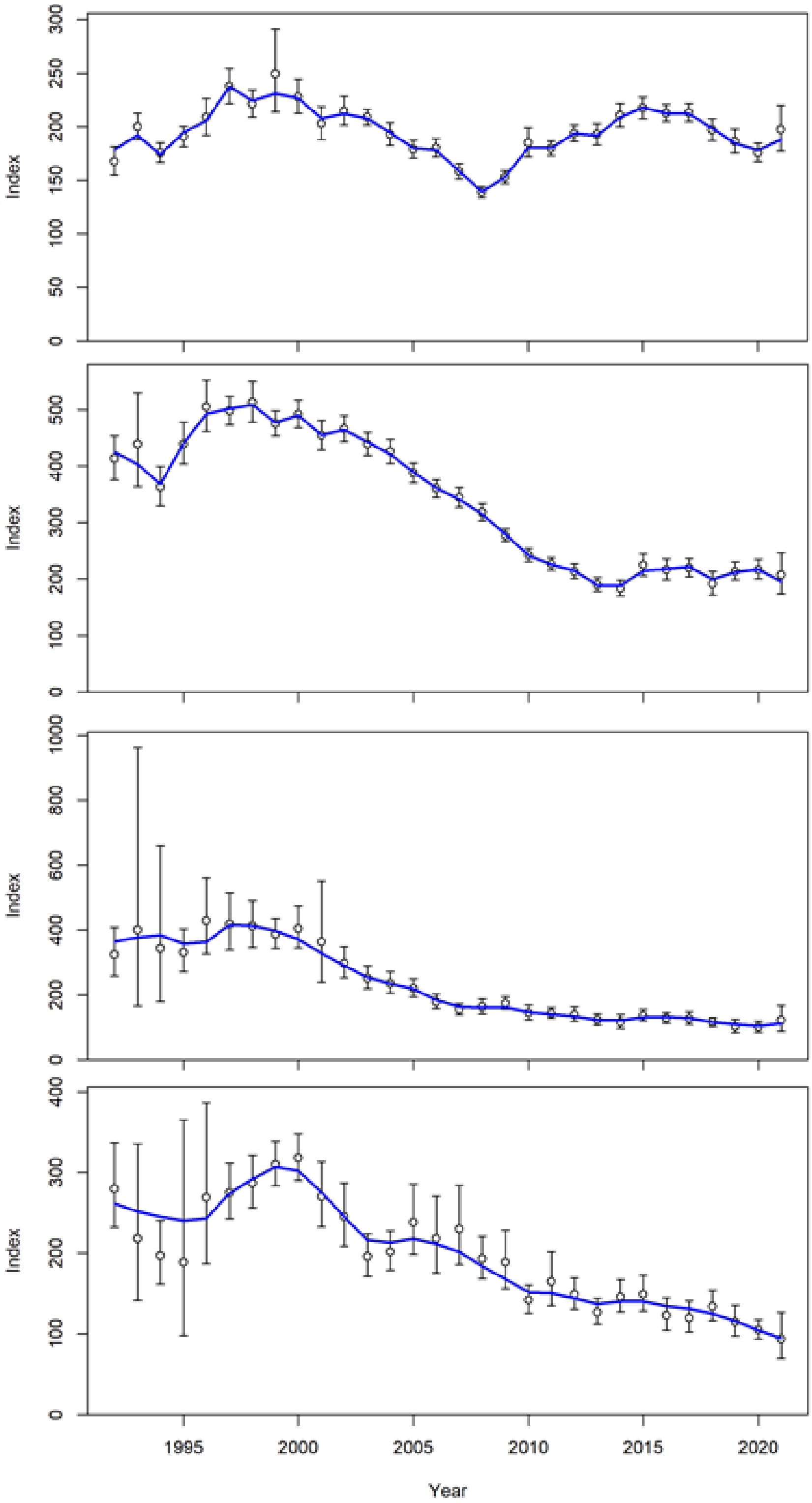


Figure 42. Fit to fishery trends in Biological Regions 2, 3, 4, and 4B (top to bottom) in the AAF short model.

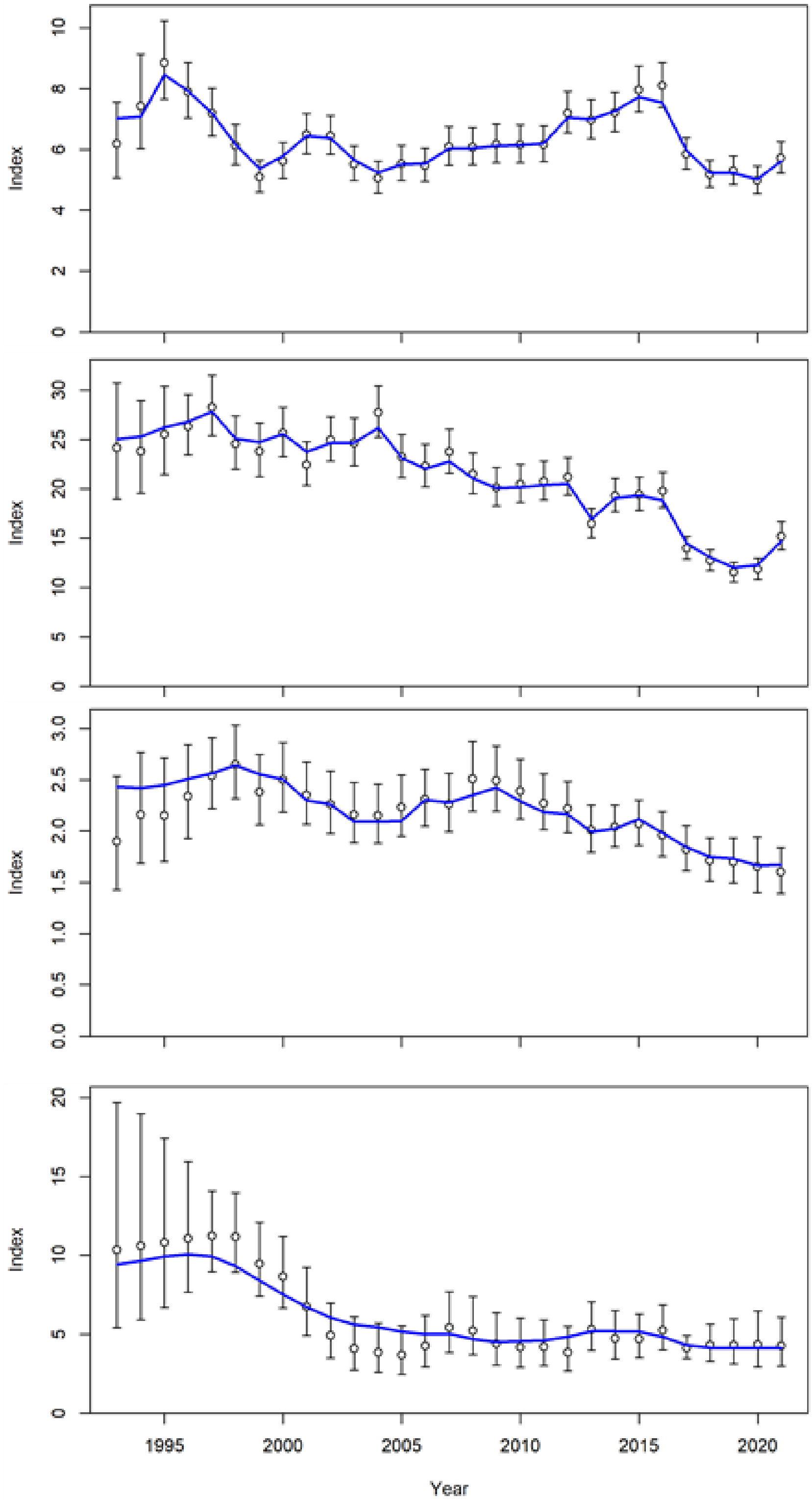


Figure 43. Fit to survey trends in Biological Regions 2, 3, 4, and 4B (top to bottom) in the AAF short model.

The estimate of female natural mortality in the AAF short model (0.211) was slightly lower than in the coastwide long model and male value much lower (0.177; Table 17). The lack of overlap on the 95% intervals indicates the clearly different explanation in this model for the observed sex-ratios, albeit restricted to the most recent portion of the time-series. This result likely indicates the trade-off between the assumption of asymptotic selectivity in the coastwide model and domed selectivity for most Regions in the AAF models. The AAF short model estimated a negative but somewhat smaller initial offset to recruitment. Due to the higher estimated *M*, the AAF short model estimated a higher absolute level of recent recruitment and spawning biomass than the coastwide short model (Table 17).

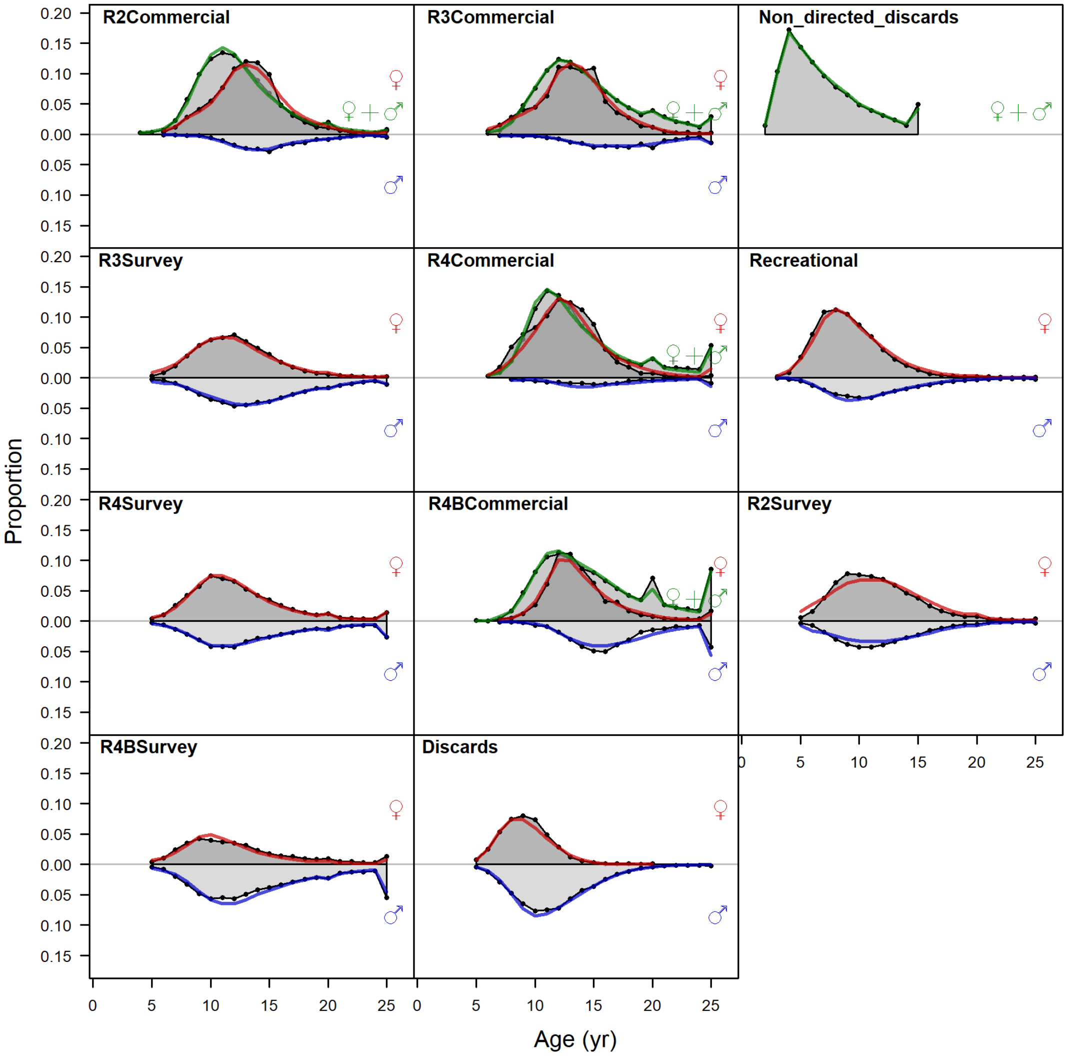


Figure 44. Aggregate fit to age data for each model fleet in the AAF short model.

Summary of strengths and weaknesses for the AAF short model:

Strengths:

- Parameter estimates are derived from the most recent time period
- Avoids aggregating data over Biological Regions with differing trends and biological patterns
- Fits the Regional fishery and FISS indices well
- Fits Regions 2 and 3 fishery age data well
- Internally consistent data weighting
- Propagates uncertainty in female and male *M* estimates

Weaknesses:

- Does not include environmental information to inform recruitment
- Modest technical overhead (complexity)
- Residual patterns in Region 4 and 4B fishery and survey age data
- Fits Regions 2 and 3 FISS age data poorly
- Does not include extensive historical data

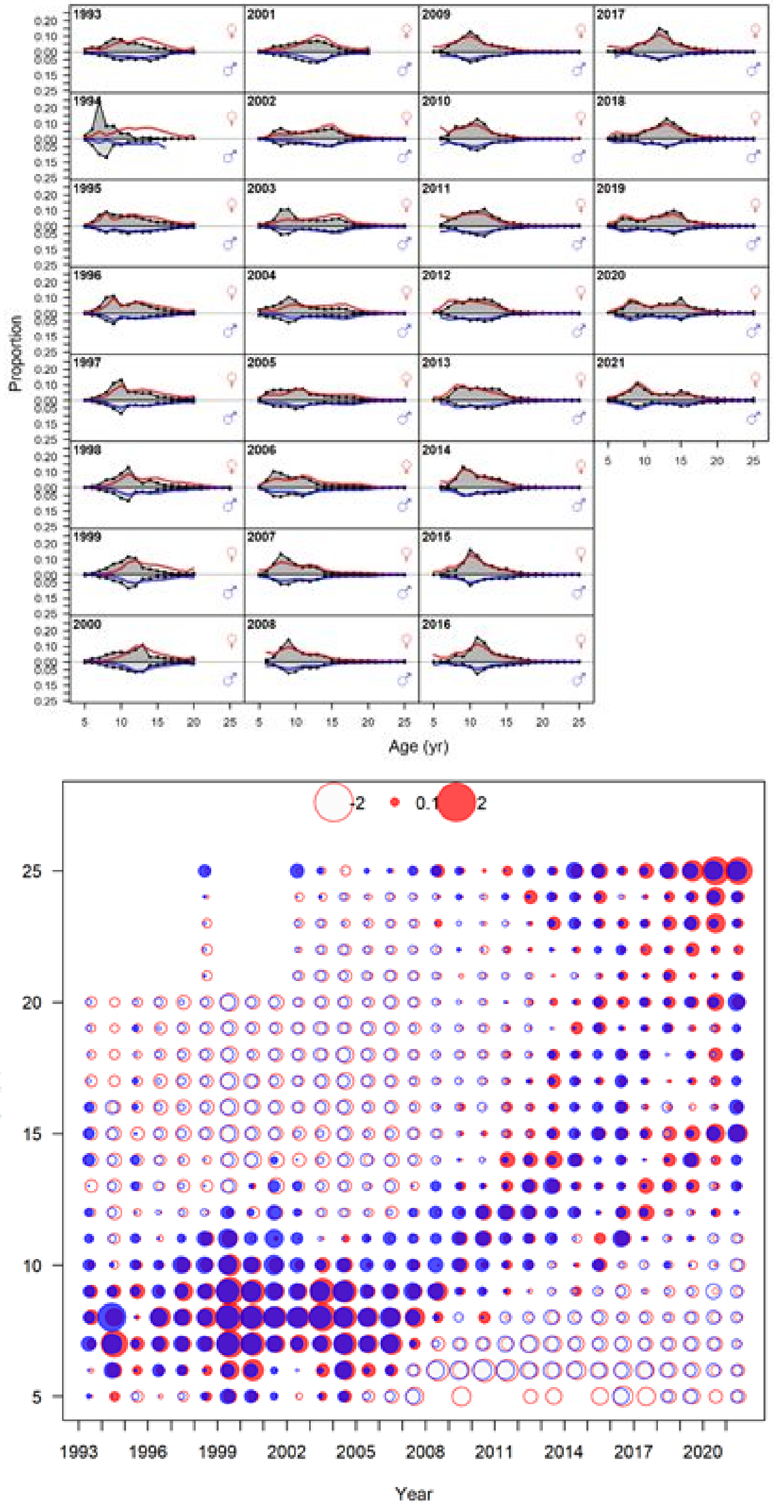


Figure 45. Fit to age data (upper panel) and Pearson residuals (lower panel) from the Region 2 FISS in the AAF short model; red circles denote female residuals, and blue circles denote male residuals.

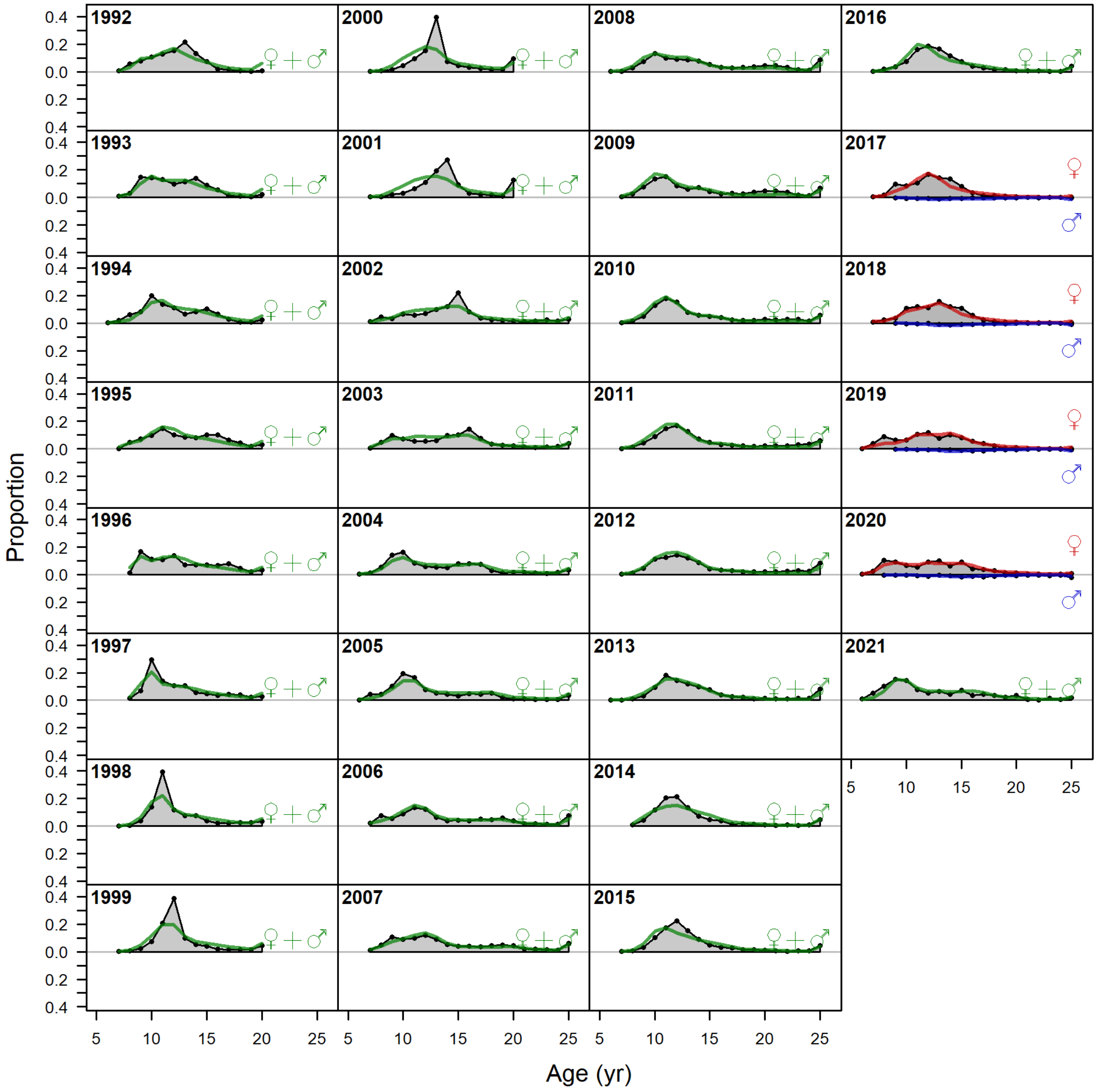


Figure 46. Fit to age data from the Region 4 commercial fishery landings in the AAF short model.

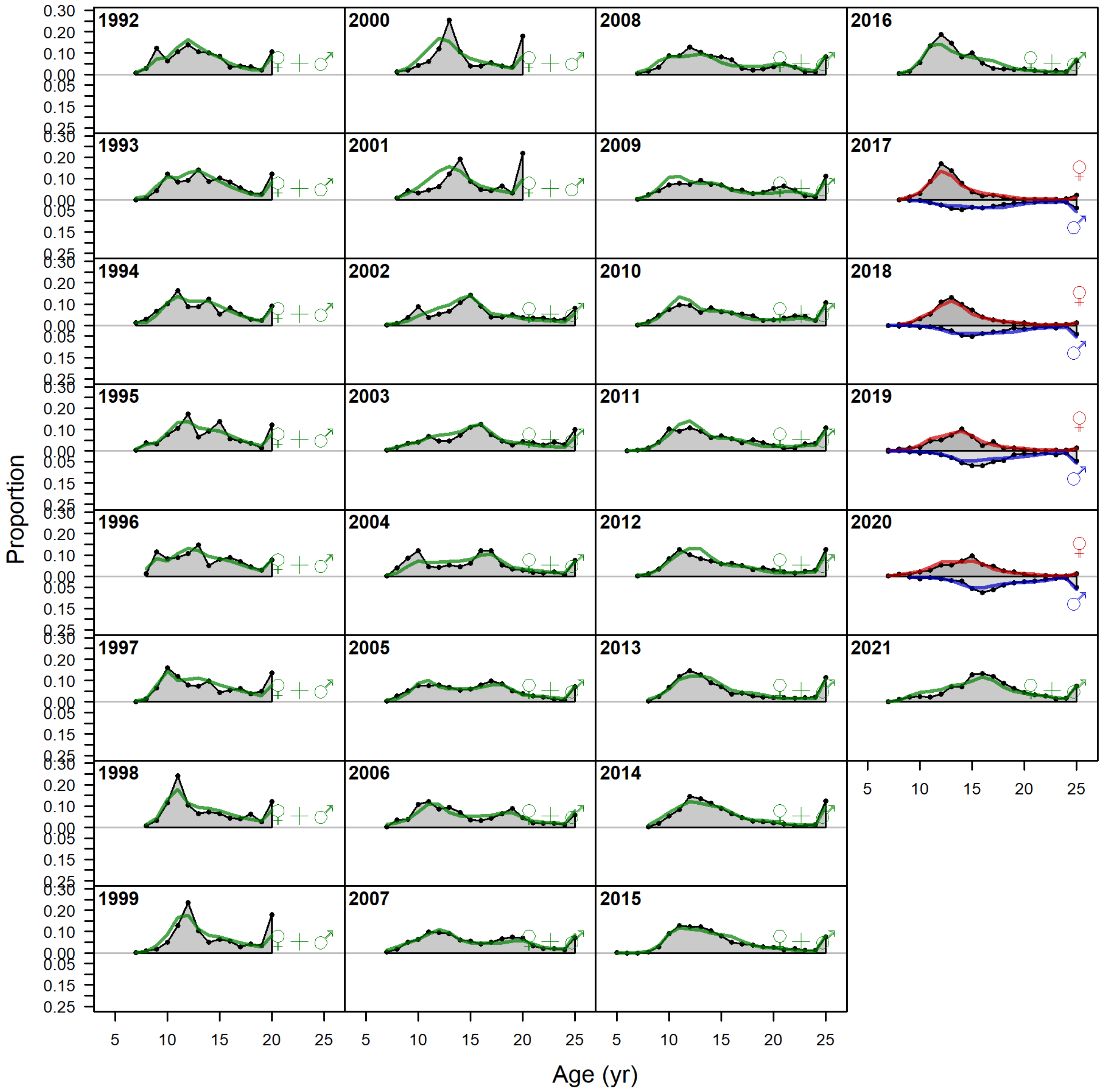


Figure 47. Fit to age data from the Region 4B commercial fishery landings in the AAF short model.

AAF long

Like the AAF short model, the AAF long model fit both the fishery and FISS trends well (Figure 48-48). Aggregate fits to the FISS age composition data showed similar patterns to those observed in the AAF short model (Figure 50). The fit to the FISS age data improved over the time series, but the Region 2 and 3 FISS age data was strongly down-weighted in order to achieve consistency with the Francis weighting (Table 16). This resulted in the worst fit by fleet (Figure 51-52). Lack of fit to the Region 3 FISS data occurred primarily in the early part of the time-series Figure 52. Among the fishery fleets, the Region 4 data were most heavily down-weighted from the bootstrapped input sample sizes (Table 16).

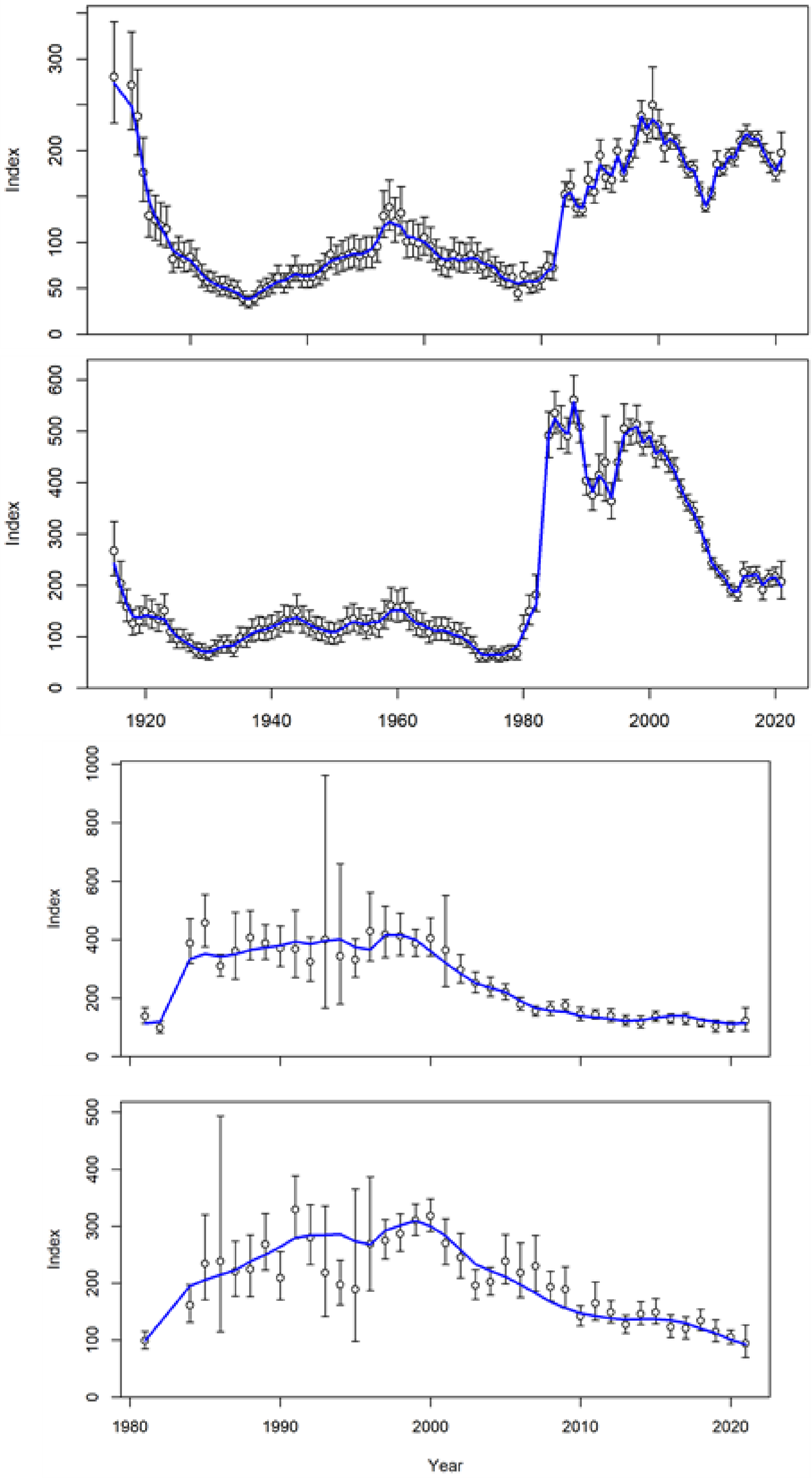


Figure 48. Fit to fishery trends in Biological Regions 2, 3, 4, and 4B (top to bottom) in the AAF long model.

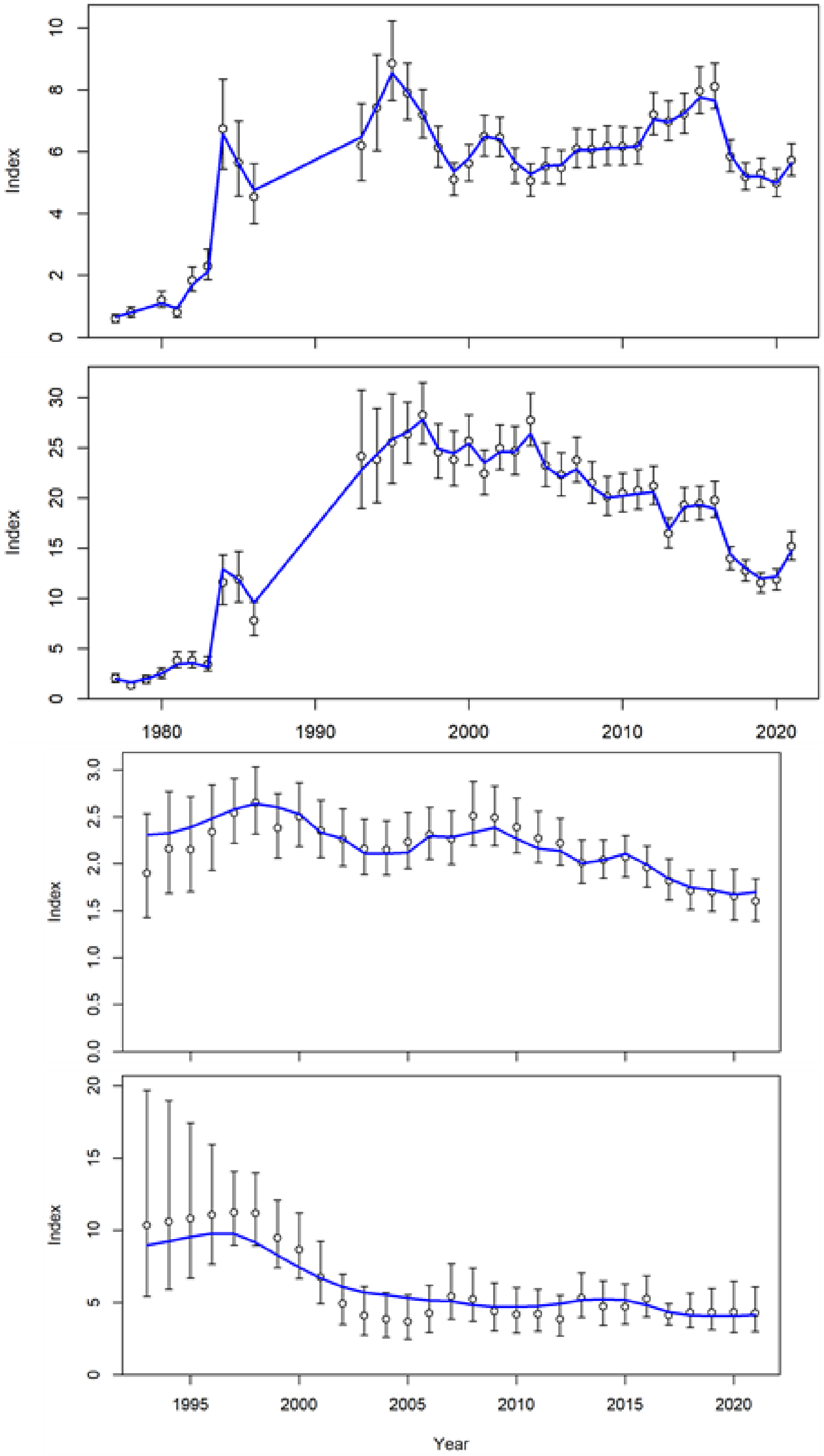


Figure 49. Fit to FISS trends in Biological Regions 2, 3, 4, and 4B (top to bottom) in the AAF long model.

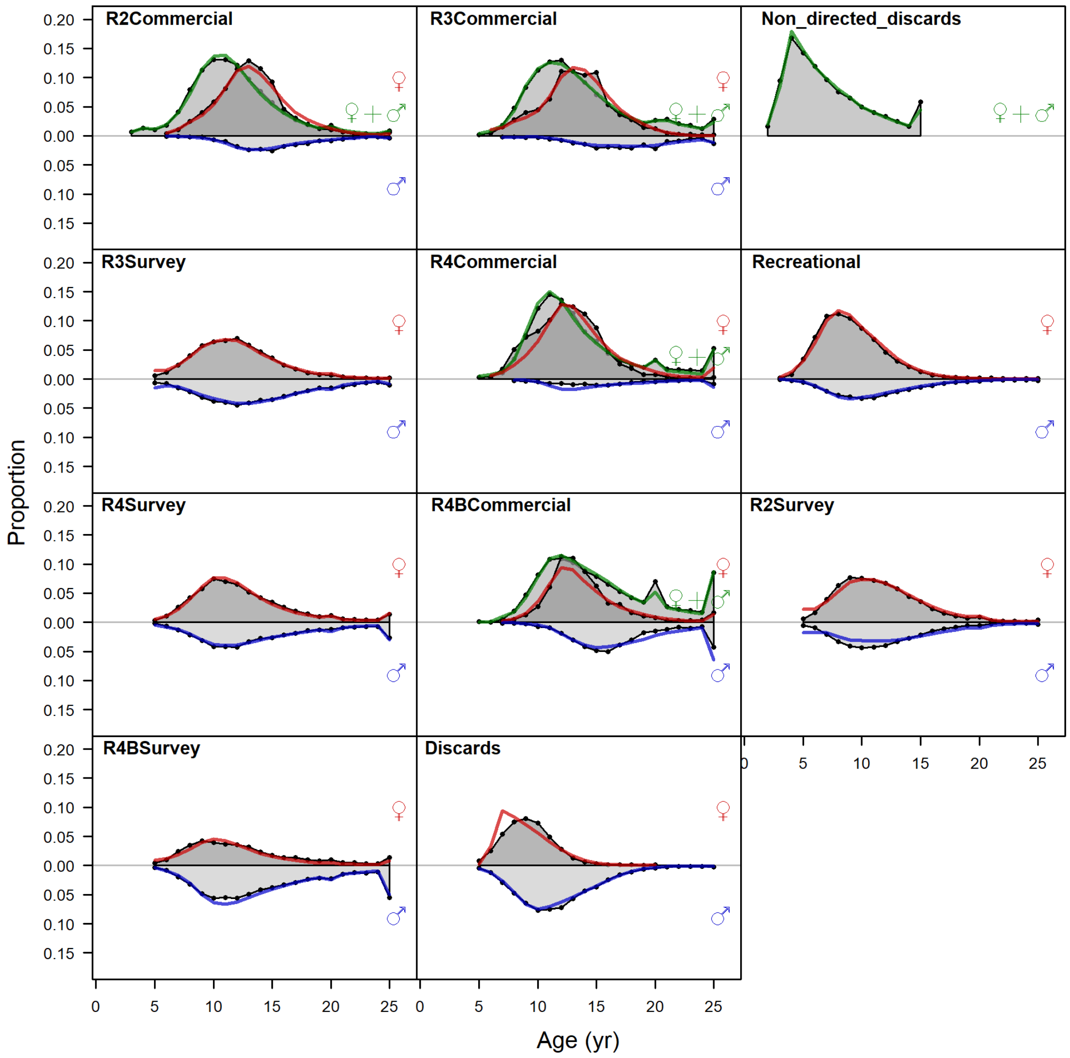


Figure 50. Aggregate fit to age data for each model fleet in the AAF long model.

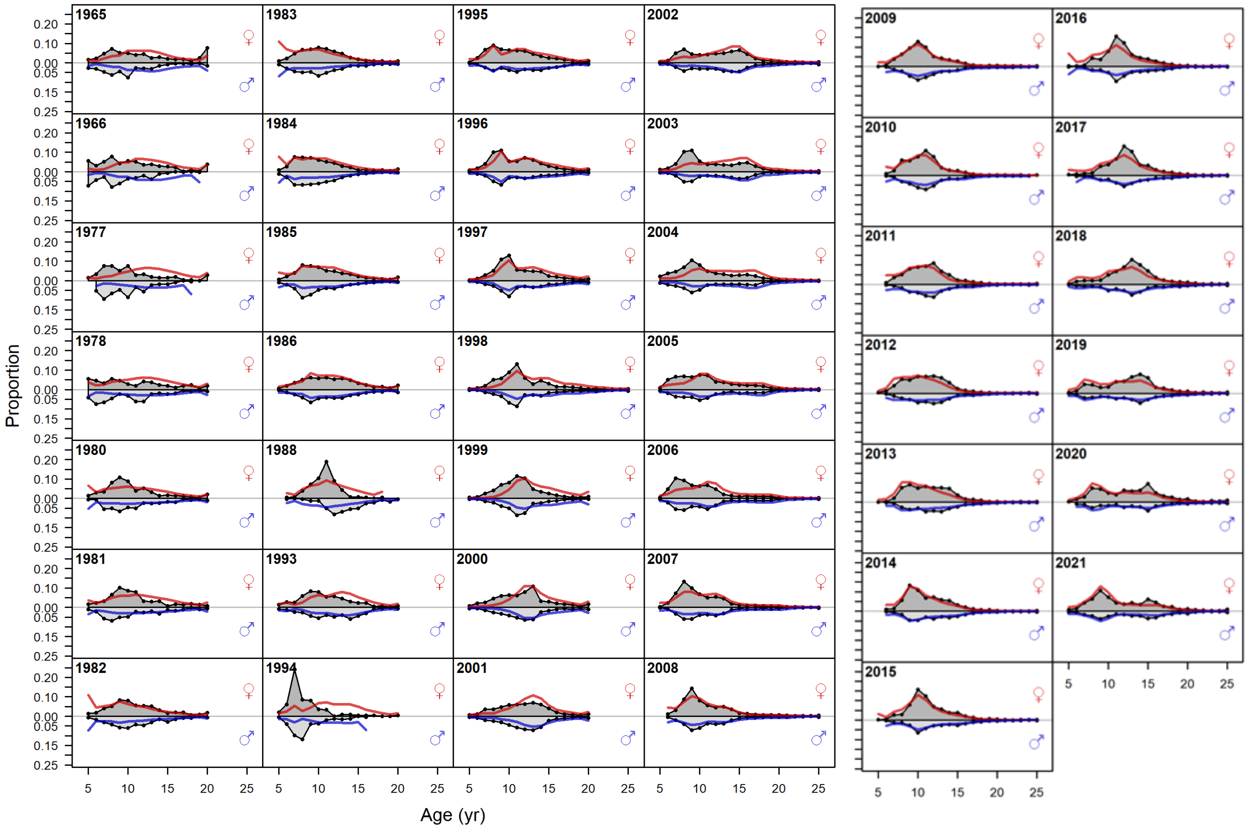


Figure 51. Fit to age data from the Region 2 FISS in the AAF long model.

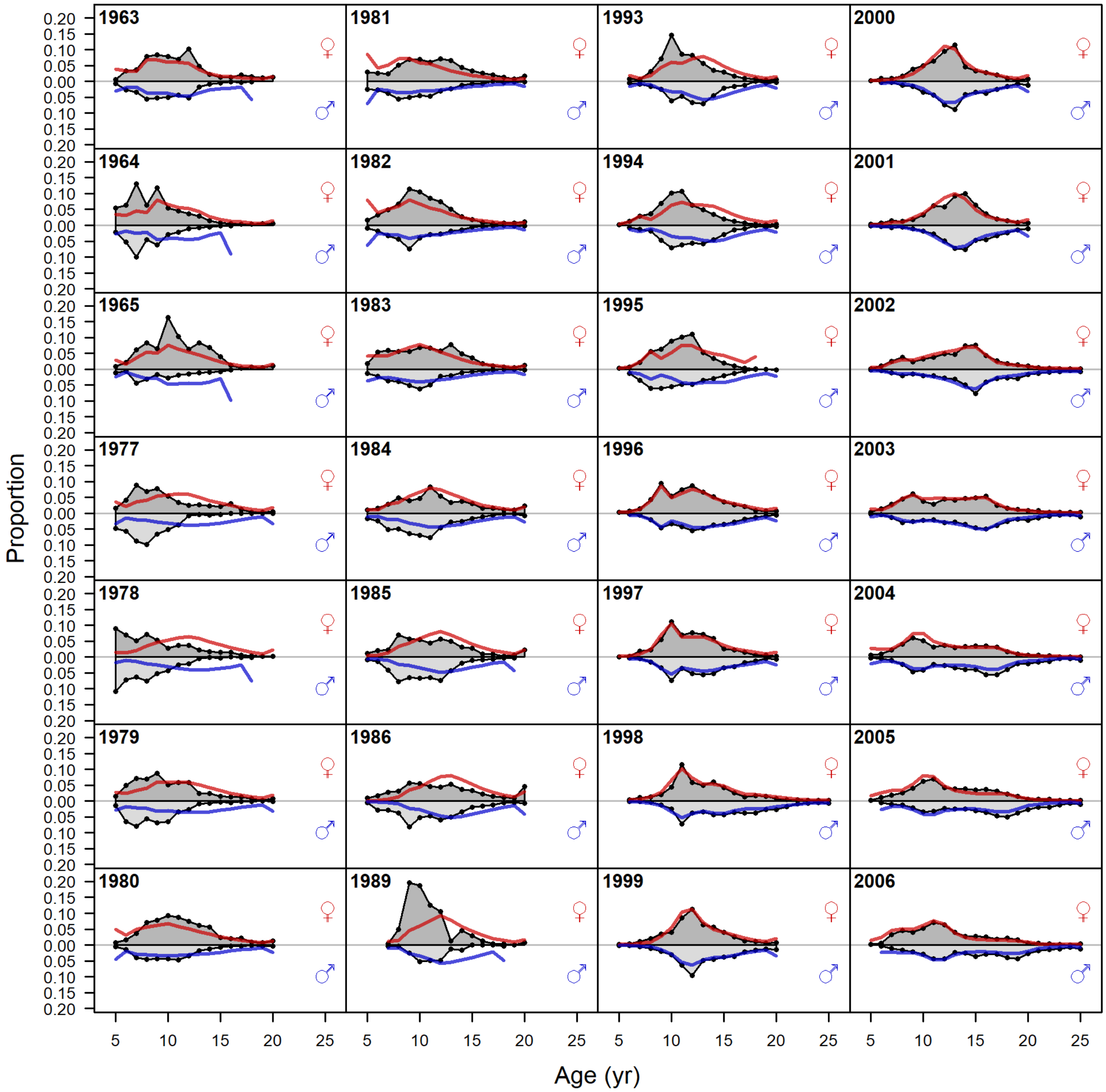


Figure 52. Fit to early age data from the Biological Region 3 FISS in the AAF long model.

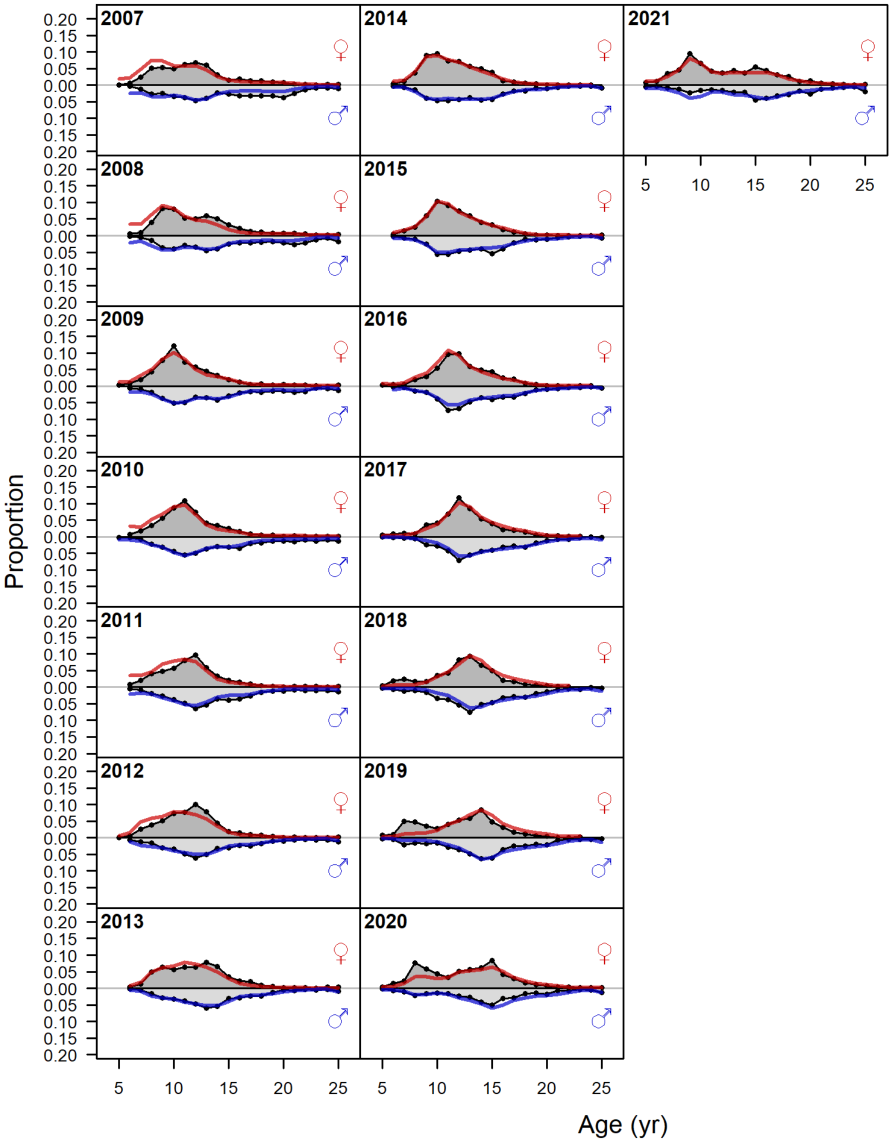


Figure 53. Fit to later age data from the Biological Region 3 FISS in the AAF long model.

Similar to the AAF short model, FISS selectivity was estimated to be asymptotic for Biological Regions 4 and 4B. Peak male selectivity in the commercial fishery landings was also estimated to be asymptotic. All fleets with data extending past the transition from J to circle hooks in 1984 showed a strong offset in the unconstrained deviation in catchability for that year (Table 17). Discard and recreational selectivity estimates were similar in the AAF long model to those estimated in the coastwide long model. Non-directed discard selectivity was estimated to be domed, again illustrating the trade-off between domed fleets in the AAF models and asymptotic selectivity over the entire time-series in the coastwide models. This likely interacts with the estimation of natural mortality, producing slightly lower values in the AAF long model (0.184 for females, and 0.164 for males) than in the coastwide long model (Table 17).

The environmental link coefficient was estimated to be slightly weaker (0.349) than in the coastwide long model, although the 95% interval did not contain zero (Table 17).

The AAF long model produced intermediate estimates of recent recruitment and female spawning biomass (Table 17). This result is consistent with the intermediate estimates of male and female *M* from this model.

Summary of strengths and weaknesses for the AAF long model:

Strengths:

- Includes uncertainty in female and male *M*
- Includes extensive historical data
- Uses environmental information to inform recruitment
- Fits the fishery and survey indices well
- Fits both the Regions 2, 3 and 4B fishery age data well
- Fits Region 4 and 4B FISS age data well
- Internally consistent data weighting

Weaknesses:

- Highest technical overhead (complexity) of the four models
- Most challenging model to check and ensure reliable convergence
- Relies heavily on only fishery trends over the historical period
- Implicitly assumes stationarity in some processes (e.g., the stock-recruitment function, *M*) over the long historical period
- Fit Biological Regions 2 and 3 survey age data poorly

Sources of uncertainty

The four models evaluated here represent, within the set itself, significant sources of uncertainty in how to treat the data (partitioning by fleets or aggregating to a single series), as well as how to treat the time-series (emphasizing the recent dynamics or including more historical information). Further, the differing assumptions of fixed vs. estimated female natural mortality rate is also embedded in the differences observed among the four model results. These factors lead to differences in both scale and trend. In aggregate, the four models together reflected much more uncertainty than any single model, while still showing a similar basic trend over the recent time-series' of both spawning biomass and recruitment.

Sensitivity analyses

Many alternative model configurations were evaluated during model development, but only a subset of these is reported here. Several of the bridging steps from the 2021 models to the 2022 preliminary models also represent sensitivity analyses. Further, the section below providing likelihood profiles over female *M* clearly illustrates *M* as one of the largest uncertainties in this assessment. Sensitivity analyses specifically intended to highlight the importance of ongoing research (e.g., whale depredation, maturity curves, etc.) are produced each year as part of the final stock assessment (Stewart and Hicks 2022).

The large differences in the scale of the spawning biomass in the historical period between the two long time series models represent the range of assumptions about the connectivity of the stock via spatial availability (Figure 54). Specifically, domed selectivity for Biological Regions 2 and 3 in the long AAF model implicitly assumes that older fish (located in northern and western areas) were historically less available and therefore not mobile enough to be readily available to those fisheries. Conversely, in the coastwide long model the assumption of asymptotic selectivity implies a high degree of availability and therefore connectivity between all geographic components in the population. Sensitivity analyses in the 2015 assessment indicted that these two models could be made much more similar by adjusting the degree of domed selectivity (Stewart and Martell 2016). The use of both models encompasses the range of uncertainty that exists over this aspect of the historical population dynamics, thus the primary sensitivity in the stock assessment is included in the ensemble results. A similar and consistent approach is employed to capture this dimension of uncertainty in the MSE operating models.

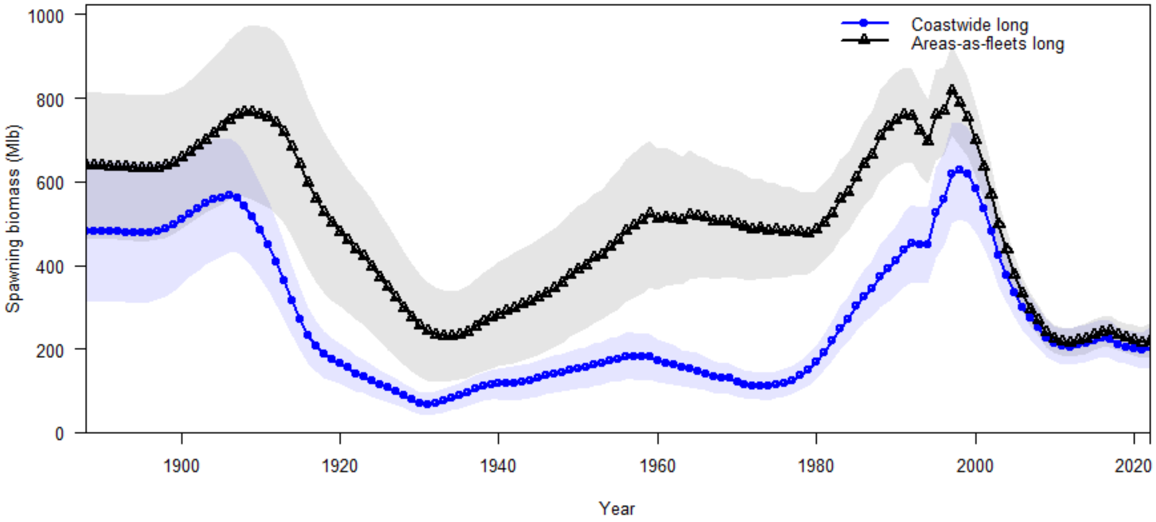


Figure 54. Comparison of the spawning biomass for the long coastwide and AAF models.

The specific technical treatment of the PDO in the two long time-series models has been identified as a research priority (IPHC 2021) and was explored extensively for this preliminary assessment. As described above, the current approach classifies the PDO into a series of binary ‘regimes’, and then estimates a coefficient describing the effect of these regimes on the equilibrium recruitment used in the stock-recruitment relationship. To the degree that there is still considerable variability remaining in the annual recruitment deviations, it is possible that alternative, or additional covariates might provide a similar or better explanation for observed recruitment variability.

It is common to test a wide range of possible covariates at different spatial and temporal scales. However, this approach may easily lead to false-positive relationships as the number of covariates can easily be very large. Instead, we explored a small subset of hypotheses regarding how the PDO might be related to Pacific halibut recruitment, recognizing that other variables have been explored in the past (Clark and Hare 2002b). The five hypotheses explored were:

1. *Status quo*: Regimes as implemented in the current models capture broad trends in productivity that are correlated with Pacific halibut recruitment on average, but because of the complexity of the links and likelihood of unobserved covariates more complex treatments are not appropriate.
2. *Annual deviations*: Although potentially only a proxy for the actual factors affecting recruitment, the PDO may explain additional variability in recruitment if the annual average value (itself already a deviation, and so corrected for trends) is used directly.
3. *Effects greater than one-year but less than the full regime*: the potential for cumulative and slightly lagged effects on recruitment could suggest that a running average of the PDO might explain more of the variability than shorter or longer time-periods. A five year moving average was used.
4. *Extreme values are more sensitive than others*: If the PDO is related most to the largest recruitments and all others are generally swamped by the 'noise' in natural variability, it is possible that treating the top *X*% of observed annual average PDO values as the covariate might allow for a stronger effect size. After some initial exploration, the top 33% was used for this test.
5. *The PDO-recruitment relationship has 'broken down' or does not add explanatory power to the current models*: Excluding the PDO from a series of model runs provides a comparison for all other hypotheses.

Each of these hypotheses was implemented in both the long coastwide model and the long AAF model. The hypotheses were evaluated based on whether the Root-Mean-Squared-Error (RMSE) of the estimated recruitment deviations from the PDO-informed stock-recruitment relationship changed. An increase in the RMSE indicates a degradation in the predictive power of the stock-recruitment relationship.

Results of this sensitivity analysis indicted the status quo approach provided the best explanatory power for estimated recruitment deviations across both of the long time-series models. The RMSE of 0.42 and 0.38 for the *status quo* approach in the coastwide and AAF long models was lower than any of the other hypotheses (Table 18). The only hypothesis not directly tested was using only the top 33% of PDO observations to indicate the 'high' regime in the long AAF model – with all the additional complexity in this model, it was not able to converge reliably with only a subset of regime years informing the estimated coefficient. The various hypotheses had a relatively limited effect on the estimated time-series' of spawning biomass (Figure 55).

Table 18. Comparison of the root-mean-squared-error (RMSE) of the estimated recruitment deviations and the estimate link coefficients for the coastwide long and AAF long models under different PDO hypotheses.

	Model			
	CW long		AAF long	
Treatment of the PDO	RMSE	Coefficient	RMSE	Coefficient
Status quo (binary regimes)	0.42	0.37	0.38	0.35
Annual deviations	0.44	0.45	0.38	0.38
5-year moving average	0.45	0.34	0.39	0.32
Binary on largest $1/3^{rd}$ of values	0.45	0.50	*Did not converge*	
Exclude PDO	0.48	NA	0.42	NA

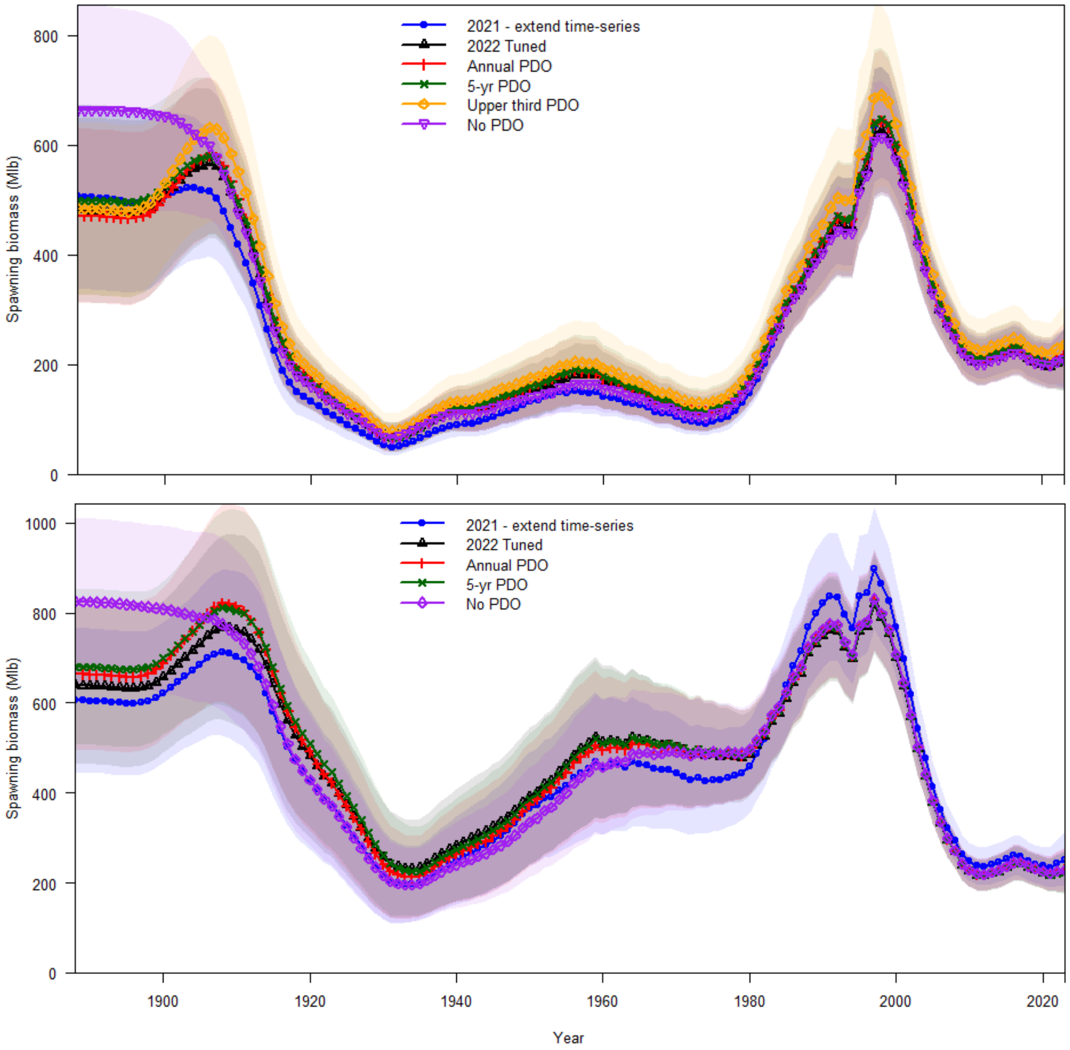


Figure 55. Comparison of the spawning biomass for the long coastwide (top panel) and long AAF (bottom panel) models across all PDO hypotheses explored.

Likelihood profiles over M

To better understand the information content of the data and the basis for estimating *M* in the Pacific halibut stock assessment a likelihood profile analysis was conducted. For each model, the value for female *M* was fixed at a series of values and all other model parameters were re-estimated. Negative Log-Likelihood (NLL) values (including the informative prior on *M*) were recorded for each fixed value of female *M* ranging from well below to well above the range included in the current models (0.1 to 0.25).

Results of the likelihood profiles indicated that the data in all four model configurations showed strong support for the upper end of the range considered. Specifically, the short coastwide model, as in all recent assessments, did not identify a minimum over the range explored (nor for several vales higher than those reported here (Figure 56). The age data, recruitment penalty and initial recruitment penalties all contributing to the higher NLL at lower female *M* values. In contrast, all three of the other models showed a minimum in the NLL informed by the same data sources and model penalties (Figure 57-58). The likelihood surface for the AAF long model was clearly irregular, illustrating that there were multiple similar parameter combinations for *M* values, particularly those below the current MLE (Figure 59). The coastwide long and AAF short models had a similar likelihood profile, with no indication that *M* was more poorly estimated in the AAF short model than in the coastwide long model where it has been reliably estimated for years.

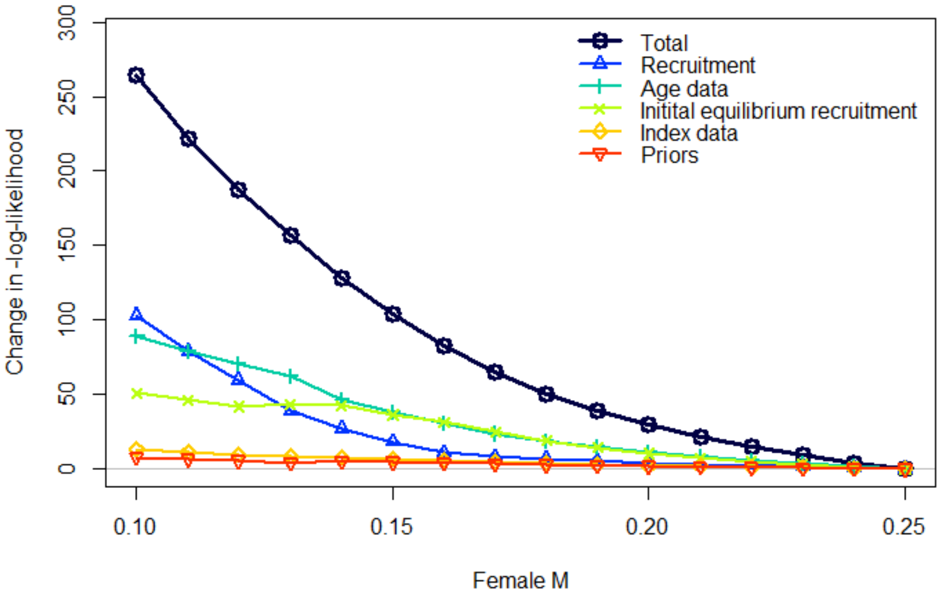


Figure 56. Likelihood components from the likelihood profile on female *M* from 0.10 to 0.25 for the coastwide short model.

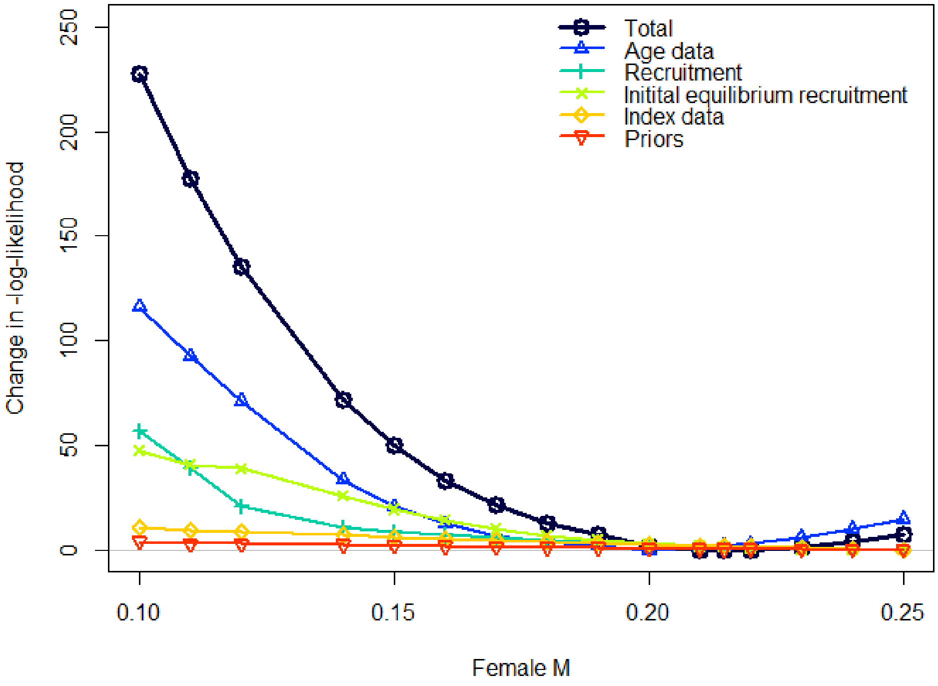


Figure 57. Likelihood components from the likelihood profile on female *M* from 0.10 to 0.25 for the AAF short model.

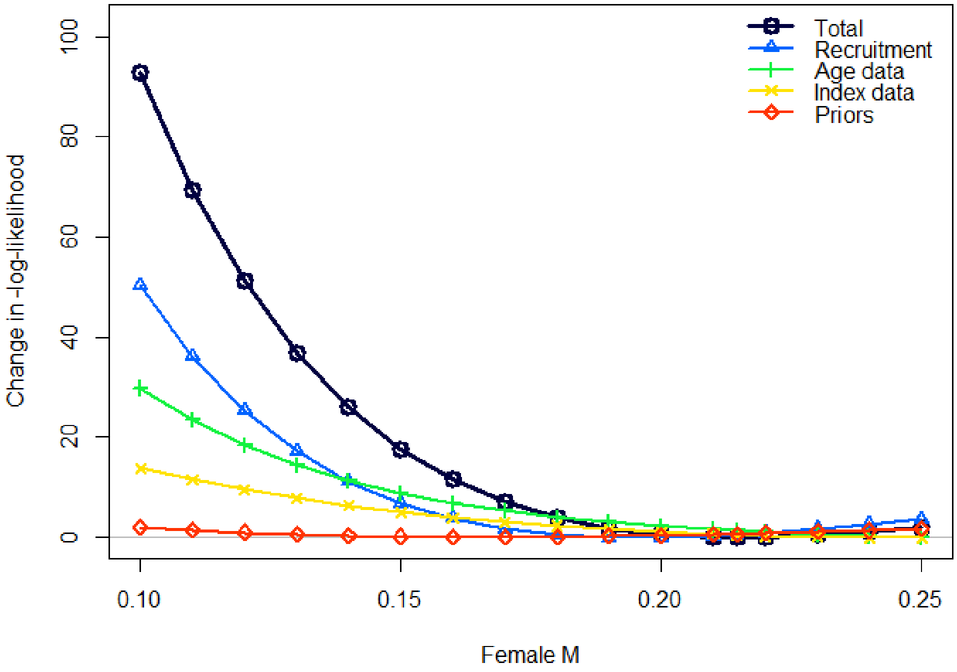


Figure 58. Likelihood components from the likelihood profile on female *M* from 0.10 to 0.25 for the coastwide long model.

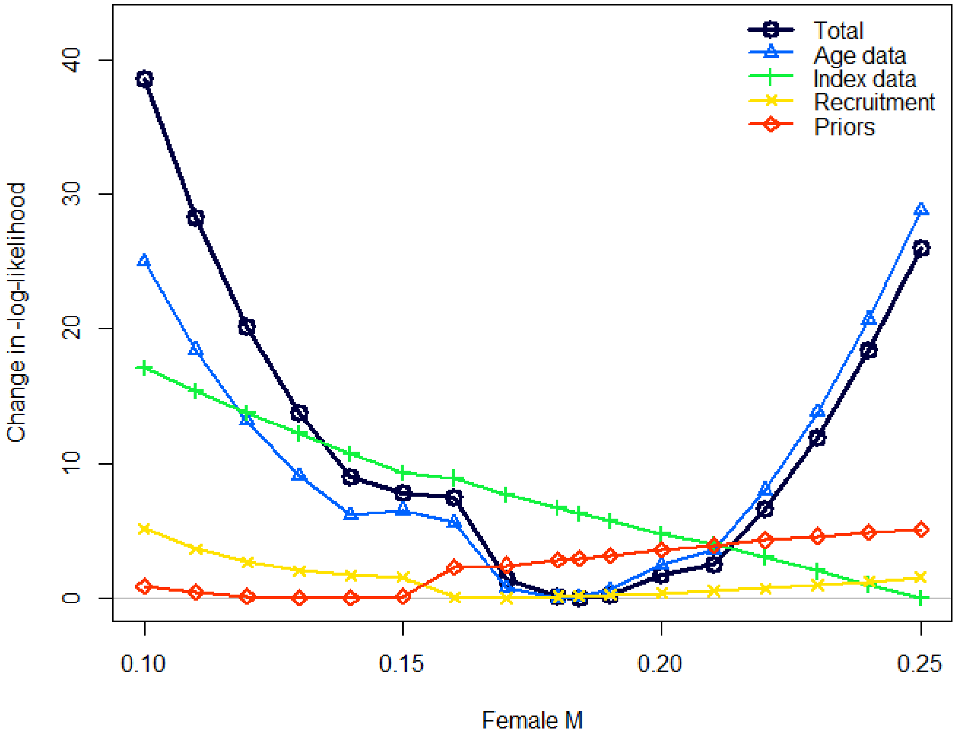


Figure 59. Likelihood components from the likelihood profile on female *M* from 0.10 to 0.25 for the AAF long model.

Similar to most fisheries stock assessments the value of *M* used in the model is closely correlated with stock productivity, and for Pacific halibut absolute size of the estimated spawning biomass. For all four models, larger values of female *M* corresponded to larger values of spawning biomass across the entire time-series (Figure 60-62).

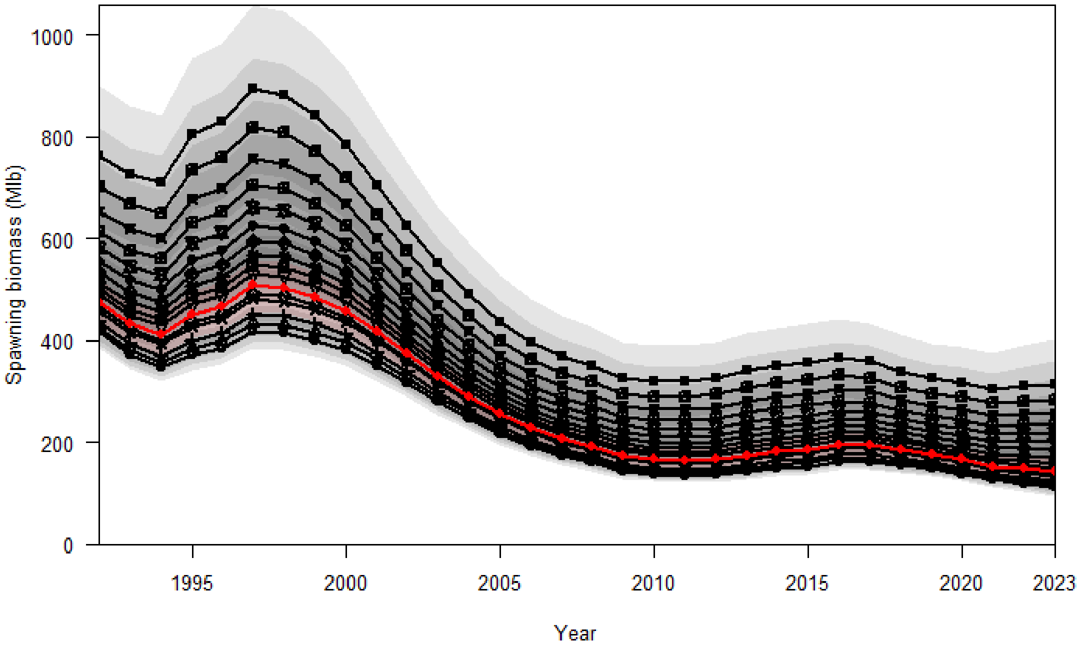


Figure 60. Spawning biomass estimates (lines and points) and corresponding 95% confidence intervals (shaded region) resulting from the likelihood profile on *M* from 0.10 to 0.25 for the coastwide short model. Red series denotes the fixed value used in the base case model.

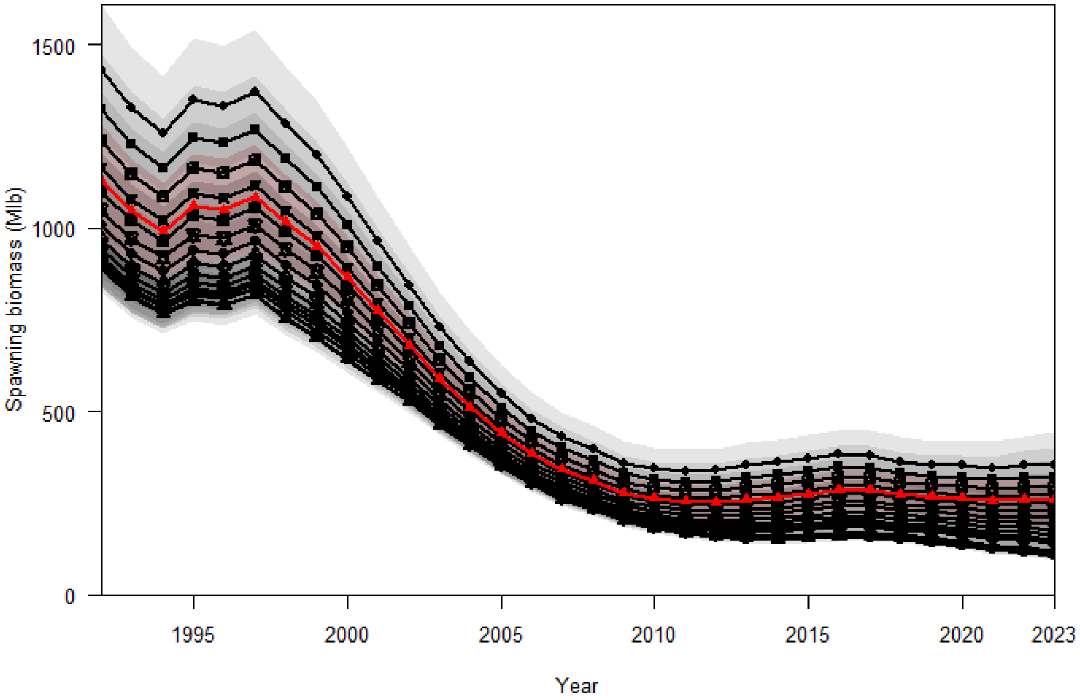


Figure 61. Spawning biomass estimates (lines and points) and corresponding 95% confidence intervals (shaded region) resulting from the likelihood profile on *M* from 0.10 to 0.25 for the AAF short model. Red series denotes the MLE (the base case model).

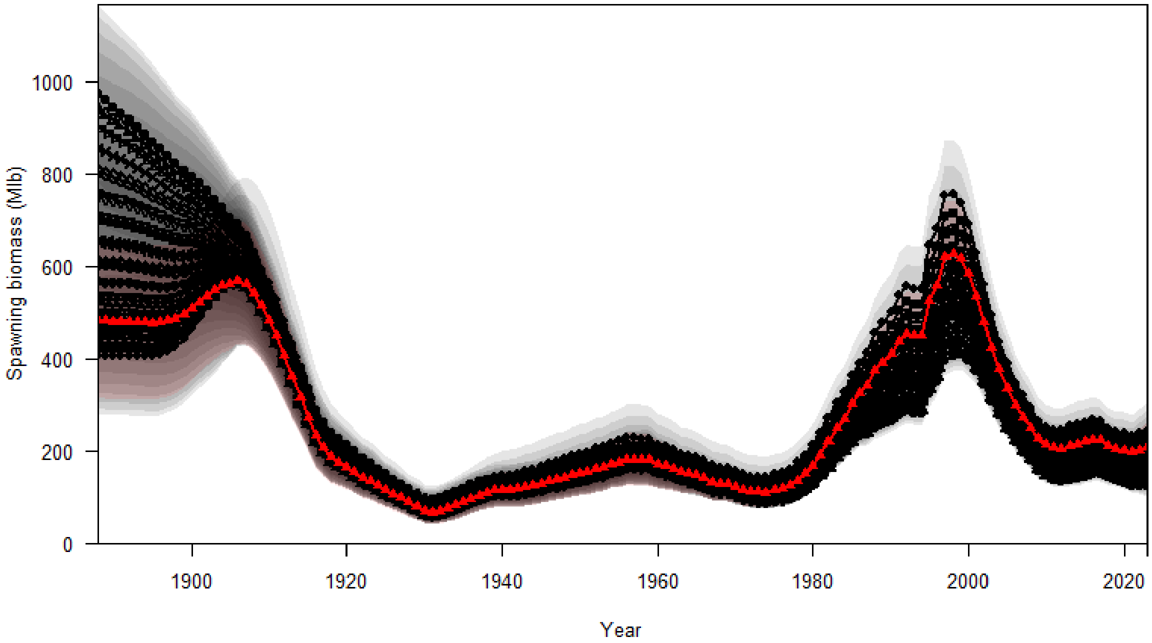


Figure 62. Spawning biomass estimates (lines and points) and corresponding 95% confidence intervals (shaded region) resulting from the likelihood profile on *M* from 0.10 to 0.25 for the coastwide long model. Red series denotes the MLE (the base case model).

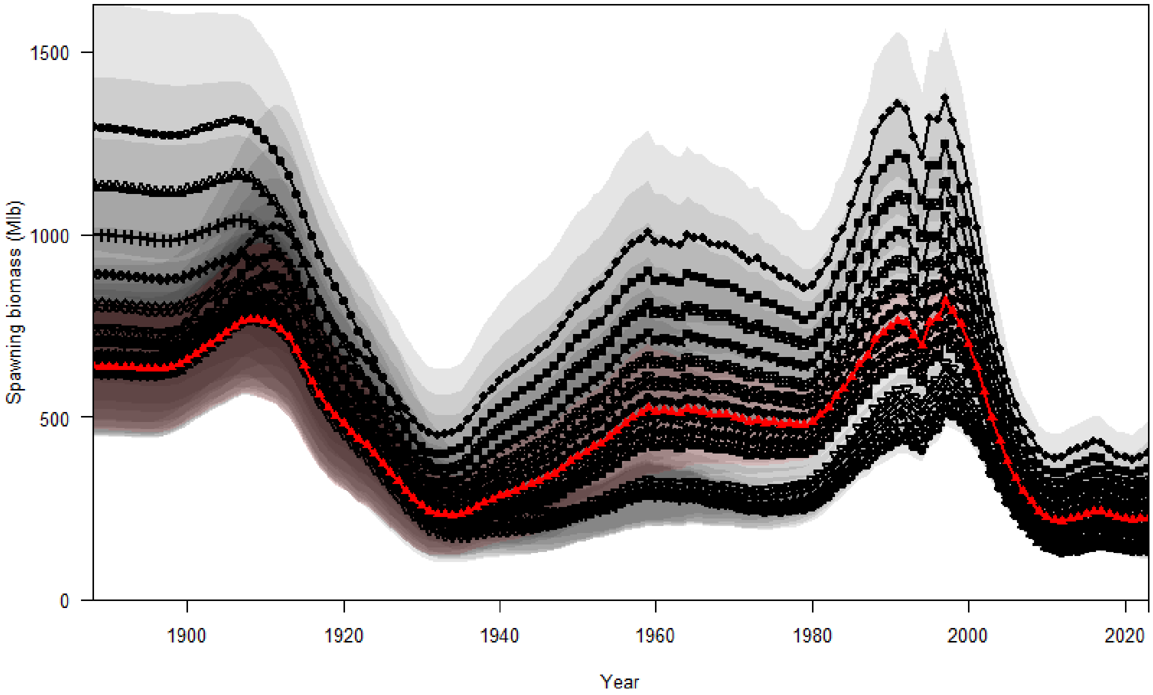


Figure 63. Spawning biomass estimates (lines and points) and corresponding 95% confidence intervals (shaded region) resulting from the likelihood profile on *M* from 0.10 to 0.25 for the AAF long model. Red series denotes the MLE (the base case model).

Retrospective analyses

The halibut model used from 2006 until 2011 was plagued by a very strong retrospective pattern, both in the scale of the most recent stock size estimates as well as the trend in those estimates (Stewart and Martell 2014; Stewart et al. 2013a). The solution to this problem was additional flexibility for process error (temporal variability) in the selectivity curves for both the fishery and survey representing not just gear (or 'contact') selectivity but also spatial availability.

Retrospective analyses were conducted for these preliminary 2022 models by sequentially removing the terminal four years of data from the model (a five-year retrospective, since the terminal year currently contains no information other than mortality projections). Limiting this approach to the most recent four years of data allows the models to be informed by at least one year of commercial fishery sex-ratio data, and therefore does not require a major change in assumptions within the retrospective (as was the case in the 2019 assessment; Stewart and Hicks 2019b).

All of the four models showed very little retrospective change as the terminal years of data were removed from the models (Figure 64-66). This an improvement over recent models which had modest trends and/or variability, although mostly confined to lie within annual confidence intervals. The cause of this reduced retrospective behavior appears to be the allowance for the scale of male selectivity to be time-varying. This effectively separates the most recent dynamics from the scaling of the fishery across all earlier years.

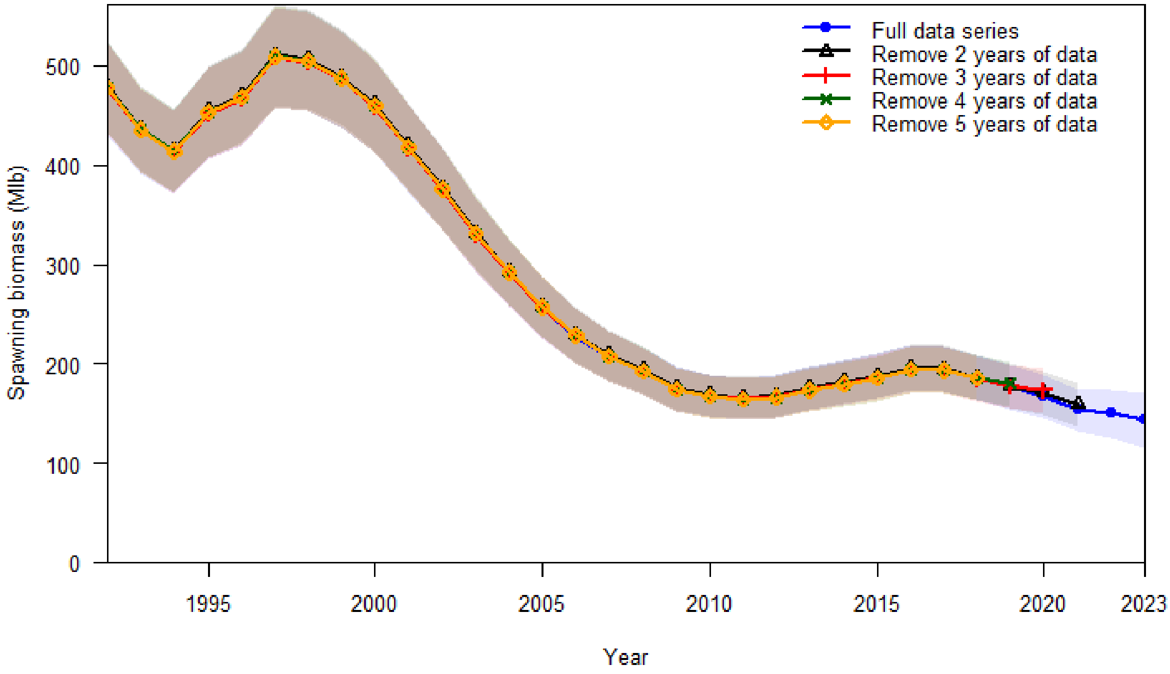


Figure 64. Five-year retrospective analysis of spawning biomass (1^{st} year is a projection with no data) based on the coastwide short model.

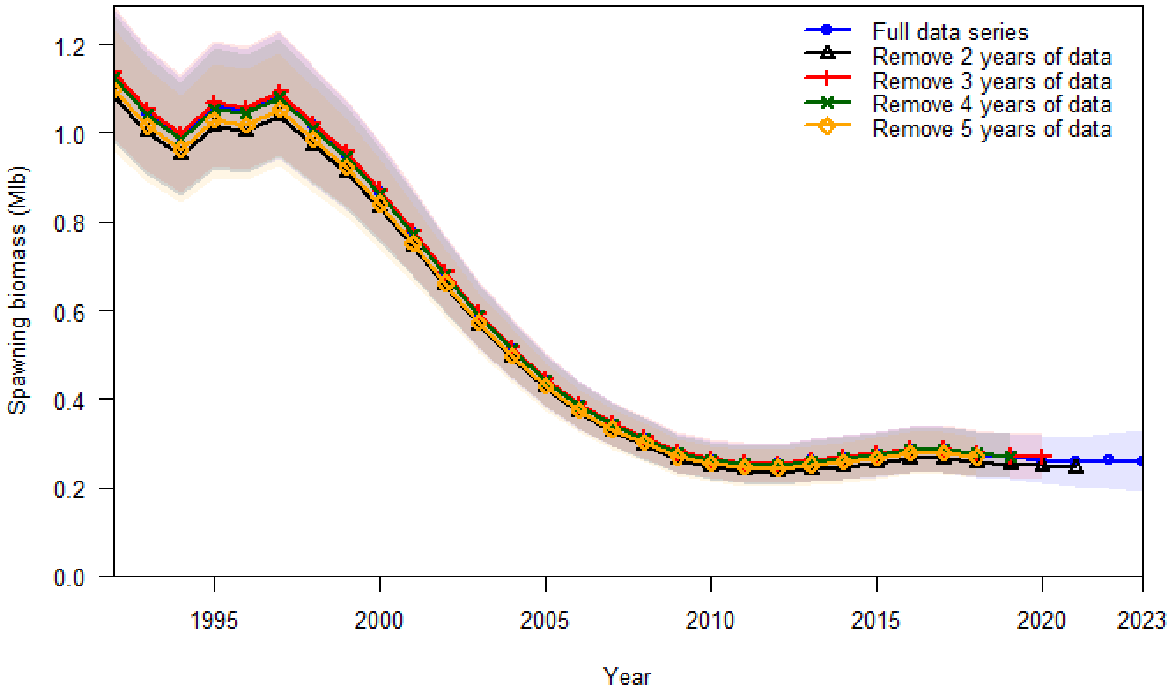


FIGURE 65. Five-year retrospective analysis of spawning biomass (1st year is a projection with no data) based on the AAF short model. Note that the y-axis is in billions of pounds.

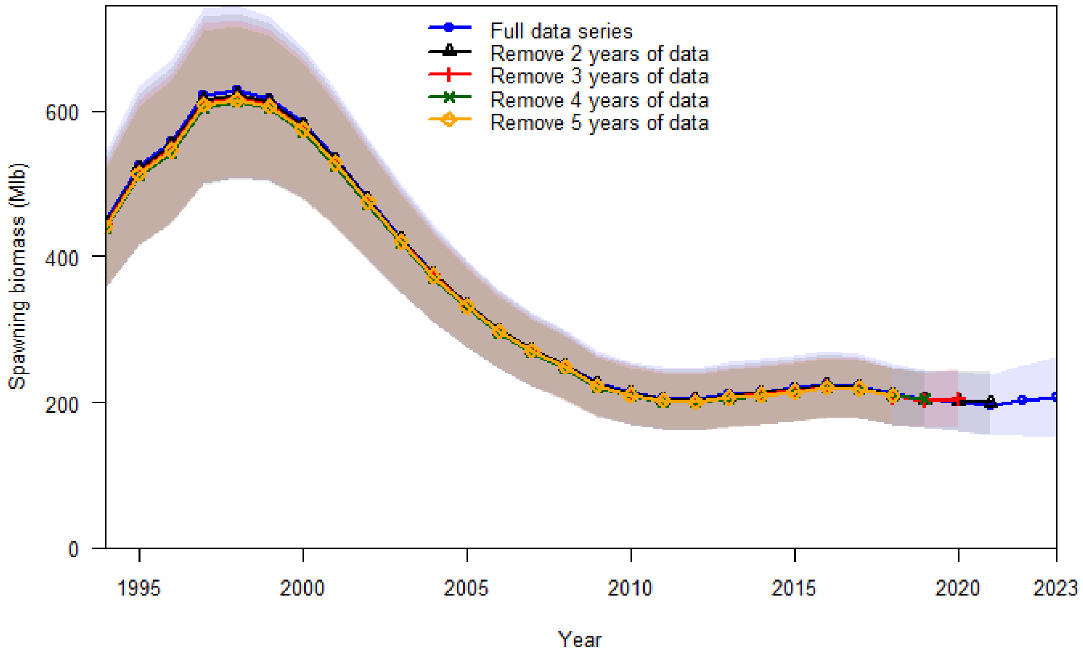
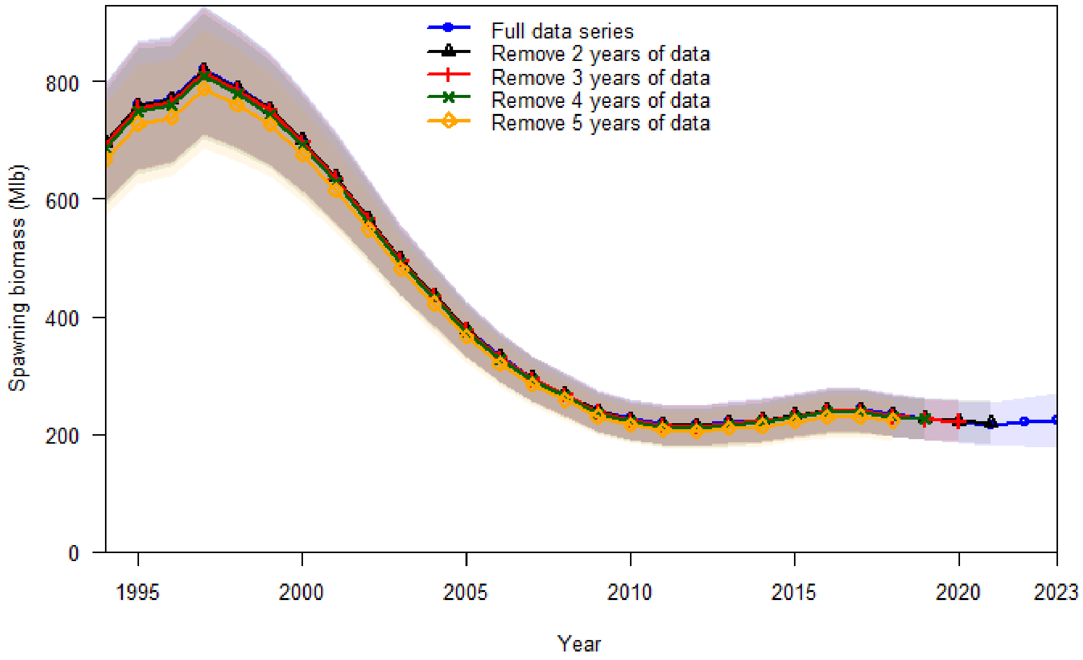


FIGURE 66. Five-year retrospective analysis of spawning biomass (1st year is a projection with no data) based on the coastwide long model. Time-series is truncated in 1994 so that differences in the terminal years are more visible.



Figures 67. Five-year retrospective analysis of spawning biomass (1st year is a projection with no data) based on the AAF long model. Time-series is truncated in 1994 so that differences in the terminal years are more visible.

Bayesian analysis

The 2019 stock assessment included a substantial evaluation of Bayesian integration for the short coastwide model (Stewart and Hicks 2019b). This effort did not produce substantially different results from the maximum likelihood and asymptotical variance methods (Fournier et al. 2012) routinely employed. However, there are a number of potential benefits to using an explicitly Bayesian approach, including better characterization of uncertainty (Magnusson et al. 2012) and a more directly interpretable characterization of the probability distributions. There is also the potential for differences in the results of Bayesian analyses due to the right-skewed nature of some distributions for key parameter and management-related quantities in complex fisheries models (Stewart et al. 2013b).

In aggregate, the 2019 results suggested that the asymptotic distributions were a reasonable approximation for the full posterior distributions in these models, and also that the process of regularizing the selectivity parameters and removing some deviations to improve integration did not having an appreciable effect on the solution. This is generally consistent with studies of process error where overparameterizing (adding the capability for variation when it wasn't present) was generally found to be unbiased, and therefore preferable to underparameterizing when temporal variability was present (e.g., Martell and Stewart 2014; Stewart and Monnahan 2017).

Additional Bayesian analysis was not included in this preliminary 2022 assessment. However, if a multi-year assessment approach was to become part of a future management procedure for the IPHC more time could be devoted to exploring Bayesian models.

Other uncertainty considerations

There are many important sources of uncertainty not captured in the four models included in this ensemble. These include myriad alternative structural assumptions such as spatially explicit population dynamics, connection with Russian waters, alternative stock-recruitment functions, time-varying mortality, different data weighting approaches, and many others. There are also several tractable sources of projection uncertainty that are not in the current approach, including uncertainty in projected weight-at-age (although the sensitivity of this was investigated at SRB request in 2016 and found to be low), projected selectivity, and projected fisheries mortality.

Within the modelled time-series there are also data-related uncertainties that could be addressed via a range of alternative approaches. Uncertainty in the time series of mortality for these models is not currently captured, as they are treated as inputs and assumed to be known without error. In previous assessments, sensitivity analyses have been conducted to the degree of discard mortality in the commercial fishery, potential effects of unobserved whale depredation, as well as to the magnitude of total bycatch mortality. In concept, these types of uncertainties could be explicitly included in the models; however, full estimation of catch in statistical catch-at-age models generally requires other stabilizing assumptions, so direct integration of this uncertainty may still prove challenging.

Additional sources of uncertainty and avenues for development are identified in the Research Priorities section below.

The ensemble

Model-integrated quantities are used as the primary output for stock assessment results, as well as the basis for decision table probabilities (Stewart and Hicks 2019a). All quantities of management interest are integrated for the recent time period (1992+), for which all four sets of model results are available. These quantities include: spawning biomass, relative spawning biomass, and the Spawning Potential Ratio (SPR; summarized as fishing intensity, $F_{XX\%}$, where the $XX\%$ represents SPR). Decision table quantities are divided into four categories: stock trend (which is the only set of metrics that are independent of any harvest strategy related assumptions), stock status, fishery trend, and fishery status. Integration is performed for all these quantities using the basic approach outlined below.

Methods

The basic approach to model integration remains unchanged from the 2015 and subsequent analyses. A sample of random draws is created from the output from each of the models included in the ensemble. For the spawning biomass time-series, the estimates and associated standard deviations for female spawning biomass from each of the four models were extracted from the report file. A vector of length n is created for each model (m), where the relative weight (w_m) is simply the relative fraction of the total draws across all models comprised by n_m:

$$w_m = \frac{n_m}{\sum_m n_m}$$

This approach allows for easily adjusted weighting of models. Routine reporting of results uses $\sum_m n_m$for all models equal to twenty million, this has been found to produce negligible Monte-Carlo error even in the tails of extremely skewed distributions, creating robust and stable reporting of all quantities of interest with smooth distribution. Although this choice could potentially be optimized for each statistic of interest, current integration code (in *R*) does not represent a constraining step in the analysis.

The harvest strategy employs a control rule that reduces the coastwide SPR target linearly from the interim 'reference level' at $SB_{30\%}$ to zero at $SB_{20\%}$. The calculation of relative spawning biomass was updated in the 2019 assessment to use a dynamic estimate of 'unfished' biomass calculated for each year of the time-series. This calculation replays the entire time-series, without the fishing mortality, assuming the same parameter values (including recruitment deviations) but accounting for the different level of spawning biomass projected for each year and its effect on subsequent expected (pre-deviation) recruitment in each year. At that time, the variance of this quantity and the covariance with estimated spawning biomass in each year was unavailable, so an approximation was developed (Stewart and Hicks 2019b). Subsequently, in 2020 the dynamic unfished biomass calculation was added to the derived quantities with variance calculations in stock synthesis, and so the approximation is no longer needed (Methot Jr et al. 2020a). This has been an important improvement as the covariance in estimated and unfished dynamic spawning biomass is an important contributor to the variance of the IPHC's reference points.

Evaluation of weighting based on predictive skill

Previous Pacific halibut assessments have applied equal weighting of all four models. However, weighting based on several potential approaches has been considered since the 2015 stock assessment (Stewart and Martell 2016). Briefly these have included:

> *AIC* – but this is known to be highly dependent on data weighting, and can only be applied in cases where the same data sets are being fit by all models under consideration
>
> *Strength of retrospective patterns* – perhaps relative to a 'null' distribution for a statistic like Mohn's rho (Mohn 1999) based on simulation (Hurtado-Ferro et al. 2015); while helpful to diagnose model performance, it does not necessarily indicate a 'good' model, as evidenced by the fact that a static prediction will have no retrospective pattern at all.
>
> *Fit to the FISS index* – without an AIC-type correction, there is no penalty for overparameterized models
>
> *Expert opinion* – this is subjective, and the tendency has been to revert to equal weighting in the absence of strong evidence to the contrary.

Meanwhile, exploration of model diagnostics for integrated models has highlighted other approaches to comparing model performance (Carvalho et al. 2021) and in particular the Mean

Absolute Standardized Error (MASE; Hyndman and Koehler 2006) may be particularly relevant for weighting stock assessment models:

$$MASE = \frac{\frac{1}{n}\sum_{t=1}^{n} |O_t - E_t|}{\frac{1}{n}\sum_{t=1}^{n} |O_t - O_{t-1}|}$$

Where *O* indicates the observation at time *t*, *E* the prediction (or expected value); calculations can be averaged over any number of years or lags relevant to the predictive problem. As defined, MASE estimates must be positive, and the range of values is interpreted as:

>1: model predictive skill is worse than the naïve prediction (last year's index) – model not worth pursuing further

1: model predictive skill is exactly equal to the naïve prediction

<1: model predictive skill exceeds that of the naïve prediction

0: model predictions perfectly match subsequent observations

This basic calculation available in the literature does not account for the observation error associated with each annual index. Conceptually, it does not make sense to treat lack of predictive skill for a year's index with a very large variance (some or all of the lack of skill may actually be observation error) equally with a year that is very precisely observed. We therefore extended the MASE calculation to use a standardized deviation rather than a raw deviation. This did not change the behavior or interpretation of the MASE values, the only addition being the standard deviation of the observation (σ_t) at time *t*:

$$MASE = \frac{\frac{1}{n}\sum_{t=1}^{n} \left|\frac{O_t - E_t}{\sigma_t}\right|}{\frac{1}{n}\sum_{t=1}^{n} \left|\frac{O_t - O_{t-1}}{\sigma_t}\right|}$$

This 'standardized' MASE statistic inherently accounts for over- or under-parameterization as it is concerned only with predictive skill. A major challenge to its widespread application is the need to determine which quantity (or quantities) should be used to evaluate predictive skill. In the case of Pacific halibut, this choice is simple: the FISS index closely tracks both the spawning biomass and the biomass available to the commercial fishery. Therefore, the relative trend in the FISS index will be directly indicative of the change in management quantities in the upcoming year. Second, the FISS index is also used as a step in the allocation of mortality limits, so the entire management procedure depends on its value each year.

For the appropriate time lag, a one-year ahead prediction is most relevant for Pacific halibut, since models are currently updated annually (although this could easily be modified for a management procedure with a two-year or longer lag between assessments). We might expect the predictive skill of each model to vary over time, and also the challenge of the prediction - years with very small changes from the previous year's index are 'harder' for models to exceed the naïve prediction than those with large changes. There must also be some variability in annual model performance that we may want to average over, specifically, we may not want to substantially down-weight a particular model due to a single poor prediction if it has generally been performing well. To explore model performance further we report results for MASE calculations spanning the most recent 1-4 years.

Since the coastwide FISS index is comprised of a composite of the spatially weighted indices from each Biological Region, it is possible to apply the same weighting to AAF model data and predictions (accounting for catchability) and thereby develop a predicted FISS index for all four of the individual models. These predictions can then be compared using the MASE statistic and weighted as described above.

In order to turn the MASE statistic into a model weight we need to specify the scale of the weighting and the behavior at the end-points. In this case, for model (*m*) within the set of models (*M*) we use the relative MASE:

$$MASE\ weight_m = \frac{1 - MASE_m}{\sum_{m=1}^{M} 1 - MASE_m}$$

This approach ensures that a model that does not outperform the naïve prediction (MASE >= 1) will get zero weight, and that a set of models all perfectly predicting the next observation will receive equal weights.

The most important prediction from the set of models is for the unobserved year (in this case 2022; Figure 68), and it has been helpful in the past to consider these predictions as part of the decision-making process. However, this prediction cannot be validated until after the decision-making process has occurred.

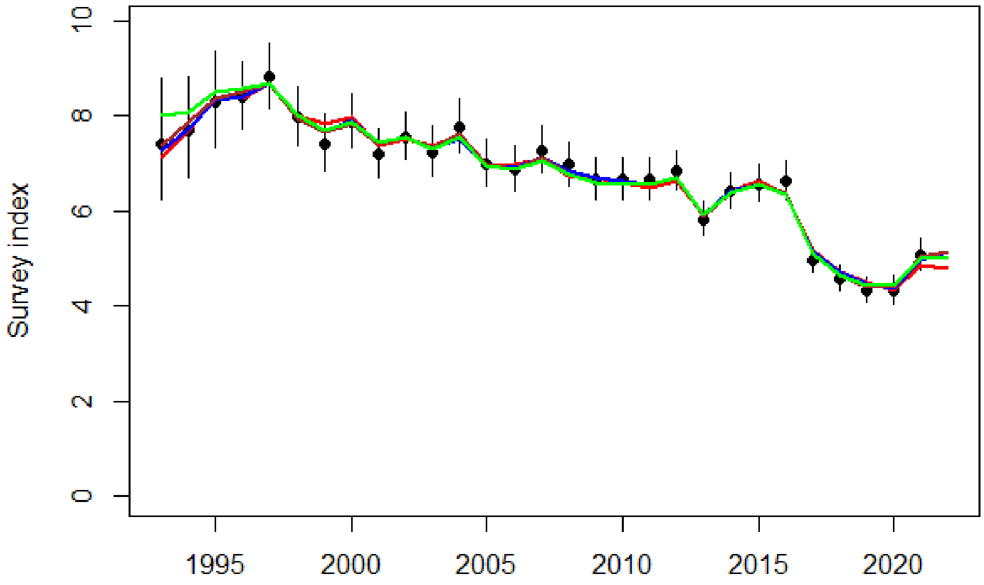


Figure 68. Predictions from each of the four models for the 2022 FISS observation using data through 2021 (black dots and CI).

In order to describe each model's predictive skill, a prediction was made for each recent year in the FISS time-series based on each step in a retrospective analysis. Specifically, one year of data was removed from the model fit, and then the prediction was made for the observed FISS index in the subsequent year. By working backwards within a single model, it is possible to evaluate how the predictions for each year's FISS index compared to the subsequent observation and the estimates from the model after the data had been included. Results for the coastwide short model are shown in Figure 69.

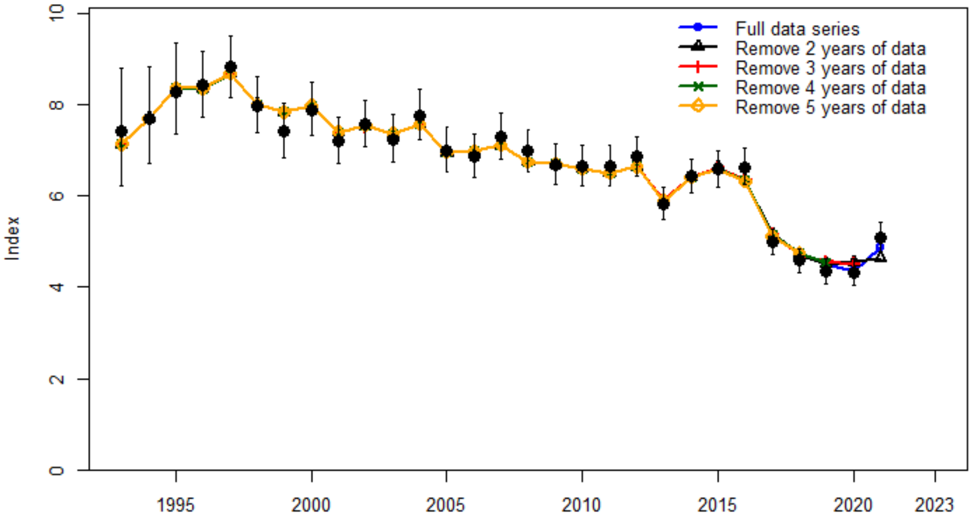


Figure 69. Predictions from the coastwide short model for the 2018-2021 FISS observations using data through 2017-2021 (black dots and CI).

When this process is repeated for all four individual models, the predictions can be visually compared at each step of the retrospective (Figure 70). The results indicate that the sharp increase in the 2021 FISS index was the most ‘challenging’ to predict (but may also be the most important recent test for these models) and that all models did appreciably better than the naïve prediction (the 2020 observed value). Further, because the 2020 observation was nearly equal to the 2019 observation, model predictions were similar to the naïve prediction. Comparison of the MASE scores averaging across the most recent 1, 2 , 3 and 4 years showed that all models performed better than the naïve prediction with MASE scores ranging from 0.44 – 0.94 (Table 19, Figure 71).

Converting these raw MASE scores into model weights, via the equation above, resulted in individual model weights varying from 9.3% to 38% across the range of models and years of averaging (Table 20, Figure 72). The aggregate ensemble results are relatively insensitive to weighting of the individual models, as the distributions are broadly overlapping and the weights are all similar. Specifically, the most extreme difference among model weights were for the three-year average MASE (9.3-38%) and the least extreme for the one-year MASE (20.5-28.3%; Table 20). Integrating over the full ensemble with these two vectors of weights produced quite similar spawning biomass trajectories (Figure 73-73). This is consistent with previous investigation of the effects of different weighting and new data on ensemble performance (Stewart and Martell 2015; Stewart and Hicks 2018).

This range of MASE weights does not clearly imply that one or more model’s contribution to the ensemble results should dramatically differ from the *status quo* assumption of equal weighting. However, there are several potential benefits to adopting a ‘dynamic’ or ‘self-weighting’ approach over static weights based on expert opinion. These include:

1) An objective basis for model weights based on predictive skill and logically tied to management information.
2) The ability to update weights each year (even during update assessments) based on the evolution of model predictive skill.

It might be expected that as stock dynamics change over time individual model skill in predicting upcoming management quantities would vary. The MASE calculation captures this evolution naturally and does not require an annual review and discussion of model weighting, except perhaps to ensure that the approach is performing as expected. Based on these benefits, we suggest that the 2022 stock assessment utilize MASE weights based on the most recent year (2022 for the final assessment, after the new data are available) of model prediction skill. Although potentially less stable than an average performance over recent years, weighting based on the terminal prediction will most closely represent the model skill if/when dynamics change over time.

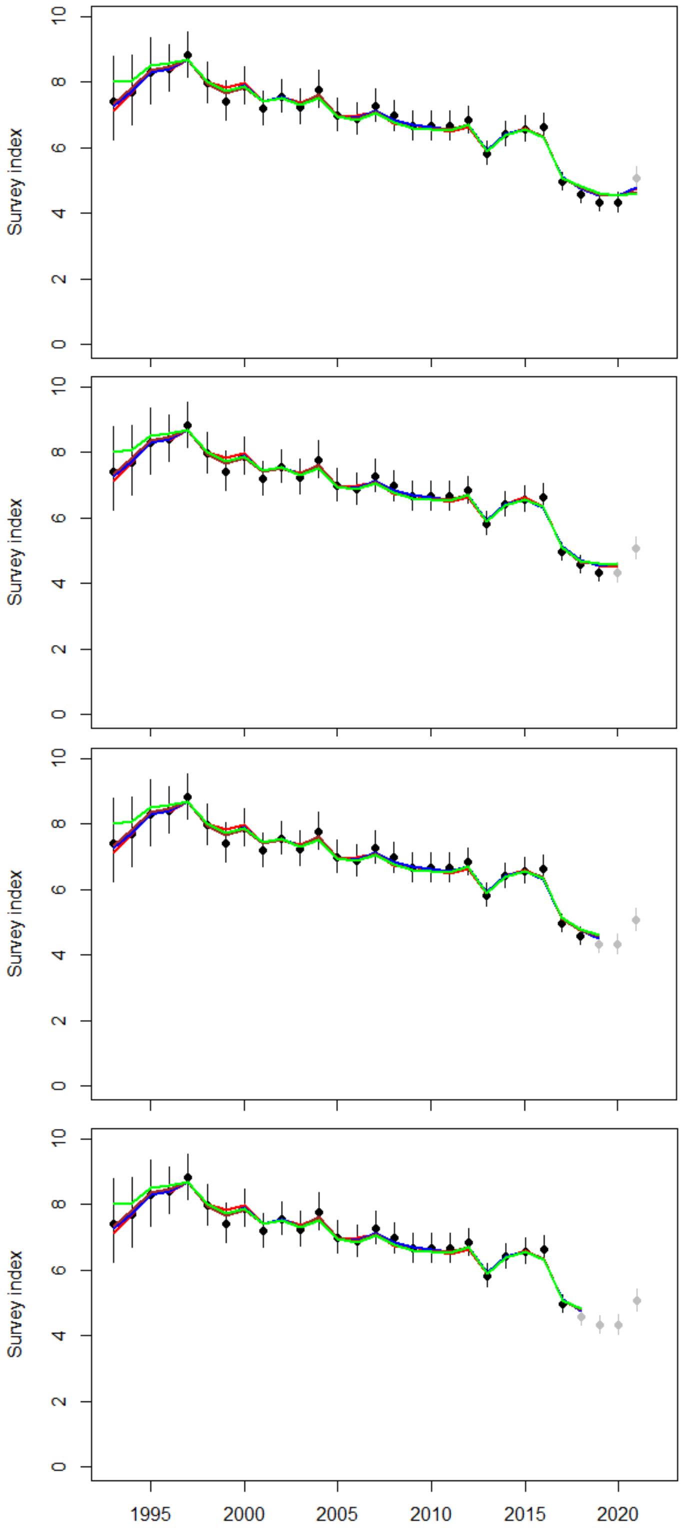


Figure 70. Predictions from each of the four models (colored lines) for the 2021 to 2018 (top to bottom panels) FISS observations (grey dots and CIs) using data through 2020 to 2017 (black dots and CI).

Table 19. One-year ahead standardized MASE estimates for each of the four stock assessment models averaged over the most recent 1, 2, 3, and 4 years.

	Model			
Years included	CW short	CW long	AAF short	AAF long
4	0.70	0.65	0.82	0.72
3	0.83	0.75	0.94	0.83
2	0.86	0.76	0.88	0.78
1	0.59	0.46	0.52	0.44

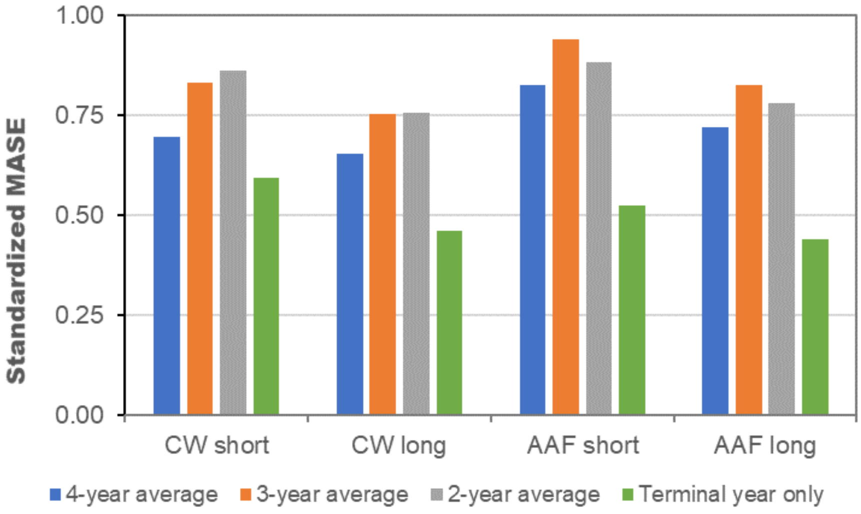


Figure 71. Comparison of standardized MASE estimates for each of the four models averaged over the most recent 1-4 years.

Table 20. One-year ahead standardized MASE weights for each of the four stock assessment models averaged over the most recent 1, 2, 3, and 4 years.

	Model			
Years included	CW short	CW long	AAF short	AAF long
4	27.5%	31.3%	15.8%	25.4%
3	26.0%	38.0%	9.3%	26.8%
2	19.1%	33.9%	16.4%	30.6%
1	20.5%	27.2%	24.0%	28.3%
Status quo weights	25.0%	25.0%	25.0%	25.0%

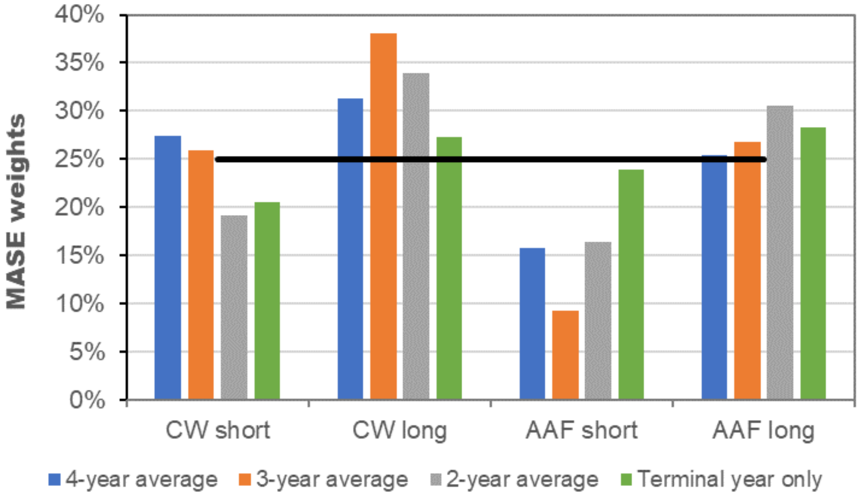


Figure 72. Comparison of standardized MASE weights for each of the four models averaged over the most recent 1-4 years. Horizontal line indicates the *status quo* equal weighting (25%).

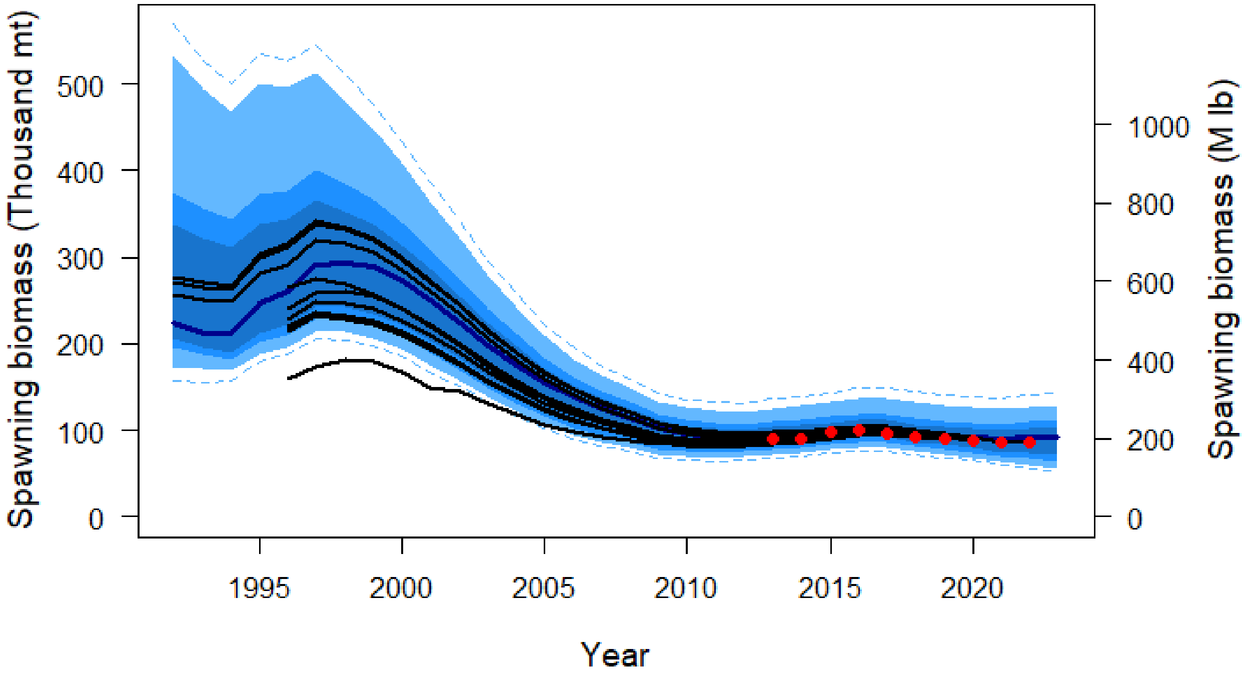


Figure 73. Comparison of the preliminary 2022 ensemble spawning biomass distribution based on the average MASE over the most recent three years (blue shading) to previous stock assessments (2012-2021; black lines, terminal estimates indicted by red dots).

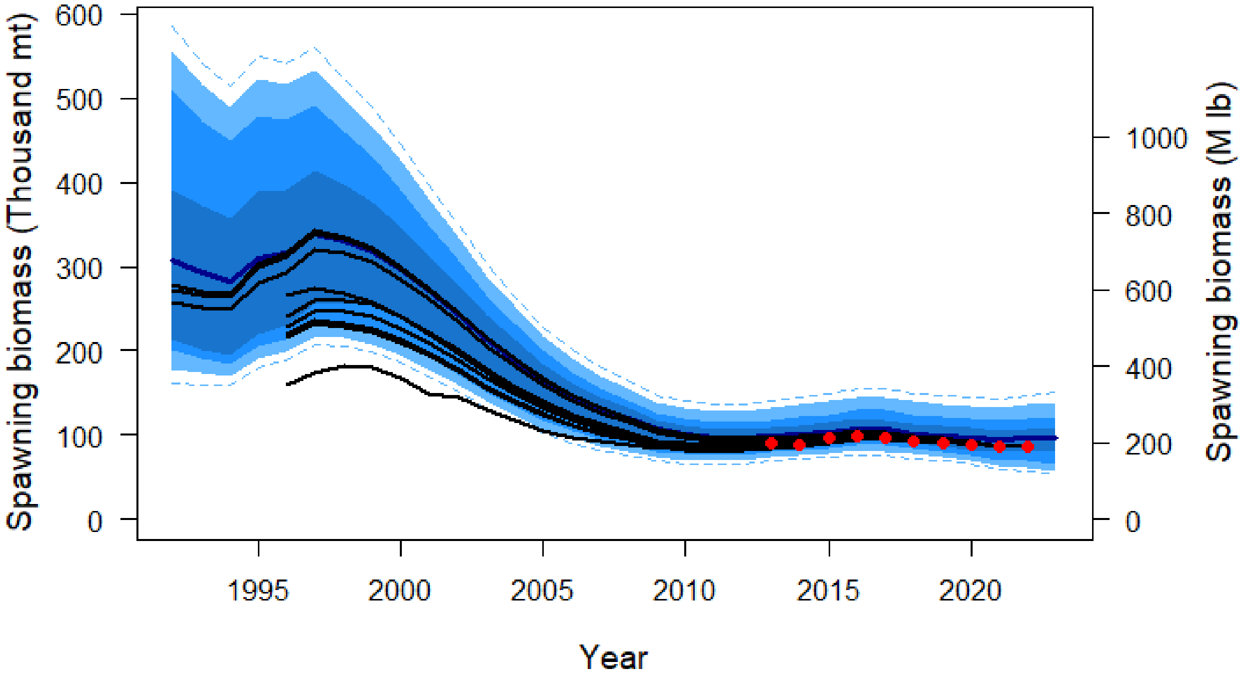


Figure 74. Comparison of the preliminary 2022 ensemble spawning biomass distribution based on terminal-year MASE (blue shading) to previous stock assessments (2012-2021; black lines, terminal estimates indicted by red dots).

Preliminary results for 2022

Comparison of the spawning biomass estimates from the four stock assessment models comprising the ensemble shows that the 95% intervals from any single model are substantially narrower than the aggregate (Figure 75). All four models indicate a similar overall trajectory, including the small increase in biomass over 2011-2016 and subsequent decrease as the effects of reduced recruitment during 2006-2011 (Figure 76; upper panel) graduate through to the spawning biomass. The differences in *M* among the four models suggest large absolute differences in recruitment estimates, but when scaled relative to the mean it is very clear that the estimates of relative strong and weak year classes are in close agreement (Figure 76; lower panel).

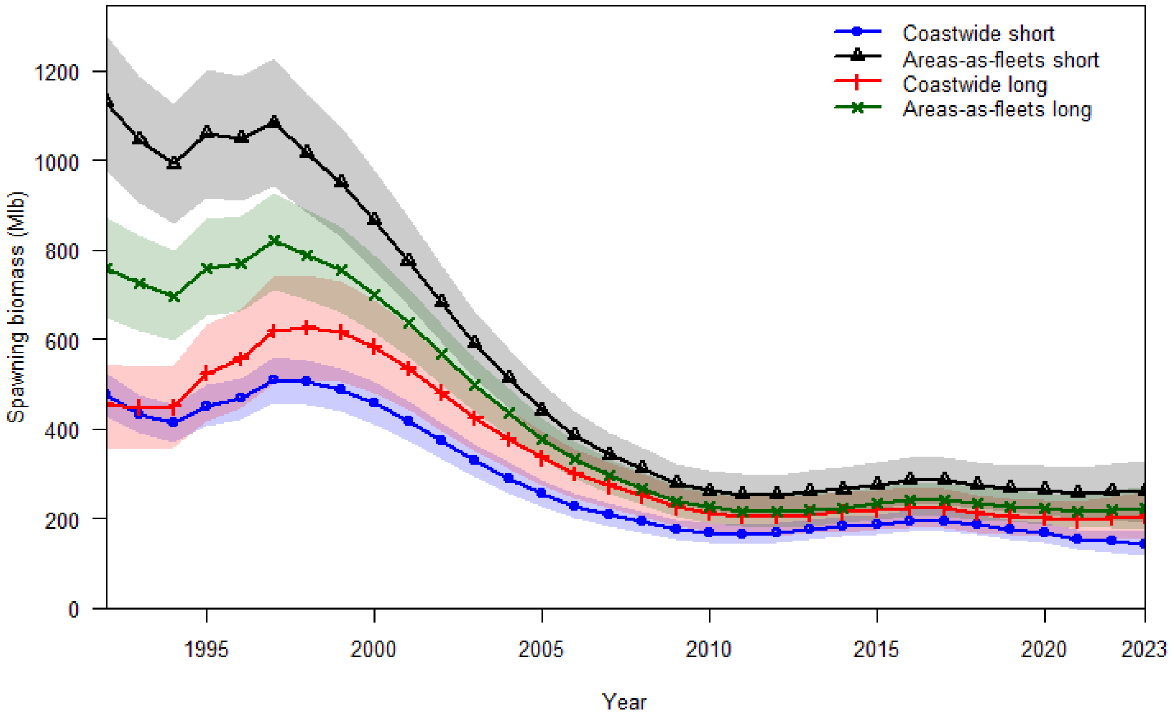


Figure 75. Comparison of spawning biomass time series (shaded regions indicate asymptotic approximations to the 95% confidence interval) from each of the preliminary models contributing to the 2022 ensemble.

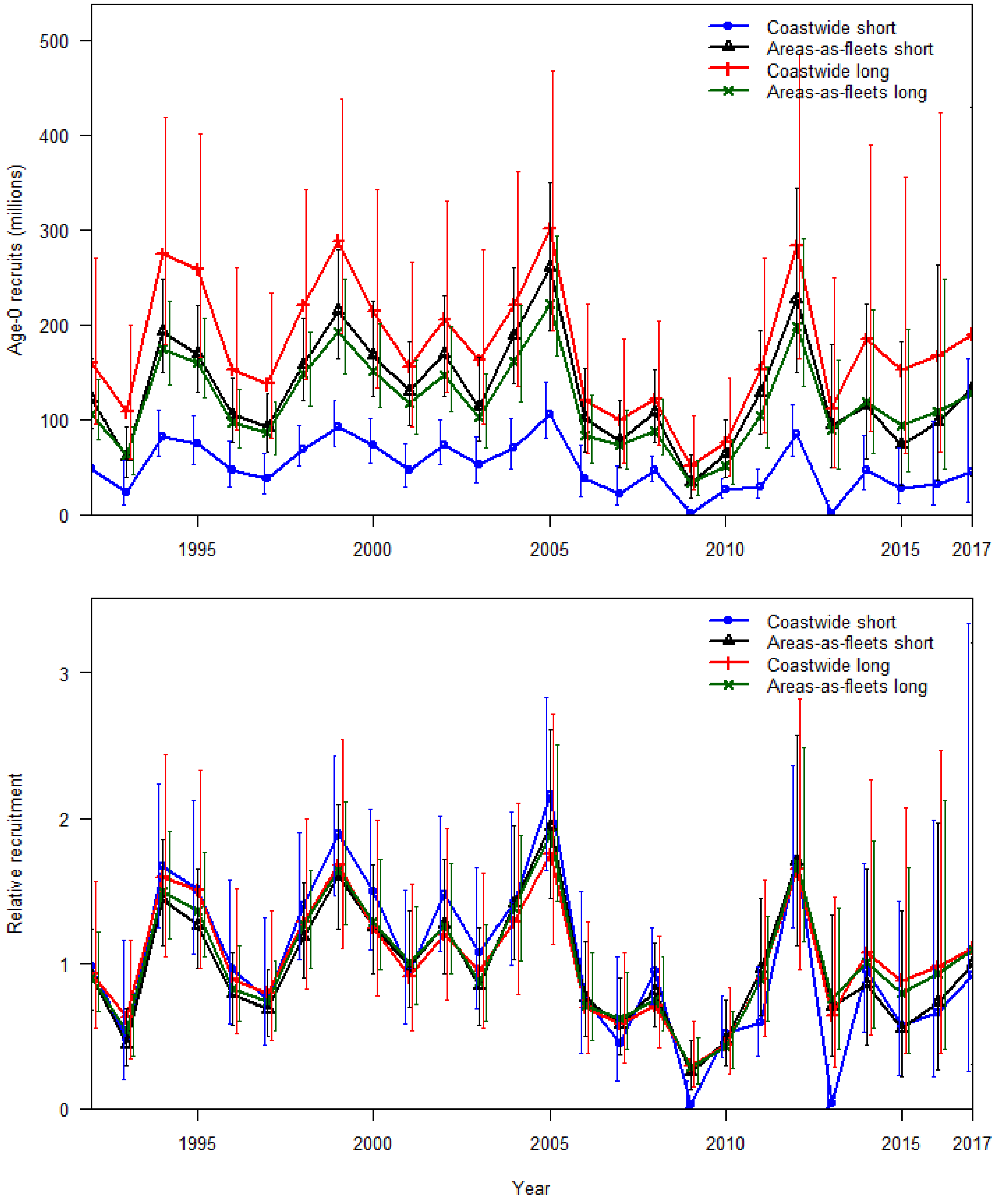


Figure 76. Comparison of recruitment time series (upper panel; vertical lines indicate asymptotic approximations to the 95% confidence interval) and relative recruitment series (each standardized to its mean; lower panel) from each of the preliminary models contributing to the 2022 ensemble.

Future development

Several extensions to this preliminary assessment will be possible for the final 2022 analysis. These include:

- Responses to suggestions and comments generated from SRB020 and SRB021.
- Addition of all 2022 data, extending existing time series (mortality, indices, ages, etc.).
- The sex-ratio of the 2021 commercial fisheries landings based on the IPHC's genetic assay will be completed and included in the final 2022 assessment.

In addition to the list of research priorities (longer list below), there are several potential avenues for development within and among the four models included in the ensemble.

The bootstrapping performed for this assessment provides a strong basis for objective interannual and among fleet weighting. Future work can now again focus on the likelihoods used for data weighting in this assessment. Options for compositional likelihoods, including those already evaluated to some degree for this assessment over the last several years (e.g., the Dirichlet-multinomial, logistic normal) continue to expand. A new candidate that can allow for automatic scaling and an estimated relationship between the observed proportion and the variance, the Tweedie distribution, is currently in press (J. Thorson, personal communication). Further, work on a calculation of composition residuals that improves upon the standard Pearson residuals currently employed by most stock assessments is also in preparation; these PIT residuals are more computationally intensive, but may have much improved distributional characteristics (Warton et al. 2017).

Other avenues for development include changes to the ensemble approach itself. The 2019 assessment explored expanding the number of models included in the ensemble to better capture the uncertainty in *M* that was missed through using a fixed value in the two short time-series models. By estimating *M* for the short AAF model in this assessment the integration of uncertainty is improved. The question of how to better address *M* in the short coastwide model remains. The next full assessment may need to explore whether structural changes could make *M* estimable and/or whether the fixed value of 0.15 is still appropriate given the increasing weight of evidence that *M* for Pacific halibut is higher, even after accounting for elevated *M* at the youngest ages.

As ensemble changes are evaluated, both weighting and technical efficiency should be considered. Technical costs of adding additional models to the ensemble include additional time spent running these additional models rather than exploring other sensitivities and identifying clear effects of newly available data during the very short assessment analysis period each fall. Pragmatically, there may be relatively little to be gained from increasing the ensemble in this manner beyond slightly smoother integrated distributions. As the IPHC's management procedure evolves, to potentially include multi-year assessments, there may be additional latitude for increased model and ensemble complexity.

The current ensemble is based on maximum likelihood estimates and asymptotic approximations to the posterior distributions for model parameters and derived quantities.

Bayesian posteriors represent a conceptually more appealing basis for probability distributions, and could better capture the full range and potential asymmetries in the distributions for model quantities (Magnusson et al. 2012; Stewart et al. 2013b). Bayesian integration may also allow for statistically correct treatment of variance parameters (such as the sigmas governing recruitment variability and selectivity or catchability process error) in the absence of true random effects capability in AD Model builder. Although it would be technically preferable to regularize and run all four assessment models as Bayesian analyses, at present this is technically infeasible given the tight time-line between data availability and the deadline for the annual stock assessment. The analysis time difference between minimization and full posterior integration, even using the most efficient methods available for the coastwide short model (see section above), is still too large. However, if the IPHC were to move to a more formal management procedure and/or to a multi-year mortality limit-setting process, the stock assessment could be conducted at a pace that would allow much greater reliance on Bayesian models.

Research priorities

The development of the IPHC's research priorities has been closely tied to the needs of the stock assessment and harvest strategy policy analyses, such that the IPHC's research projects will provide data, and hopefully knowledge, about key biological and ecosystem processes that can then be incorporated directly into analyses supporting the management of Pacific halibut. Research priorities for the Pacific halibut stock assessment can be delineated into three broad categories: improvements in basic biological understanding (including fishery dynamics), investigation of existing data series and collection of new information, and technical development of models and modelling approaches. The highest priority items in each of these categories are highlighted in the 5-year research plan and are expected to be the primary focus of ongoing efforts. However, it is helpful to maintain a longer list of items to inform future prioritization, to create a record of data and research needs, and to foster opportunistic and/or collaborative work on these topics when possible.

Biological understanding and fishery yield

Key areas for improvement in biological understanding include:

- *Highest priority*: Updating the current functional maturity schedule for Pacific halibut, including fecundity-weight relationships and the presence and/or rate of skip spawning.
- *Highest priority*: The stock structure of the Pacific halibut population. Specifically, whether any geographical components (e.g., Biological Region 4B) are isolated to a degree that modelling approximations would be improved by treating those components separately in the demographic equations and management decision-making process.
- *Highest priority*: Movement rates among Biological Regions at the adult, juvenile and larval stages remain uncertain and likely variable over time. Long-term research to inform these rates could lead to a spatially explicit stock assessment model for future inclusion into the ensemble.
- *Highest priority*: Improved understanding of discard mortality rates and the factors contributing to them may reduce potential biases in mortality estimates used for stock

assessment and allow for future reduction in mortality through improved handling practices
- The relative role of potential factors underlying changes in size-at-age is not currently understood. Delineating between competition, density dependence, environmental effects, size-selective fishing and other factors could allow improved prediction of size-at-age under future conditions.
- Improved understanding of recruitment processes and larval dynamics could lead to covariates explaining more or the residual variability about the stock-recruit relationship than is currently accounted for via the binary indicator used for the Pacific Decadal Oscillation.

Data related research

This section represents a list of potential projects relating specifically to existing and new data sources that could benefit the Pacific halibut stock assessment.

- *Highest priority*: Continued collection of sex-ratio from the commercial landings will provide valuable information for determining relative selectivity of males and females, and therefore the scale of the estimated spawning biomass, and the level of fishing intensity as measured by SPR. Potential methods for estimating historical sex-ratios from archived scales, otoliths or other samples should be pursued if possible.
- *Highest priority*: Evaluation of the magnitude of marine mammal depredation and tools to reduce it.
- The work of Monnahan and Stewart (2015) modelling commercial fishery catch rates could be used to provide a standardized fishery index for the recent time-series that would be analogous to the space-time model used for the FISS.
- A revised hook spacing relationship (Monnahan and Stewart 2017) could be included into IPHC database processing algorithms.
- There is a vast quantity of archived historical data that is currently inaccessible until organized, electronically entered, and formatted into the IPHC's database with appropriate meta-data. Information on historical fishery landings, effort, and age samples would provide a much clearer (and more reproducible) perception of the historical period.
- Additional efforts could be made to reconstruct estimates of subsistence harvest prior to 1991.
- Discard mortality estimates for the IPHC Regulatory Area 2B recreational fishery are currently unavailable, but there is an estimation system in place. Further work to develop these estimates would be preferable to the use of proxy rates from IPHC Regulatory Area 2C.
- NMFS observer data from the directed Pacific halibut fleet in Alaska could be evaluated for use in updating DMRs and the age-distributions for discard mortality. This may be more feasible if observer coverage is increased and if smaller vessels (< 40 feet LOA, 12.2 m) are observed in the future. Post-stratification and investigation of observed vs. unobserved fishing behavior may be required.

- Historical bycatch length frequencies and mortality estimates need to be reanalyzed accounting for sampling rates in target fisheries and evaluating data quality over the historical period.
- There are currently no comprehensive variance estimates for the sources of mortality used in the assessment models. In some cases, variance due to sampling and perhaps even non-sampling sources could be quantified and used as inputs to the models via scaling parameters or even alternative models in the ensemble.
- A space-time model could be used to calculate weighted FISS age-composition data. This might alleviate some of the lack of fit to existing data sets that is occurring not because of model misspecification but because of incomplete spatial coverage in the annual FISS sampling which is accounted for in the generation of the index, but not in the standardization of the composition information.

Technical development

There are a variety of technical explorations and improvements that could benefit the stock assessment models and ensemble framework. Although larger changes, such as the new data sets and refinements to the models presented in this document, naturally fit into the period full assessment analyses, incremental changes may be possible during updated assessments when and if new data or methods become available. Specifically, development is intended to occur in time for initial SRB review (generally in June), with only refinements made for final review (October), such that untested approaches are not being implemented during the annual stock assessment itself. Technical research priorities include:

- *Highest priority*: Maintaining consistency and coordination between MSE, and stock assessment data, modelling and methodology.

- *Highest priority*: 'Leading' parameter estimation. Building on the improvements to estimation of *M* in the short AAF model in this assessment, focus should be on estimation of *M* in the short coastwide model.

- *Highest priority*: Evaluation of estimating (Thorson 2019) rather than tuning (Francis 2011; Francis 2016) the level of observation and process error in order to achieve internal consistency and better propagate uncertainty within each individual assessment model. This could include tools like the 2d-autoregressive smoother for selectivity, the Dirichlet multinomial, Tweedie, and other features now implemented or in development in stock synthesis.

- Continued refinement of the ensemble of models used in the stock assessment. This may include investigation of alternative approaches to modelling selectivity that would reduce relative down-weighting of certain data sources (see section above), evaluation of additional axis of uncertainty (e.g., steepness, as explored above), or others.

- Exploration of methods for better including uncertainty in directed and non-directed discard mortalities in the assessment (now evaluated only via alternative mortality projection tables or model sensitivity tests) in order to better include these sources uncertainty in the decision table. These could include explicit discard/retention relationships, including uncertainty in discard mortality rates, and allow for some uncertainty directly in the magnitude of mortality for these sources.

- 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 (see section above).
- Alternative model structures, including a growth-explicit statistical catch-at-age approach and a spatially explicit approach may provide avenues for future exploration. Efforts to develop these approaches thus far have been challenging due to the technical complexity and data requirements of both. Previous reviews have indicated that such efforts may be more tractable in the context of operating models for the MSE, where conditioning to historical data may be much more easily achieved than fully fitting an assessment model to all data sources for use in tactical management decision making.

Acknowledgements

IPHC datasets comprise a wide array of sources based on extensive sampling and reporting efforts by state and national agencies in the U.S. and Canada. The IPHC’s annual stock assessment benefits from the hard work of all of its current and former employees providing high-quality data sets as comprehensive as any used for fisheries analysis. The Scientific Review Board and national science advisors have provided extensive guidance and constructive criticism of the treatment of data sources, the individual models and the stock assessment ensemble. Ray Webster leads, or contributes to, many of the supporting data analyses on which the assessment is based.

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Appendices

Appendix A: Supplementary material

In addition to this document, supplementary material is available electronically, including:

1) Stock synthesis input files for each of the assessment models included in the proposed ensemble: data file, weight-at-age file, control file with model configuration, starter and forecast files with additional settings. Each of these files has been extensively annotated to aid in locating the various sections, as well as identifying which options and features were implemented or are irrelevant for the configuration.

2) Output from each of the stock assessment models: a sub-directory of all plotting and diagnostic output from each model created by the r4ss package (the entire set can be loaded at once via opening the "_SS_output.html" file), and the raw report (text) file from each model. The report file has not been annotated and contains some information not relevant to the Pacific halibut model configurations; content and formats can be determined from the stock synthesis user manual (Methot Jr et al. 2021b) and technical documentation (Methot and Wetzel 2013b).

3) Copies of the primary software documentation including the general modelling approach implemented in stock synthesis (Methot and Wetzel 2013a), the technical documentation (Methot and Wetzel 2013b) and the current user manual (Methot Jr et al. 2021b). From these documents, detailed model equations, data configurations, and control settings can be evaluated for the specific features implemented in the models for Pacific halibut.

4) The overview of data sources (Stewart and Webster 2022) and the stock assessment results (Stewart and Hicks 2022) from the 2021 stock assessment.

5) The documentation from the development of the most recent (2019) full stock assessment (Stewart and Hicks 2019b).

6) Recent relevant IPHC manuscripts describing the bootstrapping method employed for fishery and FISS age compositions (Stewart and Hamel 2014), the history of the halibut stock assessment (Stewart and Martell 2014), an evaluation of data weighting and process-error considerations (Stewart and Monnahan 2017), the general rationale for the ensemble approach (Stewart and Martell 2015), and the stability properties of ensemble assessments (Stewart and Hicks 2018).

7) A full record of the historical stock assessment documentation from 1978 to the present can be found on the IPHC's web site (https://www.iphc.int/management/science-and-research/stock-assessment). Individual Scientific Review Board reports and presentations (2013-2022) are available through the IPHC's meetings webpage (https://www.iphc.int/iphc-meetings).

IPHC-2022-SRB020-08

Report on Current and Future Biological and Ecosystem Science Research Activities

PREPARED BY: IPHC SECRETARIAT (J. PLANAS, 11 MAY 2022)

PURPOSE

To provide the Scientific Review Board with a description of progress towards the finalization of IPHC's five-year Biological and Ecosystem Science Research Plan (2017-21) and the start of the IPHC's five-year Program of Integrated Research and Monitoring (2022-2026).

BACKGROUND

The primary biological and ecological research activities at IPHC that follow Commission objectives are identified and described in the IPHC Five-Year Biological and Ecosystem Science Research Plan (2017-21). These activities are integrated with stock assessment and the management strategy evaluation processes (Appendix I) and are summarized in five main areas, as follows:

1) Migration and Distribution. Studies are aimed at further understanding reproductive migration and identification of spawning times and locations as well as larval and juvenile dispersal.
2) Reproduction. Studies are aimed at providing information on the sex ratio of the commercial catch and to improve current estimates of maturity.
3) Growth and Physiological Condition. Studies are aimed at describing the role of some of the factors responsible for the observed changes in size-at-age and to provide tools for measuring growth and physiological condition in Pacific halibut.
4) Discard Mortality Rates (DMRs) and Survival. Studies are aimed at providing updated estimates of DMRs in both the longline and the trawl fisheries.
5) Genetics and Genomics. Studies are aimed at describing the genetic structure of the Pacific halibut population and at providing the means to investigate rapid adaptive changes in response to fishery-dependent and fishery-independent influences.

A ranked list of biological uncertainties and parameters for stock assessment (Appendix II) and the management strategy evaluation process (Appendix III) and their links to research activities and outcomes derived from the five-year research plan are provided.

SRB RECOMMENDATIONS AND REQUESTS

The SRB issued the following recommendations and requests in their report of SRB019 (IPHC-2021-SRB019-R):

*Recommendation 1 (*SRB019–Rec.09 (para. 43))

> ***"**The SRB **RECOMMENDED** that the IPHC Secretariat consider the value of other opportunistically collected samples that would facilitate further downstream analyses in a cost effective manner."*

The IPHC Secretariat is maximizing opportunities for sample collection from fish encountered in experimental field trials as well as in the IPHC FISS. As an example, the IPHC Secretariat will begin in 2022 the collection of fin clips of all Pacific halibut encountered in the FISS for future genetic analyses.

*Recommendation 2 (*SRB019–Rec.10 (para. 56))

> ***“****The SRB* ***RECOMMENDED*** *that the IPHC Secretariat identify those research areas with uncertainty and indicate research questions that would require the SRB to provide input and/or decision in future documentation and presentations provided to the SRB.”*

The Secretariat is working towards delineating research questions that address key areas of uncertainty for Stock Assessment and Management Strategy Evaluation.

*Request 1 (*SRB019–Req.06 (para. 46))

> ***“****The SRB* ***NOTED*** *that the IPHC Secretariat is finalising a proposed sampling design for the collection of ovaries in the 2023 FISS, for providing precise estimates of fecundity and* ***REQUESTED*** *for SRB020 in June 2022, more detail on the considerations taken to ensure the sampling maximises the opportunity to address the objectives.”*

The IPHC Secretariat is working towards selecting appropriate methods for fecundity estimations and towards devising a sampling strategy for 2023. This will be discussed during the IPHC Secretariat presentations during SRB020.

*Request 2 (*SRB019–Req.07 (para. 50))

> ***“****The SRB* ***REQUESTED*** *that the IPHC Secretariat pause further pursuit of this research until it can articulate specifically how this approach will inform the stock assessment or MSE and why this approach is preferable to investigation of age-length-weight information which is available at a much broader geographic and temporal scale. “*

The IPHC Secretariat is complying with this request.

UPDATE ON PROGRESS ON THE MAIN RESEARCH ACTIVITIES

1. Migration and Distribution.

   Research activities in this Research Area aim at improving existing knowledge on Pacific halibut larval and juvenile distribution. The relevance of research outcomes from these activities for stock assessment (SA) is in the improvement of estimates of productivity. These research outcomes will be used to generate potential recruitment covariates and to inform minimum spawning biomass targets by Biological Region and represent one of the top three biological inputs into SA (Appendix II). The relevance of these research outcomes for the management and strategy evaluation (MSE) process is in the improvement of the parametrization of the Operating Model and represent the top ranked biological input into the MSE (Appendix III).

   1.1. Larval distribution and connectivity between the Gulf of Alaska and Bering Sea.

No updates to report.

1.2. Wire tagging of U32 Pacific halibut.

No updates to report.

2. Reproduction.

Research activities in this Research Area aim at providing information on key biological processes related to reproduction in Pacific halibut (maturity and fecundity) and to provide sex ratio information of Pacific halibut commercial landings. The relevance of research outcomes from these activities for stock assessment (SA) is in the scaling of Pacific halibut biomass and in the estimation of reference points and fishing intensity. These research outputs will result in a revision of current maturity schedules and will be included as inputs into the SA (Appendix II), and represent the most important biological inputs for stock assessment (please see document IPHC-2021-SRB018-06). The relevance of these research outcomes for the management and strategy evaluation (MSE) process is in the improvement of the simulation of spawning biomass in the Operating Model (Appendix III).

2.1. Sex ratio of the commercial landings.

The IPHC Secretariat finalized the processing of genetic samples from the 2020 aged commercial landings, completing four consecutive years of sex ratio information (2017-2020) and is currently processing genetic samples from the 2021 commercial landings.

2.2. Maturity assessment.

Recent sensitivity analyses have shown the importance of changes in spawning output due to skip spawning and/or changes in maturity schedules for stock assessment (Stewart and Hicks, 2018). Information of these key reproductive parameters provides direct input to stock assessment. For example, information on fecundity-at-age and –at-size could be used to replace spawning biomass with egg output as the metric of reproductive capability in the stock assessment and management reference points. This information highlights the need for a better understanding of factors influencing reproductive biology and success of Pacific halibut. In order to fill existing knowledge gaps related to the reproductive biology of female Pacific halibut, research efforts are devoted to characterize female maturity in this species. Specific objectives of current studies include: 1) histological assessment of the temporal progression of female developmental stages and reproductive phases throughout an entire reproductive cycle; 2) update of maturity schedules based on histological-based data; and, 3) fecundity determinations.

2.2.1. Histological assessment of the temporal progression of female developmental stages and reproductive phases throughout an entire reproductive cycle. The IPHC Secretariat has conducted the first detailed examination of temporal changes in female ovarian developmental stages, reproductive phases, and biological indicators of Pacific halibut reproductive development. The results obtained by ovarian histological examination indicate that female Pacific halibut follow an annual reproductive cycle involving a clear progression of female developmental stages towards spawning within a single year. These results provide foundational information for future studies aimed at updating maturity ogives by histological assessment and at investigating fecundity in Pacific halibut. Furthermore, the potential use of easily-obtained biological indicators in predictive models to assign reproductive phase in Pacific halibut was demonstrated. The results of this study have been published in the journal *Frontiers in Marine Science* (Fish et al., 2022): https://doi.org/10.3389/fmars.2022.801759.

2.2.2. Update of maturity schedules based on histological-based data. The IPHC Secretariat is currently planning the collection of ovarian samples for histology during the 2022 FISS. Plans include the collection of 400 ovarian samples from Biological Region 3, 300 samples each from Biological Regions 2 and 4, and 250 samples from Biological Region 4B.

2.2.3. Fecundity estimations. Methods for fecundity determinations were investigated and, based on the current literature and recommendations from experts in the field, the auto-diametric method was selected as the method of choice (Witthames et al., 2009). The IPHC Secretariat is currently designing plans for ovarian sample collection for fecundity estimations within the 2023 FISS.

3. Growth.

Research activities conducted in this Research Area aim at providing information on somatic growth processes driving size-at-age in Pacific halibut. The relevance of research outcomes from these activities for stock assessment (SA) resides, first, in their ability to inform yield-per-recruit and other spatial evaluations for productivity that support mortality limit-setting, and, second, in that they may provide covariates for projecting short-term size-at-age and may help delineate between fishery and environmental effects, thereby informing appropriate management responses (Appendix II). The relevance of these research outcomes for the management and strategy evaluation (MSE) process is in the improvement of the simulation of variability and to allow for scenarios investigating climate change (Appendix III).

The IPHC Secretariat has conducted studies aimed at elucidating the drivers of somatic growth leading to the decline in SAA by investigating the physiological mechanisms that contribute to growth changes in the Pacific halibut. The two main objectives of these studies have been: 1) the identification and validation of physiological markers for somatic growth; and 2) the application of molecular growth markers for evaluating growth patterns in the Pacific halibut population.

No updates to report.

4. Discard Mortality Rates (DMRs) and Survival Assessment.

   Information on all Pacific halibut removals is integrated by the IPHC Secretariat, providing annual estimates of total mortality from all sources for its stock assessment. Bycatch and wastage of Pacific halibut, as defined by the incidental catch of fish in non-target fisheries and by the mortality that occurs in the directed fishery (i.e. fish discarded for sublegal size or regulatory reasons), respectively, represent important sources of mortality that can result in significant reductions in exploitable yield in the directed fishery. Given that the incidental mortality from the commercial Pacific halibut fisheries and bycatch fisheries is included as part of the total removals that are accounted for in stock assessment, changes in the estimates of incidental mortality will influence the output of the stock assessment and, consequently, the catch levels of the directed fishery. Research activities conducted in this Research Area aim at providing information on discard mortality rates and producing guidelines for reducing discard mortality in Pacific halibut in the longline and recreational fisheries. The relevance of research outcomes from these activities for stock assessment (SA) resides in their ability to improve trends in unobserved mortality in order to improve estimates of stock productivity and represent the most important inputs in fishery yield for stock assessment (Appendix II). The relevance of these research outcomes for the management and strategy evaluation (MSE) process is in fishery parametrization (Appendix III).

   For this reason, the IPHC Secretariat is conducting two research projects to investigate the effects of capture and release on survival and to improve estimates of DMRs in the directed longline and guided recreational Pacific halibut fisheries:

   4.1. Evaluation of the effects of hook release techniques on injury levels and association with the physiological condition of captured Pacific halibut and estimation of discard mortality using remote-sensing techniques in the directed longline fishery.

   A manuscript describing discard mortality rate estimations in the directed longline fishery has been published in the journal *North American Journal of Fisheries Management* (Loher et al., 2022). No other updates to report.

   4.2. Estimation of discard mortality rates in the charter recreational sector.

   The IPHC Secretariat is conducting a research project to better characterize the nature of charter recreational fisheries with the ultimate goal of better understanding discard practices relative to that which is employed in the directed longline fishery. This project has received funding from the National Fish and Wildlife Foundation and the North Pacific Research Board (Appendix IV) and the project narratives of both projects have been provided in previous meeting documentations. The experimental field components of this research project took place in Sitka, Alaska (IPHC Regulatory Area 2C) from 21-27 May 2021, and in Seward, Alaska (IPHC Regulatory Area 3A) from 11-16 June 2021, with methods and analyses detailed in the project narratives provided.

The fishing vessels were required to fish 6 rods at a time, three (3) rigged with 12/0 circle hooks and three (3) rigged with 16/0 circle hooks in order to establish a comparison of the two most common gear types used in the Alaskan Pacific halibut recreational fishery, as informed by the survey conducted in 2019 and subsequent discussions. The number of fish captured, sampled and released, as well as the size distribution of fish by tag type (wire tag or sPAT) was previously reported (IPHC-2021-SRB019-08).

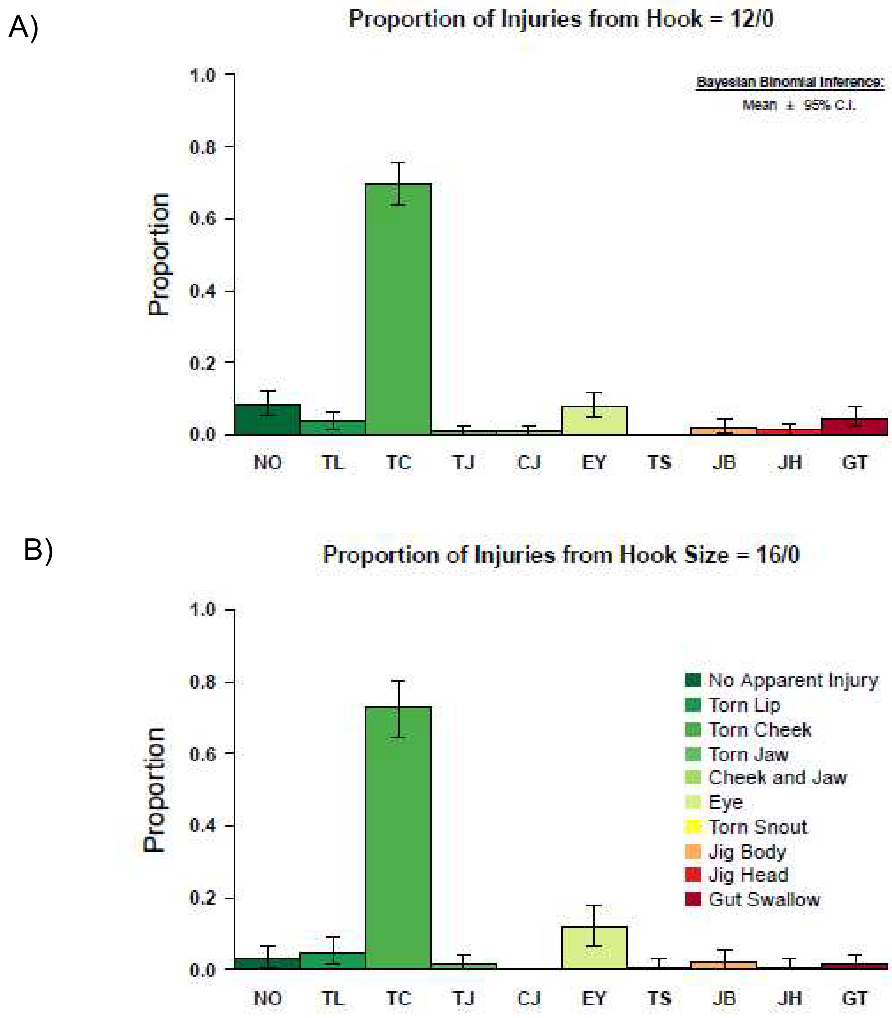

Figure 1. Proportion of the different types of injuries in fish captured with 12/0 hooks (top) and 16/0 hooks (bottom). The legend of injury types corresponds to the abbreviations in the horizontal axis.

The proportion of the different types of injuries incurred over the hooking and release process were determined for Pacific halibut captured with 12/0 hooks and 16/0 hooks. For Pacific halibut captured with 12/0 hooks, approximately 70% of the fish had injuries corresponding to torn cheek, a type of minor injury that is incurred by the hook penetrating the cheek musculature through a single location (Figure 1A) during the capture event. All other injuries were in much smaller proportion. Very similar distribution of injuries were observed in Pacific halibut captured with 16/0 hooks, again with a predominance of torn cheek injuries (Figure 1B). Overall, the predominant injury profile of Pacific halibut captured with either type of hook and subsequently released corresponded to relatively minor injuries.

To date, of the 281 fish that were tagged with opercular wire tags (243 fish in IPHC Regulatory Area 2C and 38 in IPHC Regulatory Area 3A) 27 tags have been recovered to date (25 from IPHC Regulatory Area 2C and 2 from IPHC Regulatory Area 3A).

In order to directly assess the survival of discarded fish, we tagged 80 with satellite-transmitting electronic archival tags equipped with accelerometers (sPAT tags). To date, 76 out of the 80 released sPAT tags provided data reports. Of the 4 sPAT tags that did not provide data, 2 sPAT tags never reported and 2 did not have sufficient data for successful interpretation. Therefore, 95% of the sPAT tags deployed provided survival information, a similar data transmission success as compared to our recently published report on the use of sPATs to evaluate survival of Pacific halibut discarded from the longline fishery (Loher et al. 2022). Of the 76 useable sPAT tags, 48 tags were at liberty for the full duration of the pre-programmed 96-day period, whereas 21 sPAT tags reported prematurely for unknown reasons, with an average time of at liberty reporting of 37.1 days (range of 3.6-76.8 days). The remaining 7 sPAT tags were physically recovered by fishery captures, with an average time at liberty of 58 days (range of 37.1-69.1 days). Of the physically recovered tags, one was recovered 2 Km from its release location, another one 16 Km from its release location and the remaining 5 tags were recovered less than 0.5 Km from their release location.

Preliminary analysis of the accelerometer data from all 76 tags that successfully reported data, following the survival criteria previously reported in Loher et al. (2022), indicates that only one discarded fish was confidently estimated to have died (its tag reported 8.3 days after deployment). Current analyses are devoted to evaluate whether a second potentially dead fish that reported 32.7 days after deployment fits the “dead” criteria. Therefore, preliminary estimates of discard mortality from the guided recreational fishery point towards a 1.3% discard mortality rate. The deduced preliminary discard mortality rate estimated in the present study is lower than the minimum 4.2% discard mortality rate recently estimated for Pacific halibut discarded from the longline fishery (Loher et al. 2022). The difference in estimated survival between Pacific halibut captured and discarded from the two types of fishery is consistent with the lower capture (hooking) and release time, under best practice handling conditions, of Pacific halibut captured by the recreational fishery. These results represent the first report of experimentally-derived estimates (albeit preliminary) of discard mortality of Pacific halibut captured and discarded in the recreational fishery.

5. Genetics and genomics. The IPHC Secretariat is conducting studies that incorporate genomics approaches in order to produce useful information on population structure and distribution and connectivity of Pacific halibut. The relevance of research outcomes from

these activities for stock assessment (SA) resides (1) in the introduction of possible changes in the structure of future stock assessments, as separate assessments may be constructed if functionally isolated components of the population are found (e.g. IPHC Regulatory Area 4B), and (2) in the improvement of productivity estimates, as this information may be used to define management targets for minimum spawning biomass by Biological Region. These research outcomes provide the second and third top ranked biological inputs into SA (Appendix II). Furthermore, the relevance of these research outcomes for the management and strategy evaluation (MSE) process is in biological parametization and validation of movement estimates, on one hand, and of recruitment distribution, on the other hand (Appendix III).

5.1. Population genomics.

The primary objective of the studies that the IPHC Secretariat is currently conducting is to investigate the genetic structure of the Pacific halibut population and to conduct genetic analyses to inform on Pacific halibut movement and distribution within the Convention Area.

5.1.1. Pacific halibut genome and characterization of the sex determining region in Pacific halibut. The IPHC Secretariat has updated the Pacific halibut genome assembly. The updated Pacific halibut genome has an estimated size of 602 Mb, 24 chromosome-length scaffolds that contain 99.8% of the assembly and a N_{50} scaffold length of 27.3 Mb. The Pacific halibut whole genome sequencing data are openly available in NCBI at https://www.ncbi.nlm.nih.gov/bioproject/622249, under BioProject PRJNA622249, and the updated assembly is openly available in NCBI at https://www.ncbi.nlm.nih.gov/assembly/GCA_022539355.2/ with GenBank assembly accession number GCA_022539355.2. The master record for the whole genome shotgun sequencing project has been deposited at DDBJ/ENA/GenBank under the accession JAKRZP000000000 and is openly available in NCBI at https://www.ncbi.nlm.nih.gov/nuccore/JAKRZP000000000. Sample metadata is openly available in NCBI at https://www.ncbi.nlm.nih.gov/biosample?Db=biosample&DbFrom=bioproject&Cmd=Link&LinkName=bioproject_biosample&LinkReadableName=BioSample&ordinalpos=1&IdsFromResult=622249, under BioSamples SAMN14503176, SAMN25516224, SAMN25600010 and SAMN25600011.

Using the updated genome assembly, we conducted genome-wide analyses of sex-specific genetic variation by pool sequencing by mapping reads from male and female pools to the Pacific halibut genome assembly. We identified a potential sex-determining region in chromosome 9 of approximately 12 Mb containing a high density of female-specific SNPs. Within this sex-determining region, we identified among the annotated genes a potential candidate for the master sex-determining gene in Pacific halibut. Mapping of previously identified Pacific halibut RAD-tags associated with sex (Drinan et al., 2018) to the updated Pacific halibut genome assembly resulted in the alignment of 55 of the 56 RAD-tags, all of which mapped to the putative SD region, including the two tags containing the sex-linked markers currently used for genetic sex identification (2.1.1). These results, together with data on the Pacific halibut genome sequencing and assembly, have been accepted for publication in the journal *Molecular Ecology Resources* (Jasonowicz et al., in press; provided separately).

5.1.2. Studies to resolve the genetic structure of the Pacific halibut population in the Convention Area. This project has recently received funding from the North Pacific Research Board (NPRB Project No. 2110; Appendix IV; project narrative provided in the supplementary documentation). Details on sample collection, bioinformatic processing and proposed analyses utilizing low-coverage whole genome sequencing (lcWGR) to investigate Pacific halibut population structure were provided in document IPHC-2021-SRB018-08. The bioinformatic processing pipeline has been successfully migrated to Microsoft Azure cloud computing services and the raw sequence data from three sequencing runs totaling 536 samples have now been processed. This includes alignment to the Pacific halibut reference genome (version 1) and quality filters to ensure integrity of the data prior to analysis. On a per-sample basis, the data output of the sequencing runs is comparable (Table 1). However, we observed a difference in base quality scores between the two sequencing platforms used (Figure 2). This is likely a result of the different sequencing chemistry between the two sequencing platforms used. To mitigate the possibility of batch effects resulting from sequencing across different platforms and multiple runs, we have begun implementing strategies recommended by Lou and Therkildsen (2021) into our data processing workflow. Specifically, we used more stringent sequence read trimming using the sliding window option in Trimmomatic. Furthermore, samples with less than 1,000,000 sequence reads were omitted from any summaries, single nucleotide polymorphism (SNP) identification and downstream analyses.

Library	IPHC_001	IPHC_002	IPHC_003
Number of samples*	36 (35)	250 (249)	250 (249)
Sequencing Platform	Illumina HiSeq 4000	Illumina NovaSeq S4	Illumina NovaSeq S4
Raw Reads Per Sample (Millions)**	26.4 (21.8-42.9)	24.7 (10.7-47.2)	24.9 (13.0-51.6)
Reads Retained (%)**	58 (52-67)	62 (22-69)	61 (46-70)
Coverage Per Sample (x)**	2.5 (1.9-3.7)	3.0 (0.9-5.0)	3.0 (1.3-5.9)

Table 1. Summary of raw sequence data and genome alignments for two Pacific halibut lcWGR sequencing runs. *numbers in parenthesis indicate number of samples with > 1,000,000 raw sequence reads. **expressed as mean (min – max)

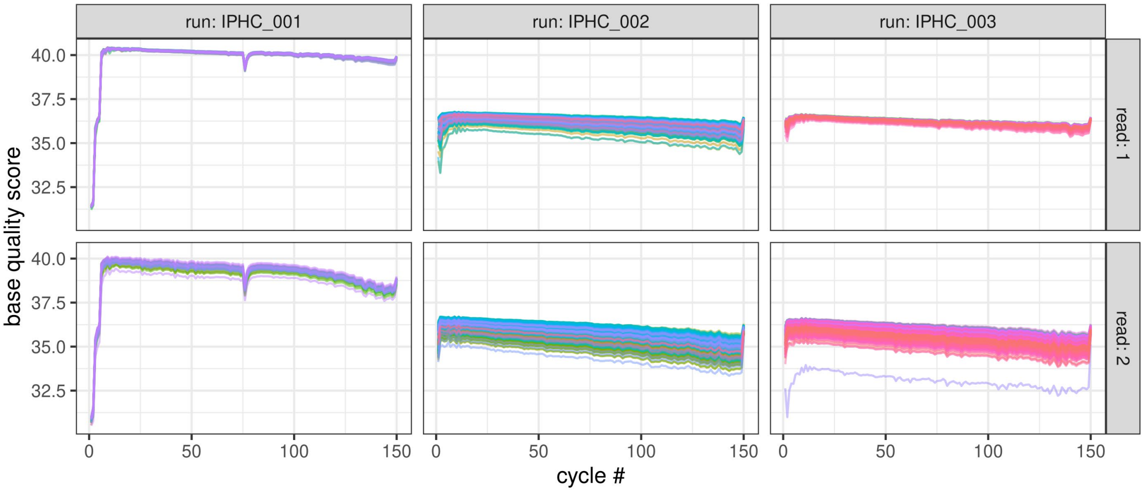

Figure 2. Average base quality score by sequencing cycle. Each sample is represented by a single line, facetted by sequencing run and read (1 = forward read, 2= reverse read).

The sequence alignments were used to identify SNPs and estimate genotype likelihoods using the samtools model implemented in ANGSD (v0.934) (Korneliussen et al. 2014). A minimum base quality score of 20 (99% probability of correct base call) was required and SNPs were retained if they had a global minor allele frequency (MAF) ≥ 0.01 or greater, p-value of 1e-6 or less for a site being variable, and present in at least 402 out of 533 (75.4%) of the individuals. A total of 10,415,578 SNPs were identified using these parameters.

Principal component analysis was used to gain a preliminary look at the structure of the data set. Prior to this, the dataset was filtered to remove SNPs in any unplaced scaffolds, the mitochondrial genome, and chromosome 9 (RefSeq: NC_048935.1), which contains a large sex-associated region (Jasonowicz et al., in review). PCAngsd (v1.02) (Meisner and Albrechtsen 2018; Meisner et al. 2021) was run using default parameters (MAF ≥ 0.5 by default) to estimate a covariance matrix among individuals using genotype likelihoods for 533 Pacific halibut. Numpy (v1.21.2) (Harris et al. 2020) was then used to compute the eigenvalues and eigenvectors for the covariance matrix obtained using PCAngsd.

A total of 4,235,107 sites were retained by PCAngsd and, as recommended by Lou and Therkildsen (2021), individual points were colored by the sequencing run to visualize patterns of non-random groupings that may be indicative of quality differences in the sequencing runs. While there were no clear differences among the NovaSeq S4 runs (Figure 3), we have reserved space on the next sequencing run for resequencing the 36 samples in IPHC_001 (Table 1) on the NovaSeq S4.

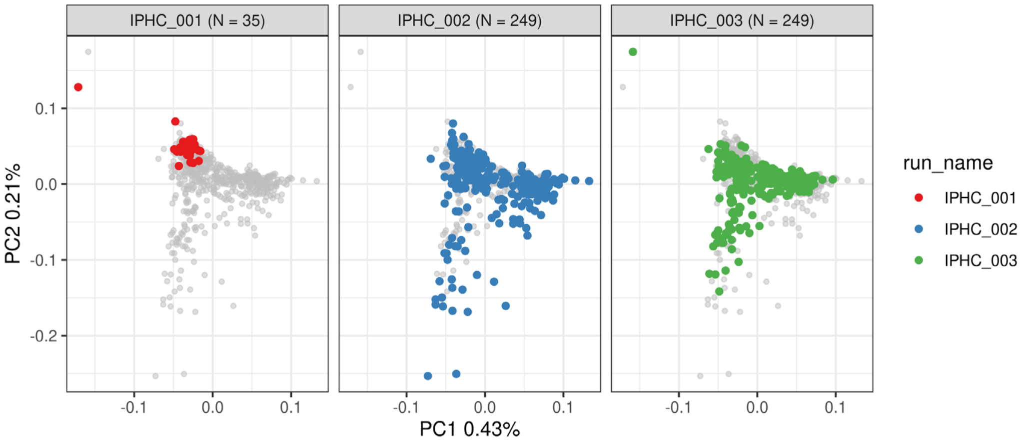

Figure 3. Principal component analysis scores of genotype likelihoods from 4,235,107 SNPs in 533 Pacific halibut sequenced to date. Points are colored by sequencing run with the remaining samples colored in gray for comparison.

Currently, 75 samples are being prepared for inclusion in the next sequencing run. This will complete the sequencing phase of the project, with a total of 611 samples having been submitted for sequencing. Once this round of sequencing is complete, the raw reads for all samples will be re-processed using version 2 of the Pacific halibut reference genome.

6. Whale depredation avoidance strategies. The IPHC Secretariat has determined that research to provide the Pacific halibut fishery with tools to reduce whale depredation is considered a high priority. This research is now contemplated as one of the research areas of high priority within the 5-year Program of Integrated Research and Monitoring (2022-2026). Towards this goal, the IPHC secretariat has recently obtained funding from NOAA's Bycatch Research and Engineering Program (BREP) to investigate gear-based approaches to catch protection as a means for minimizing whale depredation in the Pacific halibut and other longline fisheries (NOAA Award NA21NMF4720534; Appendix IV). The objectives of this study are to: 1) work with fishermen and gear manufacturers, via direct communication and through an international workshop, to identify effective methods for protecting hook-captured flatfish from depredation; and 2) develop and pilot test 2-3 simple, low-cost catch-protection designs that can be deployed effectively using current longline fishing techniques and on vessels currently operating in the Northeast Pacific Ocean.

The first phase of this project consisted in recruiting participants for a catch protection workshop from the scientific community and from the harvesters active in the waters of Alaska, British Columbia and the U.S. west coast. Initial screening of research conducted around the world led to invitations to three different groups actively working on development of catch protection devices (Sago Solutions, Norway; National Institute for Sustainable Development (IRD) – Marine Biodiversity, Exploitation, and Conservation Unit (MARBEC), University of Montpellier – CNRS-INFREMER-IRD National Centre for Scientific Research, Centre d'Etudes Biologiques de Chisé, France; and Fish Tech Inc., United States). In parallel, harvesters active in the Pacific halibut and Greenland Turbot fisheries as well as scientists involved in marine mammal research were actively recruited for participation. The "1st International Workshop on Protecting Fishery Catches from Whale Depredation (WS001)" was held electronically on 9 February 2022. The Workshop brought together 74 participants from 6 countries, ranging from research scientists to active harvesters. A report summarizing material presented and discussions was produced and posted the IPHC's website along with video recordings of the entire workshop: https://www.iphc.int/venues/details/1st-international-workshop-on-protecting-fishery-catches-from-whale-depredation-ws001.

Current efforts are devoted to the development of designs for two devices for field testing in the second half of 2022.

RECOMMENDATION/S

That the SRB:

a) **NOTE** paper IPHC-2022-SRB020-08 which provides a response to requests from SRB019, and a report on current research activities contemplated within the IPHC Five-Year Biological and Ecosystem Science Research Plan (2017-2021).

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APPENDIX I

Integration of biological research, stock assessment and harvest strategy policy (2017-21)

Biological research		Stock assessment	Stock assessment MSE
Research areas	Research outcomes	Relevance for stock assessment	Inputs to stock assessment and MSE development
Reproduction	Sex ratio Spawning output Age at maturity	Spawning biomass scale and trend Stock productivity Recruitment variability	Sex ratio Maturity schedule Fecundity
Growth	Identification of growth patterns Environmental effects on growth Growth influence in size-at-age variation	Temporal and spatial variation in growth Yield calculations Effects of ecosystem conditions Effects of fishing	Predicted weight-at-age Mechanisms for changes in weight-at-age
Discard Survival	Bycatch survival estimates Discard mortality rate estimates	Scale and trend in mortality Scale and trend in productivity	Bycatch and discard mortality estimates Variability in bycatch and uncertainty in discard mortality estimates
Migration	Larval distribution Juvenile and adult migratory behavior and distribution	Geographical selectivity Stock distribution	Information for structural choices Recruitment indices Migration pathways and rates Timing of migration
Genetics and Genomics	Genetic structure of the population Sequencing of the Pacific halibut genome	Spatial dynamics Management units	Information for structural choices

APPENDIX II

List of ranked biological uncertainties and parameters for stock assessment (SA) and their links to potential research areas and research activities (2017-21)

SA Rank	Research outcomes	Relevance for stock assessment	Specific analysis input	Research Area	Research activities
1. Biological input	Updated maturity schedule	Scale biomass and reference point estimates	Will be included in the stock assessment, replacing the current schedule last updated in 2006	Reproduction	Histological maturity assessment
	Incidence of skip spawning		Will be used to adjust the asymptote of the maturity schedule, if/when a time-series is available this will be used as a direct input to the stock assessment		Examination of potential skip spawning
	Fecundity-at-age and -size information		Will be used to move from spawning biomass to egg-output as the metric of reproductive capability in the stock assessment and management reference points		Fecundity assessment
	Revised field maturity classification		Revised time-series of historical (and future) maturity for input to the stock assessment		Examination of accuracy of current field macroscopic maturity classification
2. Biological input	Stock structure of IPHC Regulatory Area 4B relative to the rest of the Convention Area	Altered structure of future stock assessments	If 4B is found to be functionally isolated, a separate assessment may be constructed for that IPHC Regulatory Area	Genetics and Genomics	Population structure
3. Biological input	Assignment of individuals to source populations and assessment of distribution changes	Improve estimates of productivity	Will be used to define management targets for minimum spawning biomass by Biological Region		Distribution
	Improved understanding of larval and juvenile distribution		Will be used to generate potential recruitment covariates and to inform minimum spawning biomass targets by Biological Region	Migration	Larval and juvenile connectivity studies
1. Assessment data collection and processing	Sex ratio-at-age	Scale biomass and fishing intensity	Annual sex-ratio at age for the commercial fishery fit by the stock assessment	Reproduction	Sex ratio of current commercial landings
	Historical sex ratio-at-age		Annual sex-ratio at age for the commercial fishery fit by the stock assessment		Historical sex ratios based on archived otolith DNA analyses
2. Assessment data collection and processing	New tools for fishery avoidance/deterence; improved estimation of depredation mortality	Improve mortality accounting	May reduce depredation mortality, thereby increasing available yield for directed fisheries. May also be included as another explicit source of mortality in the stock assessment and mortality limit setting process depending on the estimated magnitude	Mortality and survival assessment	Whale depredation accounting and tools for avoidance
1. Fishery yield	Physiological and behavioral responses to fishing gear	Reduce incidental mortality	May increase yield available to directed fisheries	Mortality and survival assessment	Biological interactions with fishing gear
2. Fishery yield	Guidelines for reducing discard mortality	Improve estimates of unobserved mortality	May reduce discard mortality, thereby increasing available yield for directed fisheries	Mortality and survival assessment	Best handling practices: recreational fishery

APPENDIX III

List of ranked biological uncertainties and parameters for management strategy evaluation (MSE) and their potential links to research areas and research activities (2017-21)

MSE Rank	Research outcomes	Relevance for MSE	Research Area	Research activities
1. Biological parameterization and validation of movement estimates	Improved understanding of larval and juvenile distribution	Improve parametization of the Operating Model	Migration	Larval and juvenile connectivity studies
	Stock structure of IPHC Regulatory Area 4B relative to the rest of the Convention Area		Genetics and Genomics	Population structure
2. Biological parameterization and validation of recruitment variability and distribution	Assignment of individuals to source populations and assessment of distribution changes	Improve simulation of recruitment variability and parametization of recruitment distribution in the Operating Model		Distribution
	Establishment of temporal and spatial maturity and spawning patterns	Improve simulation of recruitment variability and parametization of recruitment distribution in the Operating Model	Reproduction	Recruitment strength and variability
3. Biological parameterization and validation for growth projections	Identification and application of markers for growth pattern evaluation	Improve simulation of variability and allow for scenarios investigating climate change	Growth	Evaluation of somatic growth variation as a driver for changes in size-at-age
	Environmental influences on growth patterns			
	Dietary influences on growth patterns and physiological condition			
1. Fishery parameterization	Experimentally-derived DMRs	Improve estimates of stock productivity	Mortality and survival assessment	Discard mortality rate estimate: recreational fishery

APPENDIX IV

Summary of active research grants during the reporting period

Project #	Grant agency	Project name	PI	Partners	IPHC Budget ($US)	Management implications	Grant period
1	**National Fish & Wildlife Foundation**	Improving the characterization of discard mortality of Pacific halibut in the recreational fisheries (NFWF No. 61484)	IPHC	Alaska Pacific University, U of A Fairbanks, charter industry	$98,902	Bycatch estimates	1 April 2019 – 1 November 2021
2	**North Pacific Research Board**	Pacific halibut discard mortality rates (NPRB No. 2009)	IPHC	Alaska Pacific University,	$210,502	Bycatch estimates	1 January 2021 – 31 March 2022
3	**Bycatch Reduction Engineering Program - NOAA**	Gear-based approaches to catch protection as a means for minimizing whale depredation in longline fisheries (NA21NMF4720534)	IPHC	Deep Sea Fishermen's Union, Alaska Fisheries Science Center-NOAA, industry representatives	$99,700	Mortality estimations due to whale depredation	November 2021 – October 2022
4	**North Pacific Research Board**	Pacific halibut population genomics (NPRB No. 2110)	IPHC	Alaska Fisheries Science Center-NOAA	$193,685	Stock structure	December 2021- January 2024
Total awarded ($)					**$602,789**		

IPHC-2022-SRB020-09

Pacific Halibut Multiregional Economic Impact Assessment (PHMEIA): project report

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PURPOSE

The purpose of this document is to provide the Scientific Review Board (SRB) with the Pacific halibut multiregional economic impact assessment (PHMEIA) model project, which has now concluded. PHMEIA was a core product of the IPHC socioeconomic study directly responding to the Commission's "*desire for more comprehensive economic information to support the overall management of the Pacific halibut resource in fulfillment of its mandate*" (economic study terms of reference adopted at FAC095 (IPHC-2019-FAC095) and endorsed at AM095 in 2019). The update complements the full project report available as an information paper IPHC-2022-ECON-01. The project was concluded at the 98th Session of the IPHC Annual Meeting (AM098) (IPHC–2022–AM098–R, par. 70).

BACKGROUND

The goal of the IPHC socioeconomic study was to provide stakeholders with an accurate and all-sectors-encompassing assessment of the socioeconomic impact of the Pacific halibut resource that includes the full scope of Pacific halibut's contribution to regional economies of Canada and the United States of America. To that end, the Secretariat developed the Pacific halibut multiregional economic impact assessment (PHMEIA) model that informs stakeholders on the importance of the Pacific halibut resource and fisheries to their respective communities, but also broader regions and nations, and contributes to a wholesome approach to Pacific halibut management that is optimal from both biological and socioeconomic perspective, as mandated by the Convention.

The PHMEIA is a multiregional social accounting matrix (SAM)-based model developed to assess three **economic impact (EI)** components pertaining to Pacific halibut. The **direct EIs** reflect the changes realized by the direct Pacific halibut resource stock users (fishers, charter business owners), as well as the forward-linked Pacific halibut processing sector (i.e., EI related to downstream economic activities). The **indirect EIs** are the result of business-to-business transactions indirectly caused by the direct EIs. The indirect EIs provide an estimate of the changes related to expenditures on goods and services used in the production process of the directly impacted industries. In the context of the PHMEIA, this includes an impact on upstream economic activities associated with supplying intermediate inputs to the direct users of the Pacific halibut resource stock, for example, impact on the vessel repair and maintenance sector or gear suppliers. Finally, the **induced EIs** result from increased personal income caused by the direct and indirect effects. In the context of the PHMEIA, this includes economic activity generated by households spending earnings that rely on the Pacific halibut resource, both directly and indirectly.

The three EI components are assessed by detailing the within-region production structure of the Pacific halibut sectors and accounting for economic interdependencies between sectors and regions by embedding Pacific halibut sectors into the model of the entire economy of Canada and the USA. To accommodate an increasing economic interdependence of regions and nations, the model accounts for interregional spillovers. These represent economic stimulus in regions other than the one in which the exogenous change is considered. Economic benefits from the primary area of the resource extraction are leaked when inputs are imported, when wages earned by nonresidents are spent outside the place of employment, or when earnings from quota holdings flow to nonresident beneficial owners. At the same time, there is an inflow of economic benefits to the local economies from when products are exported, or services are offered to non-residents.

While the economic impact is most commonly expressed in terms of output, that is the total production linked (also indirectly) to the evaluated sector, the estimates herein focus on the Pacific halibut contribution to households' prosperity (income by place of residence) as the most meaningful metric to the general population.

MODEL SETUP

The model reflects the interdependencies between eleven major sectors and two Pacific halibut-specific sectors. These include the Pacific halibut fishing sector, as well as the forward-linked Pacific halibut processing sector. While the complete path of landed fish includes, besides harvesters and processors, also seafood wholesalers and retailers, and services when it is served in restaurants, it is important to note that there are many seafood substitutes available to buyers. Thus, including economic impacts beyond wholesale in PHMEIA, as opposed to assessing the snapshot contribution to the GDP along its entire value chain, would be misleading when considering that it is unlikely that supply shortage would result in a noticeable change in retail or services level gross revenues (Steinback and Thunberg, 2006). Supplementary snapshot assessment of Pacific halibut contribution to the GDP along the entire value chain, **from the *hook-to-plate***, is available in IPHC-2021-ECON-06-R01 (last updated 6 January 2022).

The extended model (referred here as PHMEIA-r) introduces to the SAM also the saltwater charter sector that is disaggregated from the services-providing industry. The estimates assume that the economic impact of Pacific halibut charter fishing is equivalent to estimating the total economic loss resulting from the saltwater charter sector in each region shrinking by share of Pacific halibut effort in total effort. The results for the charter sector, however, should be interpreted cautiously because of the uncertainty on how much of the saltwater angling effort directly depends on Pacific halibut.

The list of industries considered in the PHMEIA and PHMEIA-r models, as well as the primary commodities they produce, is available in **Table 1**. Production by these industries is allocated between three primary Pacific halibut producing regions, as well as residual regions to account for cross-boundary effects of fishing in the Pacific Northwest:

- Alaska (AK)
- US West Coast (WOC – including WA, OR, and CA)
- British Columbia (BC)
- Rest of the United States (US-r)
- Rest of Canada (CA-r)

- Rest of the world (ROW)[1]

The adopted methodology is an extension from the multiregional SAM model for Southwest Alaska developed by Seung, Waters, and Taylor (2019) (see IPHC-2021-ECON-03 for details on adopted methodology) and draws on a few decades' worth of experience in developing IO models with applications to fisheries (see IPHC-2021-ECON-01). Model description can be also found in the economic study section of the IPHC website. The complete model documentation (project report) is available as an information paper (IPHC-2022-ECON-01).

Table 1: Industries and commodities considered in the PHMEIA and PHMEIA-r models.

	Industry	Primary commodity produced
1	Pacific halibut fishing	Pacific halibut
2	Other fish and shellfish fishing	Other fish and shellfish$^{(1)}$
3	Agriculture and natural resources (ANR)	Agriculture and natural resources
4	Construction	Construction
5	Utilities	Utilities
6	Pacific halibut processing	Seafood
7	Other fish and shellfish processing	Seafood
8	Food manufacturing (excluding seafood manufacturing)	Food (excluding seafood)$^{(2)}$
9	Manufacturing (excluding food manufacturing)	Manufactured goods (excluding food)
10	Transport	Transport
11	Wholesale	Wholesale
12	Retail	Retail
13	Services (including public administration)	Services (including public administration)
14	Saltwater charter sector$^{(3)}$	Saltwater fishing trips

Notes: $^{(1)}$In the case of Canada, other fish and shellfish commodity includes, besides wild capture production, also aquaculture output produced by the aquaculture industry that is a part of the ANR industry. Other fish and shellfish processing industry in the USA component, on the other hand, draws more on the ANR commodity that includes aquaculture output. However, this misalignment between model components is not concerning as linking these is based on the trade of aggregated seafood commodity. $^{(2)}$There is a slight misalignment between model components related to the allocation of beverage and tobacco manufacturing products that, in some cases, are considered non-durable goods and lumped with the food commodity. In the case of the USA component, this misalignment is corrected with the use of additional data available from the Annual Survey of Manufactures (ASM) (US Census, 2021). $^{(3)}$Saltwater charter sector extension included in PHMEIA-r model. Model results rely on the estimated share of the sector output that directly depends on Pacific halibut.

Demand for goods and services related to anglers' fishing trips, both guided and unguided, also contributes to the economy. In addition to economic impact related to Pacific halibut sectors, PHMEIA-derived multipliers are used to estimate economic impact related to marine angler expenditures on fishing trips (travel, lodging, other trip-related expenses) and durable goods (rods, tackle, boat purchase, other fishing equipment and accessories, second home, or additional vehicle purchase).

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[1] The ROW region in the model is considered exogenous. This implies that the trade relations with the ROW are unaffected by the changes to the Pacific halibut sectors considered in this project. While the full inclusion of the ROW component allows for assessment of impact outside Canada and the United States if trade with ROW was to be considered responsive to changes in Pacific halibut sector activity, this is not typically seen in the literature.

THE MODEL

The current PHMEIA incorporates a series of improvements to the economic impact assessment[2] model presented to the SRB019. These are as follows:

(1) The model uses an updated set of data, and estimates are now available for 2020. At the SRB019, the estimates were available up to 2019. Note that using the updated set of data implies re-estimation of the model for the entire analyzed period (2014-2020) using revised 2014-2019 data. Thus, final estimates for earlier years may have changed. However, no substantial adjustments have been recorded. Extending the model to 2020 illustrates the Covid-19 impact on the Pacific halibut fisheries.

(2) The model incorporates improved estimates of the flow of earnings related to all Pacific halibut sectors in the model. See IPHC-2021-ECON-02-R03 for the compilation of data on the flows of benefits in the Pacific halibut sectors. These are particularly pronounced in Alaska where substantial flows are identified from harvest location to buyer's headquarters, from the landing area to vessel owner residence and quota holder residence, and from sport fishing location to Charter Halibut Permit owner residence.

(3) The latest update of the PHMEIA provides refined estimates of community effects. The model informs on the county-level economic impacts in Alaska and highlights areas particularly dependent on Pacific halibut fishing-related economic activities. The current model update makes use of regional COAR (COAR, 2021) data for assessment of the spatial distribution of the processing sector contribution to the economy of each Alaskan county (an improvement from results presented in IPHC-2021-SRB019-09).

(4) The extended model (labeled PHMEIA-r) provides estimates for the saltwater charter sector that is disaggregated from the services-providing industry.

(5) The model incorporates estimates of angler expenditures on fishing trips and durable goods. These are used in conjunction with an estimate of the share of marine angler effort that relies directly on the Pacific halibut stock.

(6) The model adopts an improved production structure for commercial fishing in British Columbia making use of data on quota lease price (Castlemain, 2019).

(7) This update on the PHMEIA development is supplemented by an analysis of the formation of the price paid for Pacific halibut products by final consumers (end-users) that is intended to provide a better picture of Pacific halibut contribution to the GDP along the entire value chain, ***from the hook-to-plate*** (IPHC-2021-ECON-06-R01).[3]

It is important to note that the model continues to rely heavily on secondary data sources,[4] and as such, the results are conditional on the adopted assumptions for the components for which up-to-date data are not available (details on data inputs are available in IPHC-2021-ECON-02-R03). That said, the

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[2] While this type of assessment is typically termed "economic impact assessment," calculated alongside the impact in terms of output also the impact on employment and wages, and households' prosperity, introduce a broader socioeconomic context.

[3] This analysis will be further refined as a part of collaboration with NOAA Alaska Fisheries Science Center on market profiles for Alaska Groundfish.

[4] That is data collected by other parties, not the IPHC.

Secretariat made the best use of data collection programs of national and regional agencies, academic publications on the topic, and grey literature reporting on fisheries in Canada and the United States of America. The model also uses a set of non-fisheries data inputs described in IPHC-2021-ECON-07.

PRIMARY DATA COLLECTION

More accurate EI estimates could be achieved by incorporating into the model more extensively primary economic data collected directly from members of Pacific halibut-dependent sectors. An essential input to the SAM model is data on production structure (i.e. data on the distribution of revenue between profit and expenditure items, or the origin of production inputs). The IPHC is collecting these data directly from stakeholders since the AM096 through the web-based survey available:

- Here, for Pacific halibut commercial harvesters;
- Here, for Pacific halibut processors; and
- Here, for Pacific halibut charter business owners.

However, it should be recognized that the project was challenged by the Covid-19 pandemic that impacted the components directly dependent on the inputs from stakeholders.

STUDY OBJECTIVES

Appendix A summarizes the progress against the IPHC economic study objectives, as first defined in IPHC-2020-IM096-14, but now concluded.

PHMEIA MODEL RESULTS

The model results suggested that Pacific halibut commercial fishing's total estimated impact in 2019 amounts to USD 196 mil. (CAD 260 mil.) in households' earnings,[5] including an estimated USD 52.5 mil (CAD 69.7 mil) in direct earnings in the Pacific halibut fishing sectors and USD 12.2 mil. (CAD 16.1 mil.) in the processing sector. This translates to USD 179 mil (CAD 238 mil.) in household income (**Table 2**). Income reflects earnings adjusted for any transfers, including interregional spillovers, i.e. income is related to the place of residence, not the place of work.

Detailed results are provided for 2019 as this represents a more typical year for the economy. The estimates for 2020 suggest that Pacific halibut commercial sectors' contribution to households decreased by 25%, and output related to Pacific halibut commercial fishing decreased by 27%. **Figure 1** depicts EI estimates for Pacific halibut commercial fishing for 2014-2020 in comparison with landed value. To make the values comparable over time, the estimates are adjusted for inflation.[6]

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[5] Earnings include both employee compensation and proprietors' income.

[6] Using the GDP deflator data published by the Organisation for Economic Co-operation and Development (OECD, 2021). The estimates are expressed in 2020 USD.

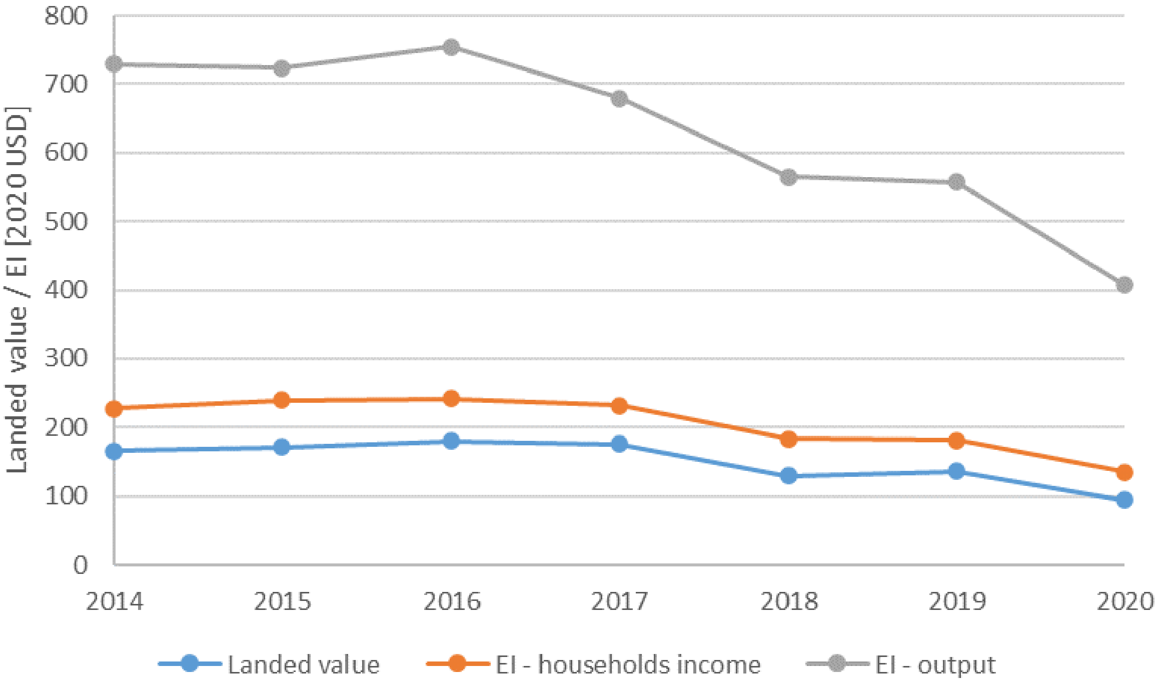

Figure 1: Pacific halibut commercial fishing EI estimates for 2014-2020 in comparison with landed value in mil 2020 USD.

PHMEIA model also informs on the economic impact by county (limited to Alaska), highlighting regions where communities may be particularly vulnerable to changes in the access to the Pacific halibut resource. In 2019, from USD 23.7 mil. (CAD 31.4 mil.) of direct earnings from Pacific halibut commercial sectors in Alaska, 70% was retained in Alaska.[7] These earnings were unevenly distributed between Alaskan counties (**Figure 2**). The most direct earnings per dollar landed are estimated for Ketchikan Gateway, Petersburg and Sitka countries, while the least for Aleutians East, Yakutat and Aleutians West counties. Low earnings per 1 USD of Pacific halibut landed in the county are a result of the outflow of earnings related to vessels' home base, vessels' ownership and quota ownership, processing locations, and processing companies' ownership.

The total contribution of the Pacific halibut charter sector to household income is assessed at USD 42 mil. (CAD 56 mil.) for 2019. Accounting for angler expenditures adds another USD 108 mil. (CAD 143 mil.) to the economic impact of the recreational sector. This translates into 19% less for the charter sector and 45% less for the recreational sector overall in comparison with the commercial sector when looking at impact per USD of landed value (for the commercial sector) and USD spent (for the

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[7] Community effects assessment is currently limited to Alaska. The feasibility of a similar assessment for other regions is under investigation. For example, Canadian quotas (L fishery), which are vessel-based, can be allocated based on vessel owner's residency, searchable in the Canadian Register of Vessels available through Transport Canada's Vessel Registration Query System.

recreational sector, including trip costs and expenditures on durable goods). This is not surprising since the commercial sector's production supports not only suppliers to the harvesting sector, but also the forward-linked processing sector (thus, also households employed by these sectors). Recreational sector results, on the other hand, to a large degree are driven by expenditures on goods that are often imported, consequently supporting households elsewhere.

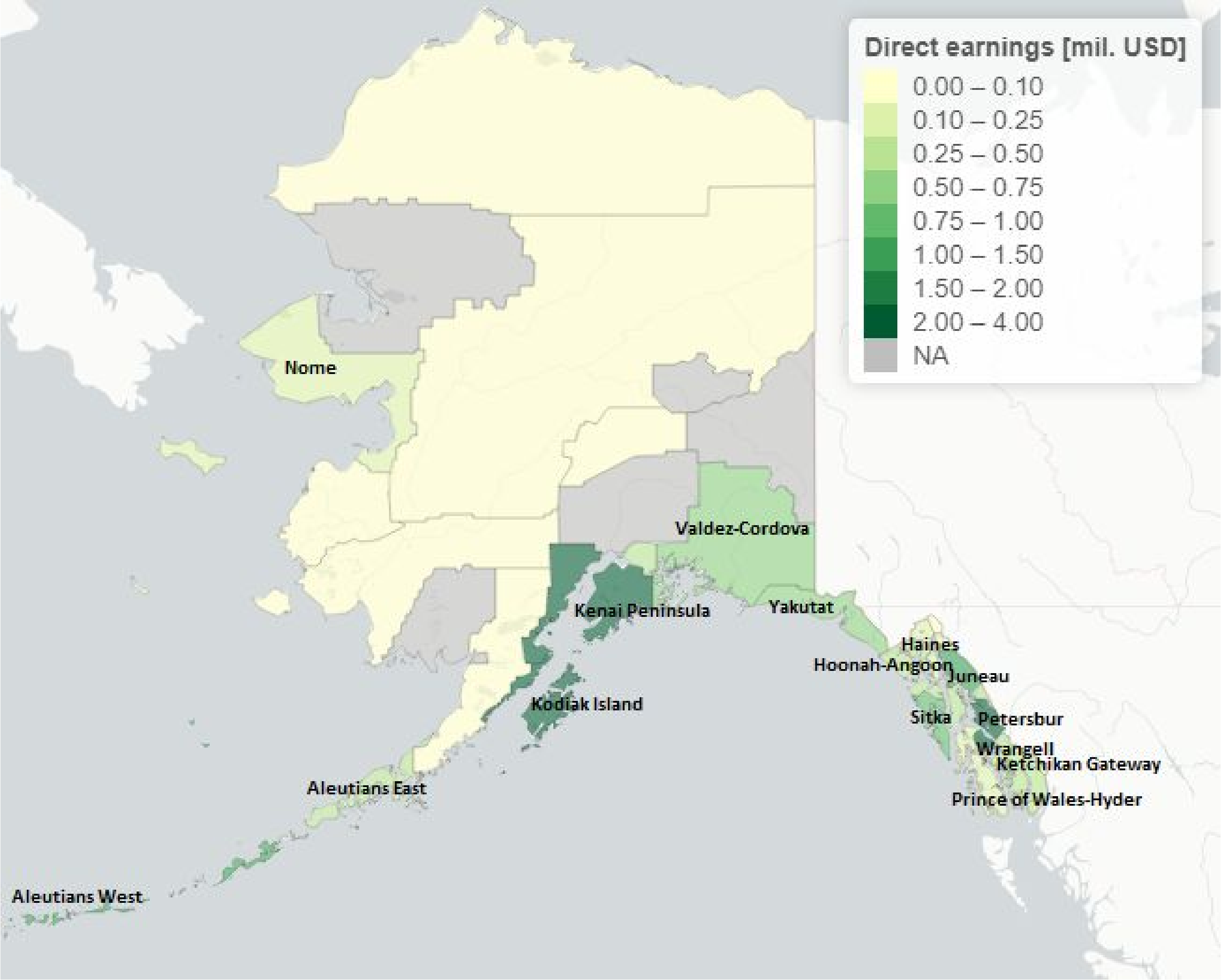
A somewhat different picture emerges when comparing EI per pound of Pacific halibut removal counted against allowed catch by area in the stock assessment. This measure is 63% higher for the charter sector, and more than double for the recreational sector overall when compared with the commercial sector. These differences, however, are less pronounced when focusing only on the EI retained within the harvest region (56% and 139%, respectively).

It should also be noted, however, that this analysis should not be used as an argument in sectoral allocations discussions because, as a snapshot analysis, it does not reflect the implications of shifting supply-demand balance. Participation in sport fishing do not typically scale in a linear fashion with changes to harvest limits.

Table 2: Economic impact on households

Economic impact	**Unit**	**Commercial**	**Charter**(1)	**Recreational**
EI on households	Total in mil. USD/CAD	179.1/237.6	42.2/55.9	146.9/194.9
EI locally (excludes spillovers)	Total in mil. USD/CAD	114.1/151.4	27.6/36.6	79.0/104.9
EI on households	USD/CAD per 1 USD/CAD of landed value/ 1 USD/CAD spent	1.34	1.08	0.74(2)
EI locally (excludes spillovers)	USD/CAD per 1 USD/CAD of landed value/ 1 USD/CAD spent	0.85	0.71	0.40(2)
EI on households	USD/CAD per 1 lb of removals	7.4/9/8	12.0/15.9(3)	20.9/27.7
EI locally (excludes spillovers)	USD/CAD per 1 lb of removals	4.7/6.2	7.3/9.7(3)	11.2/14.9

Notes: (1) This includes only the economic impact generated through businesses offering charter trips, i.e., it excludes the impact of angler expenditures other than charter fees. (2)In A considerable share of angler expenditures originates from import, which drives the estimate down. (3)Charter sector impact per 1 lb of removals was based on EI on households for Alaska where removals estimates are clearly divided between guided and unguided sectors.

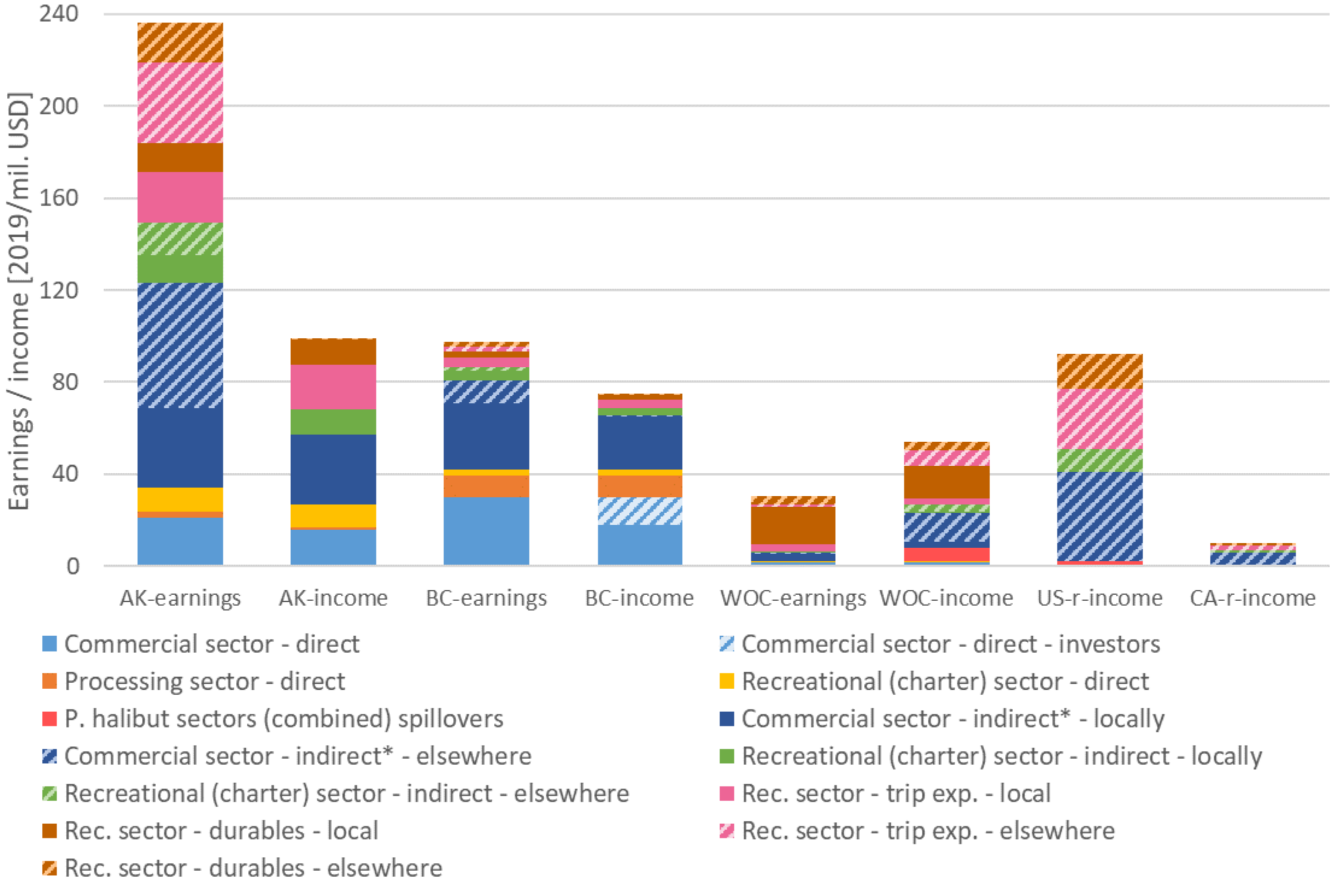


Notes: Alaska retains 70% of direct earnings within the state.

Figure 2: County-level estimates of direct earnings in the Pacific halibut commercial sectors in Alaska in 2019.

Figure 3 depicts the impact of Pacific halibut commercial and recreational fishing on household earnings and income, highlighting the importance of considering cross-regional effects. Earnings estimates (bars with '-earnings' suffix) summarize economic impact by place of work (i.e., where the fishing activity occurs). Income estimates (bars with '-income' suffix) reflect earnings after adjustments for cross-regional flows, i.e., provide estimates by the place of residence of workers, business owners, or owners of production factors (i.e., quota or permit owners).

Results in terms of output, depicted in a similar fashion, are available in **Appendix B**.



Notes: Legend description available in Box 1. Figure omits the impact on ROW (marginal).*Commercial indirect effects include processing.

Figure 3: Pacific halibut impact on household earnings and income (2019).

Box 1: Figure 3 legend description

a) **Commercial sector – direct**: includes earnings and income directly attributable to the Pacific halibut commercial fishing sector within the indicated region.
b) **Commercial sector - direct – investors**: indicates the share of the income described in **Commercial sector – direct** that is retained in the region, but flows from the fishing sector to investors. This component captures the value of the leased quota paid to non-fishing stakeholders.
c) **Processing sector – direct**: includes earnings and income directly attributable to the Pacific halibut processing sector within the indicated region.
d) **Recreational (charter) sector – direct**: includes earnings and income directly attributable to businesses offering Pacific halibut sport fishing within the indicated region.
e) **P. halibut sectors (combined) spillovers**: include income attributable to Pacific halibut sectors (commercial fishing, processing, sport fishing) that leaks from the region where the activity occurs as a result of cross-regional flows.
f) **Commercial sector - indirect** - locally**: includes combined indirect and induced impact on earnings and income resulting from changes in business-to-business transactions and personal income caused by Pacific halibut commercial and processing sector. This component includes only EI resulting from fishing activity in the specified region occurring locally (i.e., in the same region).
g) **Commercial sector - indirect** - elsewhere**: as above, but includes impact on earnings resulting from fishing activity in the specified region occurring elsewhere (‘-earnings’ bars), and impact on income resulting from fishing activity elsewhere realized in the specified region (‘-income’ bars).
h) **Recreational (charter) sector - indirect – locally**: includes combined indirect and induced impact on earnings and income resulting from changes in business-to-business transactions and personal income caused by the Pacific halibut charter sector. This component includes only EI resulting from fishing activity in the specified region occurring locally (i.e., in the same region).
i) **Recreational (charter) sector - indirect – elsewhere**: as above, but includes impact on earnings resulting from fishing activity in the specified region occurring elsewhere (‘-earnings bars), and impact on income resulting from fishing activity elsewhere realized in the specified region (‘-region’ bars).
j) **Rec. sector - trip exp. – local**: includes an estimate of the economic contribution of Pacific halibut-dependent angler trip expenditures on earnings and income that is realized locally, i.e., within the region where the fishing activity is occurring.
k) **Rec. sector - trip exp. – elsewhere**: includes an estimate of the economic contribution of Pacific halibut-dependent angler trip expenditures to earnings elsewhere (‘-earnings’ bars) or income within the indicated region realized as a result of fishing activity elsewhere (‘-income’ bars).
l) **Rec. sector - durables – local**: includes an estimate of the economic contribution of Pacific halibut-dependent angler expenditures on durable goods on earnings and income that is realized locally, i.e., within the region where the fishing activity is occurring.
m) **Rec. sector - durables – elsewhere**: includes an estimate of the economic contribution of Pacific halibut-dependent angler expenditures on durable goods to earnings elsewhere (‘-earnings’ bars) or income within the indicated region realized as a result of fishing activity elsewhere (‘-income’ bars).

ECONOMIC IMPACT VISUALIZATION TOOL

The section on PHMEIA and PHMEIA-r results focuses on the economic impact on households. However, the EI can be expressed with various other policy-relevant metrics. In addition to household welfare impacts, PHMEIA provides estimates in terms of output, compensation of employees, contribution to the gross domestic product (GDP), and employment opportunities. Regulators and stakeholders may be also interested in assessment of various combinations of regional allocations of mortality limits, impact on a subset of sectors, or looking for estimates of localized impacts disproportionally hurting a subset of communities. The full set of PHMEIA and PHMEIA-r results can be viewed through our economic impact visualization tool.[8] The use of this interactive web-based application can be guided by the PHMEIA app manual (IPHC-2021-ECON-04-R02).

ECONOMIC IMPACT OF SUBSISTENCE FISHING

Previous research suggested that noncommercial or nonmarket-oriented fisheries' contribution to national GDP is often grossly underestimated, particularly in developing countries (e.g., Zeller, Booth, and Pauly 2006). Subsistence fishing is also important in traditional economies, often built around indigenous communities. Wolfe and Walker (1987) found that there is a significant relationship between the percentage of the native population in the community and reliance on wildlife as a food source in Alaska. However, no comprehensive assessment of the economic contribution of the subsistence fisheries to the Pacific northwest is available. The only identified study, published in 2000 by Wolfe (2000), suggests that the replacement value of the wild food harvests in rural Alaska may be between 131.1 and 218.6 million dollars, but it does not distinguish between different resources and assumes equal replacement expense per lb. Aslaksen et al. (2008) proposed an updated estimate for 2008 based on the same volume, noting that transportation and food prices have risen significantly between 2000 and 2008, and USD 7 a pound is a more realistic replacement value. This gives the total value of USD 306 million, but the approach relies upon the existence of a like-for-like replacement food (in terms of taste and nutritional value), which is arguably difficult to accept in many cases (Haener *et al.*, 2001) and ignores the deep cultural and traditional context of the Pacific halibut in particular (Wolfe, 2002). A more recent study by Krieg, Holen, and Koster (2009) suggests that some communities may be particularly dependent on wildlife, consuming annually up to 899 lbs per person, but no monetary estimates are derived. Moreover, although previous research points to the presence of sharing and bartering behavior that occurs in many communities (Wolfe, 2002; Szymkowiak and Kasperski, 2020), the economic and cultural values of these networks have yet to be thoroughly explored.

The subsistence component of the study is a subject of a collaborative project with NOAA Alaska Fisheries Science Center: Fish, Food, and Fun - Exploring the Nexus of Subsistence, Personal Use, and Recreational Fisheries in Alaska (SPURF project).

FINAL REMARKS

The PHMEIA model fosters stakeholders' better understanding of a broad scope of regional impacts of the Pacific halibut resource. Leveraging multiple sources of socioeconomic data, it provides essential input for designing policies with desired effects depending on regulators' priorities. By tracing the socioeconomic impacts cross-regionally, the model accommodates the transboundary nature of the Pacific halibut and supports joint management of a shared resource, such as the case of collective management by the IPHC. Moreover, the study informs on the vulnerability of communities to changes in the state of the Pacific halibut stock throughout its range, highlighting regions particularly dependent on economic activities that rely on Pacific halibut. A good understanding of the localized effects is pivotal to policymakers who are often concerned about community impacts, particularly in terms of

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[8] The tool is available at: http://iphcecon.westus2.cloudapp.azure.com:3838/ModelApp_azure/ (full link for printed version).

impact on employment opportunities and households' welfare. Fisheries policies have a long history of disproportionally hurting smaller communities, often because potential adverse effects were not sufficiently assessed (Carothers, Lew, and Sepez 2010; Szymkowiak, Kasperski, and Lew 2019).

The results suggest that the revenue generated by Pacific halibut at the harvest stage accounts for only a fraction of economic activity that would be forgone if the resource was not available to fishers in the Pacific Northwest. On average, in 2019, one USD/CAD of Pacific halibut commercial landings was linked to over four USD/CAD-worth economic activity in Canada and the United States and contributed USD/CAD 1.3 to households. In the recreational sector, one USD/CAD spent by recreational anglers was linked to USD/CAD 2.3 circulating in the economy and USD/CAD 0.7 impact on households. The total economic activity linked to Pacific halibut sectors is estimated at USD 1,014 mil. (CAD 1,346 mil), and contribution to households at USD 326 mil. (CAD 432 mil.), highlighting how important Pacific halibut is to regional economies. The estimates of county-level earnings in Alaska were unevenly distributed, but most importantly to resource managers and policymakers, the model suggests that the local earnings were often not aligned with how much was landed within the county.

Understanding the complex interactions within the fisheries sectors is now more important than ever considering how globalized it is becoming. Local products compete on the market with a large variety of imported seafood. High exposure to international markets makes seafood accessibility fragile to perturbations, as shown by the covid-19 outbreak (OECD, 2020). Pacific halibut contribution to households' income dropped by a quarter throughout the pandemic. While signs of strong recovery were present in 2021 (Fry, 2021), the study calls attention to Pacific halibut sectors' exposure to external factors beyond stock condition. Fisheries are also at the forefront of exposure to the accelerating impacts of climate change. A rapid increase in water temperature of the coast of Alaska, termed *the blob*, is affecting fisheries (Cheung and Frölicher, 2020) and may have a profound impact on Pacific halibut distribution.

Integrating economic approaches with stock assessment and management strategy evaluation (MSE) can assist fisheries in bridging the gap between the current and the optimal economic performance without compromising the stock biological sustainability. Economic performance metrics presented alongside already developed biological/ecological performance metrics bring the human dimension to the research products, and could add to the IPHC's portfolio of tools for assessing policy-oriented issues (as requested by the Commission, IPHC-2021-AM097-R, AM097-Req.02). Moreover, the study can also inform on socioeconomic drivers (human behavior, human organization) that affect the dynamics of fisheries, and thus contribute to improved accuracy of the stock assessment and the MSE (Lynch, Methot and Link, 2018). As such, it can contribute to research integration at the IPHC (as presented in IPHC-2021-IM097-12) and provide a complementary resource for the development of harvest control rules.

Lastly, while the quantitative analysis is conducted with respect to components that involve monetary transactions, Pacific halibut's value is also in its contribution to the diet through subsistence fisheries and importance to the traditional users of the resource. To native people, traditional fisheries constitute a vital aspect of local identity and a major factor in cohesion. One can also consider the Pacific halibut's existence value as an iconic fish of the Pacific Northwest. While these elements are not quantified at this time, recognizing such an all-encompassing definition of the Pacific halibut resource contribution, the project echoes a broader call to include the human dimension into the research on the impact of management decisions, as well as changes in environmental or stock conditions.

RECOMMENDATION/S

That the SRB:

1) **NOTE** paper IPHC-2022-SRB020-09 which provides the status of the Pacific halibut multiregional economic impact assessment (PHMEIA), now concluded.

LITERATURE

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Appendix A

The study objectives – summary of progress and notes on outputs

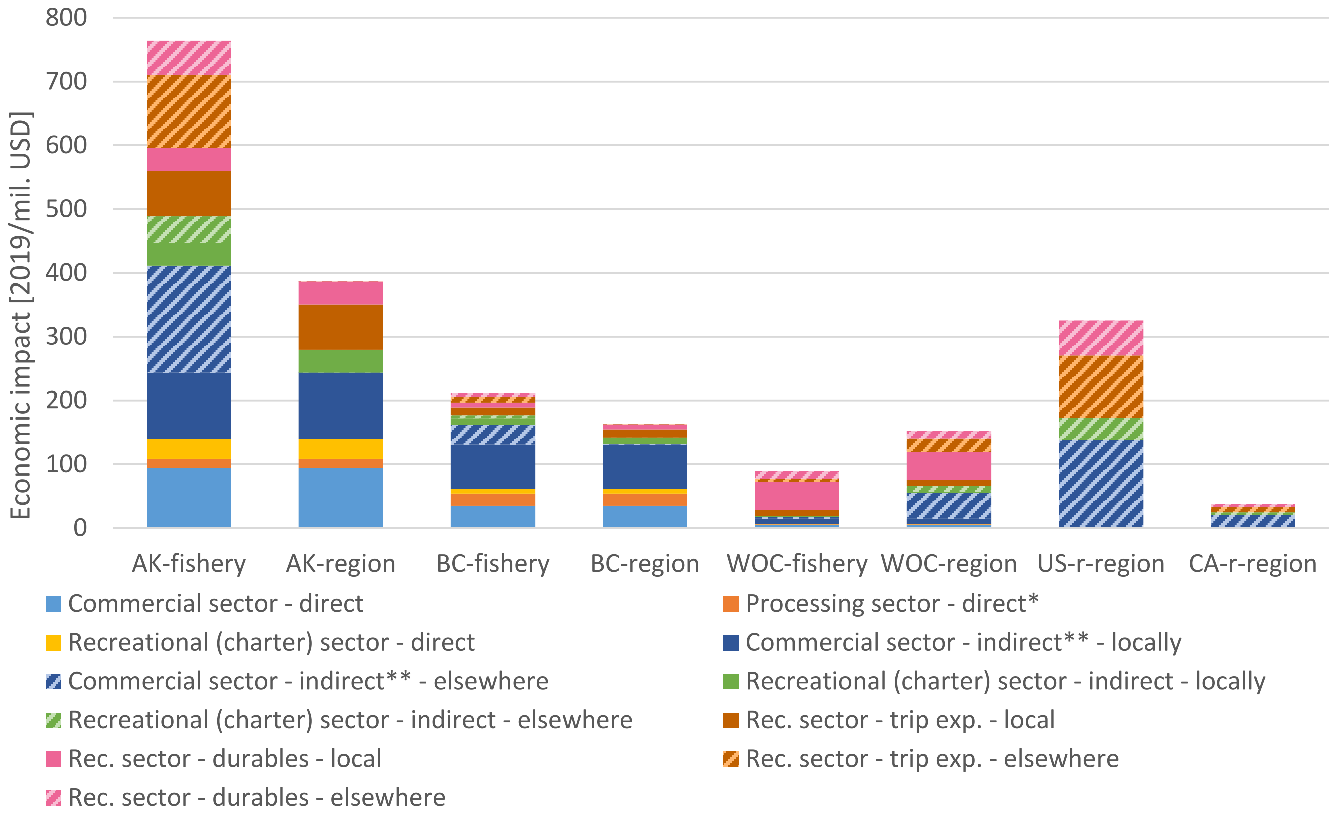
Objective	Status*	Output
Item 1: Survey of previous studies and existing information	---	---
Item 1.a: Literature review	**COMPLETED**	See IPHC-2021-ECON-01 (last revised on 2/9/2021) and project report (IPHC-2022-ECON-01)
Item 1.b: Description of ongoing regular data collection programs	**COMPLETED**	See IPHC-2021-ECON-02-R03 (last revised on 12/31/2021) and project report (IPHC-2022-ECON-01)
Item 1.c: Collection of primary data – commercial sector survey	**IN PROGRESS**	Developed in response to the identified data gaps: Commercial Vessel Expenditures Survey Processor Expenditures Survey Survey results available via IPHC economic survey results app
Item 1.d: Collection of primary data – charter sector survey	**IN PROGRESS**	Developed in response to the identified data gaps: Charter Sector Expenditures Survey Survey results available via IPHC economic survey results app
Item 2: Comprehensive qualitative structural description of the current economics of the Pacific halibut resource	---	---
Item 2.a: Description of the economics of the Pacific halibut commercial sector	**COMPLETED**	See Economic Research section of the IPHC website and project report (IPHC-2022-ECON-01)
Item 2.b: Description of the economics of the Pacific halibut recreational sector	**COMPLETED**	See Economic Research section of the IPHC website and project report (IPHC-2022-ECON-01)
Item 2.c: Description of the economics of other Pacific halibut sectors (bycatch, subsistence, ceremonial, research, non-directed)	**IN PROGRESS**	See section on subsistence and ceremonial fishing in project report (IPHC-2022-ECON-01) The economic impact of bycatch (U32) was considered in the size limits paper (IPHC-2021-AM097-09) Note also additional work proposed in the *IPHC's 5-year program of integrated research and monitoring (2022-26)* (IPHC-2021-IM097-12)

Item 3: Quantitative analysis of the economic impact of the directed Pacific halibut fishery	**---**	**---**
Item 3.a: Methodology – a model of the economy	**COMPLETED**	See details in project report (IPHC-2022-ECON-01)
Item 3.b: Methodology – inclusion of the commercial sector in the SAM	**COMPLETED(1)**	See project report (IPHC-2022-ECON-01)and Economic Research section of the IPHC website
Item 3.c: Methodology – inclusion of the recreational sector in the SAM	**COMPLETED(1)**	See project report (IPHC-2022-ECON-01)and Economic Research section of the IPHC website
Item 3.d: Methodology – economic value of the subsistence use	**IN PROGRESS**	Subject of collaboration with NOAA Alaska Fisheries Science Center (Fish, Food, and Fun: Exploring the Nexus of Subsistence, Personal Use, and Recreational Fisheries (SPURFs) in Alaska)
Item 4: Account of the geography of the economic impact of the Pacific halibut sectors	**---**	**---**
Item 4.a: Visualization of region-specific economic impacts	**COMPLETED(1)**	See online economic impact visualization tool
Item 5: Analysis of the community impacts of the Pacific halibut fishery throughout its range, including all user groups	**---**	**---**
Item 5.a: Community impacts assessment of the Pacific halibut fishery	**COMPLETED(1)**	See project report (IPHC-2022-ECON-01) See economic impact visualization tool (*Community impacts in AK* tab) Further improvement of spatial granularity of the estimates was proposed in the *IPHC's 5-year program of integrated research and monitoring (2022-26)*
Item 6: Summary of the methodology and results of the IPHC study in comparison to other economic data and reports for the Pacific halibut resource, other regional fisheries, and comparable seafood industry sectors	**---**	**---**
Item 6.a: Putting results into perspective	**COMPLETED(1)**	See project report (IPHC-2022-ECON-01)

* All items marked as COMPLETED are subject to updates based on the direction of the project and the evolution of the situation in the Pacific halibut fisheries. (1)Subject to changes based on the data collected through the IPHC economic survey and publication or revision of relevant secondary data.

Appendix B
Pacific halibut economic impact in terms of output

Figure 4 depicts the economic impact of Pacific halibut commercial and recreational fishing in terms of output. The figure distinguishes between the impact by fishery (i.e., by region where the fishing activity occurs, bars with '-fishery' suffix) and impact by region (i.e., by region where the impact is realized; bars with '-region' suffix).



Notes: The figure omits the impact on the ROW (marginal). *Adjusted to the wholesale mark-up and does not include fish buying cost; **Commercial indirect impact includes processing.

Figure 4: Pacific halibut economic impact in terms of output (2019).

The figure specifies the following components:

a. **Commercial sector – direct**: includes direct output of the Pacific halibut commercial fishing sector, which is equivalent to the landing value or value of sales by Pacific halibut directed commercial fisheries. This component is equal in the 'by fishery' and 'by region' EI estimate.
b. **Processing sector – direct**: includes direct output of the Pacific halibut processing sector (wholesale value) adjusted to include only the wholesale mark-up. This means that the estimate does not include the fish buying cost, avoiding this way double counting the landing value of the Pacific halibut commercial sector in the EI estimate. This component is equal in the 'by fishery' and 'by region' EI estimate.

c. **Recreational (charter) sector – direct**: includes value of direct sales by businesses offering services in the form of guided Pacific halibut recreational (sport) fishing (charter boats, fly-in loges, package deals, etc.). The estimate intends to capture the share of output by the sport fishing sector that depends on the Pacific halibut resource availability, i.e., it is adjusted for mixed target species offers. This component is equal in the 'by fishery' and 'by region' EI estimate.
d. **Commercial sector - indirect** - locally**: includes combined indirect and induced impact resulting from changes in business-to-business transactions and personal income caused by Pacific halibut commercial and processing sector. This component includes only EI resulting from fishing activity in the specified region occurring locally (i.e., in the same region). This component is equal in the 'by fishery' and 'by region' EI estimate.
e. **Commercial sector - indirect** - elsewhere**: as above, but includes EI resulting from fishing activity in the specified region occurring elsewhere (i.e., in the regions other than the fishing area specified; '-fishery' bars), and EI resulting from fishing activity elsewhere occurring in the specified region ('-region' bars).
f. **Recreational (charter) sector - indirect – locally**: includes combined indirect and induced impact resulting from changes in business-to-business transactions and personal income caused by the Pacific halibut charter sector. This component includes only EI resulting from fishing activity in the specified region occurring locally (i.e., in the same region). This component is equal in the 'by fishery' and 'by region' EI estimate.
g. **Recreational (charter) sector - indirect – elsewhere**: as above, but includes EI resulting from fishing activity in the specified region occurring elsewhere (i.e., in the regions other than the fishing area specified; '-fishery' bars), and EI resulting from fishing activity elsewhere occurring in the specified region ('-region' bars).
h. **Rec. sector - trip exp. – local**: includes an estimate of the economic contribution of marine angler trip expenditures (travel, lodging, other trip-related expenses) that is realized locally, i.e., within the region where the fishing activity is occurring, and can be attributed to Pacific halibut fishing opportunities. This component is equal in the 'by fishery' and 'by region' EI estimate.
i. **Rec. sector - trip exp. – elsewhere**: includes an estimate of the economic impact of marine angler trip expenditures (share attributed to Pacific halibut) that is realized elsewhere ('-fishery' bars) or realized within the indicated region as a result of fishing activity elsewhere ('-region' bars).
j. **Rec. sector - durables – local**: includes an estimate of the economic contribution of marine angler expenditures on durable goods (rods, tackle, bout purchase, other fishing equipment and accessories, second home, or additional vehicle purchase) that is occurring locally, i.e., within the region where the fishing activity is occurring, and can be attributed to Pacific halibut fishing opportunities. This component is equal in the 'by fishery' and 'by region' EI estimate.
k. **Rec. sector - durables – elsewhere**: includes an estimate of the economic impact of marine angler expenditures on durable goods (share attributed to Pacific halibut) that is realized elsewhere ('-fishery' bars) or realized within the indicated region as a result of fishing activity elsewhere ('-region' bars).

INTERNATIONAL PACIFIC HALIBUT COMMISSION 5-YEAR PROGRAM OF INTEGRATED RESEARCH AND MONITORING (2022-26)

PREPARED BY: IPHC SECRETARIAT (D. WILSON, J. PLANAS, I. STEWART, A. HICKS, B. HUTNICZAK, R. WEBSTER, J. JANNOT; 13 MAY 2022)

PURPOSE

To provide the SRB with the current draft of the new IPHC 5-year program of integrated research and monitoring (2022-26)

BACKGROUND

The IPHC has a long-standing history (since 1923) of collecting data, undertaking research, and stock assessment, devoted to describing and understanding the Pacific halibut (*Hippoglossus stenolepis*) stock and the fisheries that interact with it.

The IPHC Secretariat conducts activities to address key issues identified by the Commission, its subsidiary bodies, the broader stakeholder community, and of course, the IPHC Secretariat itself. The process of identifying, developing, and implementing our science-based activities involves several steps that are circular in nature, but result in clear project activities and associated deliverables. The process includes developing and proposing projects based on direct input from the Commission, the experience of the IPHC Secretariat given our broad understanding of the resource and its associated fisheries, and concurrent consideration by relevant IPHC subsidiary bodies, and where deemed necessary, additional external peer review.

An overarching goal of the IPHC 5-Year Program of Research and Monitoring (2022-26) is therefore to promote integration and synergies among the various science and research activities of the IPHC Secretariat in order to improve our knowledge of key inputs into the Pacific halibut stock assessment, and Management Strategy Evaluation (MSE) processes.

DISCUSSION

The SRB is invited to again review and provide additional guidance to assist the IPHC Secretariat finalise the draft plan provided at Appendix A.

RECOMMENDATION

That the SRB:

1) **NOTE** paper IPHC-2022-SRB020-10 which provides the current draft of the new IPHC 5-year program of integrated research and monitoring (2022-26).

APPENDICES

Appendix A: DRAFT: IPHC 5-Year program of integrated research and monitoring (2022-26) (D. Wilson, J. Planas, I. Stewart, A. Hicks, B. Hutniczak, R. Webster, & J. Jannot)

INTERNATIONAL PACIFIC HALIBUT COMMISSION

5-YEAR PROGRAM OF INTEGRATED RESEARCH AND MONITORING

(2022 - 2026)

INTERNATIONAL PACIFIC
HALIBUT COMMISSION

Commissioners

Canada	United States of America
Paul Ryall	Glenn Merrill
Neil Davis	Robert Alverson
Peter DeGreef	Richard Yamada

Executive Director

David T. Wilson, Ph.D.

BIBLIOGRAPHIC ENTRY

IPHC 2022. International Pacific Halibut Commission 5-Year program of integrated research and monitoring (2022-26). Seattle, WA, U.S.A. *IPHC–2022-5YPIRM, 52 pp.*

INTERNATIONAL PACIFIC
HALIBUT COMMISSION

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DRAFT

ACRONYMS

<<<To be completed>>>

DEFINITIONS

A set of working definitions are provided in the IPHC Glossary of Terms and abbreviations: https://iphc.int/the-commission/glossary-of-terms-and-abbreviations

TABLE OF CONTENTS

EXECUTIVE SUMMARY

To be developed once draft below is finalised

1. Introduction

The International Pacific Halibut Commission (IPHC) is a public international organization so designated via Presidential Executive Order 11059, and established by a Convention between Canada and the United States of America. The IPHC Convention was concluded in 1923 and entered into force that same year. The Convention has been revised several times since, to extend the Commission's authority and meet new conditions in the fishery. The most recent change occurred in 1979 and involved an amendment to the 1953 Halibut Convention. The amendment, termed a "protocol", was precipitated in 1976 by Canada and the United States of America extending their jurisdiction over fisheries resources to 200 miles. The 1979 Protocol along with the U.S. legislation that gave effect to the Protocol (Northern Pacific Halibut Act of 1982) has affected the way the fisheries are conducted, and redefined the role of IPHC in the management of the fishery. Canada does not require specific enabling legislation to implement the protocol.

The basic texts of the Commission are available on the IPHC website: https://www.iphc.int/the-commission, and prescribe the mission of the organization as:

*"….. **to develop the stocks of [Pacific] halibut in the Convention waters to those levels which will permit the optimum yield from the fishery and to maintain the stocks at those levels**. ….." IPHC Convention*, Article I, sub-article I, para. 2). The IPHC Convention Area is detailed in Fig. 1.

The IPHC Secretariat, formed in support the Commission's activities, is based in Seattle, WA, USA. As its shared vision, ***the IPHC Secretariat aims to deliver positive economic, environmental, and social outcomes for the Pacific halibut resource for Canada and the U.S.A. through the application of rigorous science, innovation, and the implementation of international best practice.***

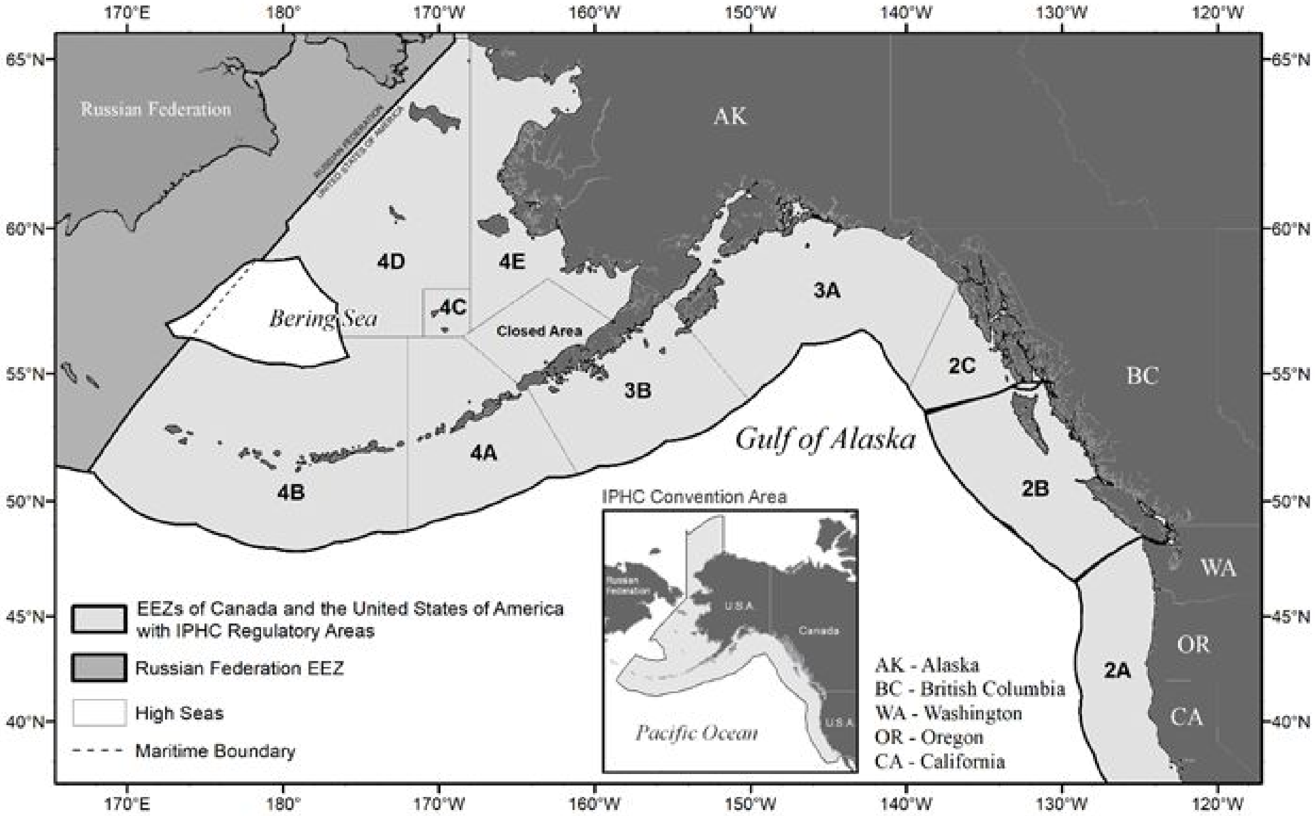

Figure 1. Map of the IPHC Convention Area (map insert) and IPHC Regulatory Areas.

2. Objectives

The IPHC has a long-standing history (since 1923) of collecting data, undertaking research, and stock assessment, devoted to describing and understanding the Pacific halibut (*Hippoglossus stenolepis*) stock and the fisheries that interact with it.

The IPHC Secretariat conducts activities to address key issues identified by the Commission, its subsidiary bodies, the broader stakeholder community, and of course, the IPHC Secretariat itself. The process of identifying, developing, and implementing our science-based activities involves several steps that are circular in nature, but result in clear research activities and associated deliverables. The process includes developing and proposing projects based on direct input from the Commission, the experience of the IPHC Secretariat given our broad understanding of the resource and its associated fisheries, and concurrent consideration by relevant IPHC subsidiary bodies, and where deemed necessary, additional external peer review.

Over the last five years (2017-2021), the research conducted by the IPHC Secretariat has been guided by a 5-Year Biological and Ecosystem Science Research Plan (IPHC–2019–BESRP-5YP) that aimed at improving knowledge on the biology of Pacific halibut in order to reduce uncertainty in stock assessment and in the management strategy evaluation (MSE) process. The IPHC-2019-BESRP-5YP contemplated research activities in five focal areas, namely Migration and Distribution, Reproduction, Growth and Physiological Condition, Discard Mortality Rates and Survival, and Genetics and Genomics. Research activities were highly integrated with the needs of stock assessment and MSE by their careful alignment with biological uncertainties and parameters and the resulting prioritization (Appendix II). The outcomes of the IPHC-2019-BESRP-5YP have provided key inputs into stock assessment and the MSE process and, importantly, have provided foundational information for the successful pursuit of continuing and novel objectives within the new 5-Year Program of Integrated Research and Monitoring (2022-2026) (5YPIRM) (Appendix II).

[To be added: 2nd Performance Review of the IPHC process and relevant recommendations]

The work outlined in this document builds on the previous 5-year research plan, closing completed projects, extending efforts where needed, and adding new avenues in response to new information. Appendix II provides a detailed summary of the previous plan and the status of the work specific undertaken. Key highlights relevant to the stock assessment and MSE include:

- Completion of the genetic assay for determining sex from tissue samples, processing of commercial fishery samples collected during 2017-2020, inclusion of this information in the 2019 and subsequent stock assessments, and transfer of this effort from research to ongoing monitoring.
- Incremental progress toward population-level sampling and analysis of maturity and fecundity.
- Continued development of the understanding of physiological and environmental mechanisms determining growth for future field application.
- Published estimates of discard mortality rates for use in data processing and management accounting.
- Collection of genetic samples and genome sequencing to provide a basis for ongoing evaluation of stock structure at population-level and finer scales.

All of these research areas continue to represent critical areas of uncertainty in the stock assessment and thus are closely linked to management performance. The previous 5-year plan was successful in either providing direct new information to the stock assessment or building the foundation for the collection/analysis of such information in this updated plan. As noted below, some new priorities have emerged and others have evolved based on the work completed to date. The incorporation of research objectives in the 5YPIRM that address climate change as a factor influencing Pacific halibut biology and ecology as well as fishery performance and dynamics constitutes a timely and relevant contribution towards advancing IPHC-led research to the forefront of fisheries science.

An **overarching goal** of the *IPHC 5-Year Program of integrated research and monitoring (2021-26)* is therefore to promote integration and synergies among the various research and support activities of the IPHC Secretariat in order to improve our knowledge of key inputs into the Pacific halibut stock assessment and Management Strategy Evaluation (MSE) processes, in order to provided the best possible advice for management decision making processes.

Along with the implementation of the short- and medium-term activities contemplated in this *IPHC 5-Year Program of Integrated Research and monitoring (2022-26)*, and in pursuit of the overarching objective, the IPHC Secretariat will also aim to undertake:

1) Cutting-edge research programs in fisheries research in support of fisheries management of Pacific halibut;
2) Groundbreaking methodological research;
3) High impact and applied research;
4) Establish new collaborative agreements and interactions with research agencies and academic institutions;
5) To promote the international involvement of the IPHC by continued and new participation in international scientific organizations and by leading international science and research collaborations.
6) To incorporate talented students and early researchers in research activities contemplated.

The research and monitoring activities conducted by the IPHC Secretariat are directed towards fulfilling the following four (4) **objectives** within areas of data collection, biological and ecological research, stock assessment, and Management Strategy Evaluation. In addition, the IPHC responds to Commission requests for additional inputs to management and policy development. The overall aim is to provide a program of integrated research and monitoring (Fig 2):

Research

1) **Stock assessment**: apply the resulting knowledge to improve the accuracy of and reduce uncertainty in current stock assessment models and the stock management advice provided to the Commission;
2) **Management Strategy Evaluation (MSE)**: to provide inputs that inform the MSE process, which will evaluate the consequences of alternative management options, known as harvest strategies;
3) **Biology and Ecology**: identify and assess critical knowledge gaps in the biology and ecology of Pacific halibut within its known range, including the influence of environmental conditions on population and fishery dynamics;

Monitoring

4) **Monitoring**: collect representative fishery dependent and fishery-independent data on the distribution, abundance, and demographics of Pacific halibut through ongoing monitoring activities;

Management support

5) **Management support**: respond to Commission requests for any additional information supporting management and policy development.

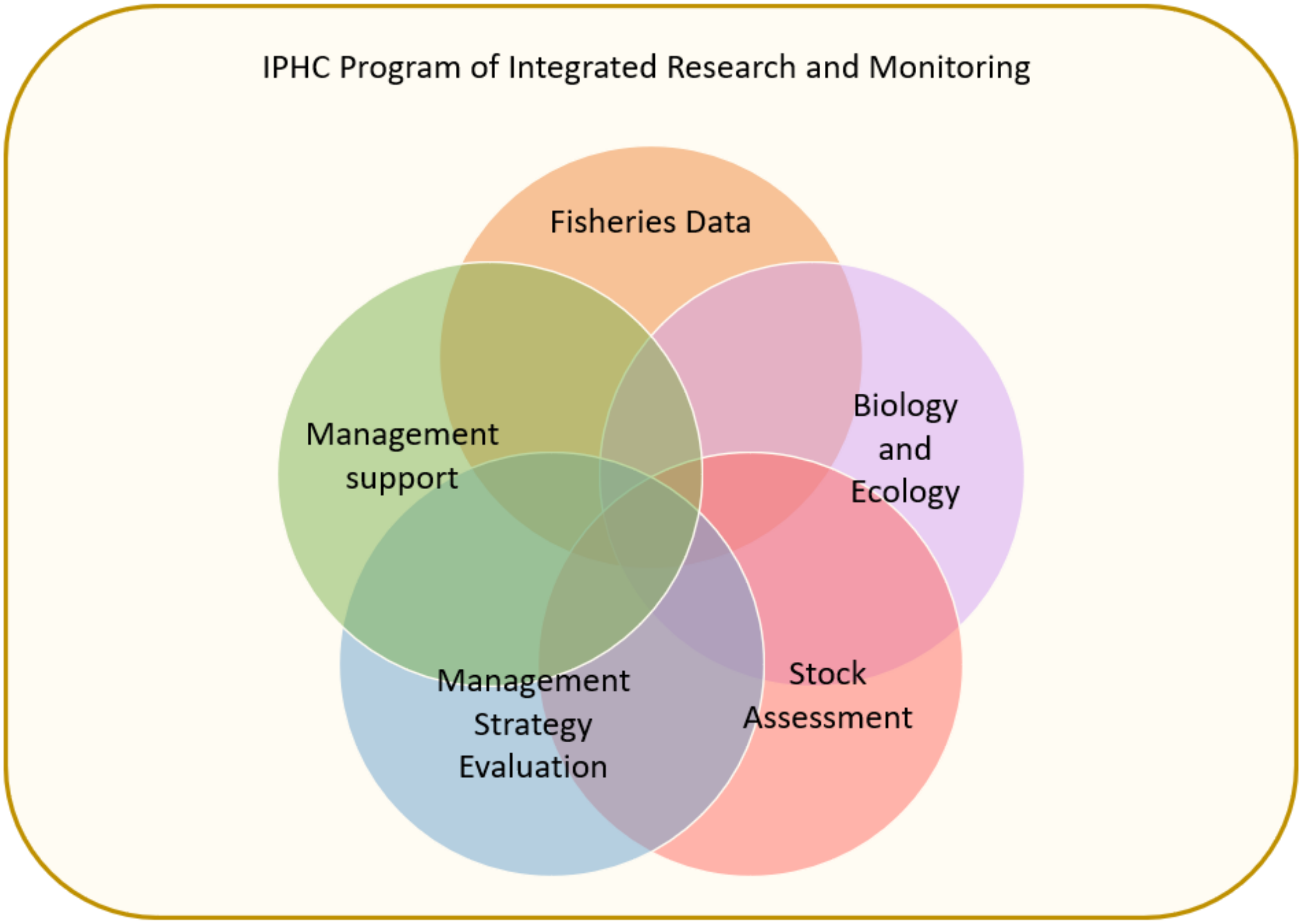

Figure 2. Core areas of the IPHC's integrated program of research and monitoring.

3. *Strategy*

The IPHC Strategic Plan (2019-23) (the Plan) contains five (5) enduring strategic goals in executing our mission, including our overarching goal and associated science and research objectives. Although priorities and tasking will change over time in response to events and developments, the Plan provides a framework to standardise our approach when revising or setting new priorities and tasking. The Strategic goals as they apply to the science and research activities of the IPHC Secretariat, will be operationalised through a multi-year tactical activity matrix (Appendix I) at the organisational and management unit (Branch) level (Fig. 3). The tactical activity matrix is described in the sections below, and has been developed based on the core needs of the Commission, in developing and implementing robust, scientifically-based management decisions on an annual, and multi-year level. Relevant IPHC subsidiary bodies will be involved in project development and ongoing review.

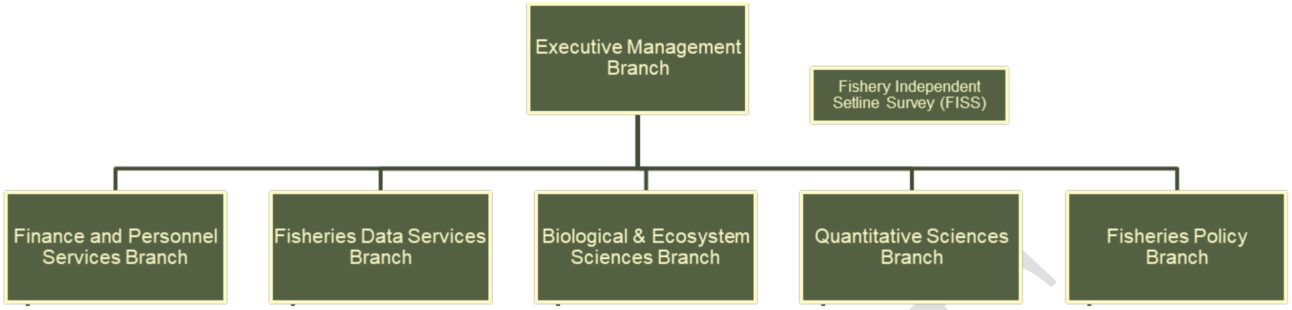

Figure 3. IPHC Secretariat organisation chart (2022).

4. *Measures of Success*

The Secretariat's success in implementing the *IPHC 5-Year Program of Integrated Research and Monitoring (2022-26)* will be measured according to the following four criteria relevant to the stock assessment, the MSE and for all inputs to IPHC management:

1) Timeliness – was the research conducted, analyzed, published and provided to the Commission at the appropriate points to be included in annual management decisions?
2) Transparency – was the research published and presented in such a way that it was available to other scientists, stakeholders and decision-makers?
3) Accuracy - did the research improve the perceived accuracy of the stock assessment, MSE or decisions made by the commission?
4) Reduction in uncertainty – did the research allow for more precise information for use in management?

4.1 *Delivery of specified products*

Each project line item will contain specific deliverables that constitute useful inputs into the stock assessment and the management strategy evaluation process, as well as support their implementation in the decision making process at the level of the Commission.

4.2 *Communication*

[In development]

4.3 *External research funding*

The Secretariat has set a funding goal of at least 20% of the funds for this program to be sourced from external funding bodies on an annual basis. Continuing the successful funding-recruitment strategy adopted during the previous 5-yr research plan (IPHC–2019–BESRP-5YP) (Appendix II), the Secretariat will identify and select external funding opportunities that are timely and that aim at addressing key research objectives (as outlined in Appendix II) that have important implications for stock assessment and the MSE process. Secretariat staff have the necessary expertise to propose novel and important research questions to funding agencies and to recruit external collaborators from research agencies and universities as deemed necessary. The IPHC Secretariat will continue to capitalize on the strong analytical contributions of quantitative scientists to the development of biological research questions within the framework of research projects funded by external as well as internal funding sources.

4.4 *Peer-reviewed journal publication*

Publication of research outcomes in peer-reviewed journals will be clearly documented and monitored as a measure of success. This may include single publications at the completion of a particular project, or a series of publications throughout the project as well as at its completion. Each sub-project shall be published in a timely manner, and shall be submitted no later than 12 months after the end of the research. In the sections that follow, the expected publications from each research stream and cross-stream are defined.

5. Core focal areas – Background

The goals of the main activities of the *5-Year program of integrated research and monitoring (2022-26)* are integrated across the organisation, involving 1) monitoring (fisheries-dependent and –independent data collection), and 2) research (biological, ecological), modelling (FISS and stock assessment), and Management Strategy Evaluation (MSE), as outlined in the following sub-sections. These components are closely linked to one another, and all feed into management decision making (Fig. 4). Additionally, management-supporting information constitute a range of additional decision-making drivers beyond IPHC's current research and monitoring programs. The current program builds on the outcomes and experiences of the Commission arising from the implementation of the 2017-21 5-Year Biological and Ecosystem Science Research Plan (IPHC–2019–BESRP-5YP), and which is summarized in Appendix II.

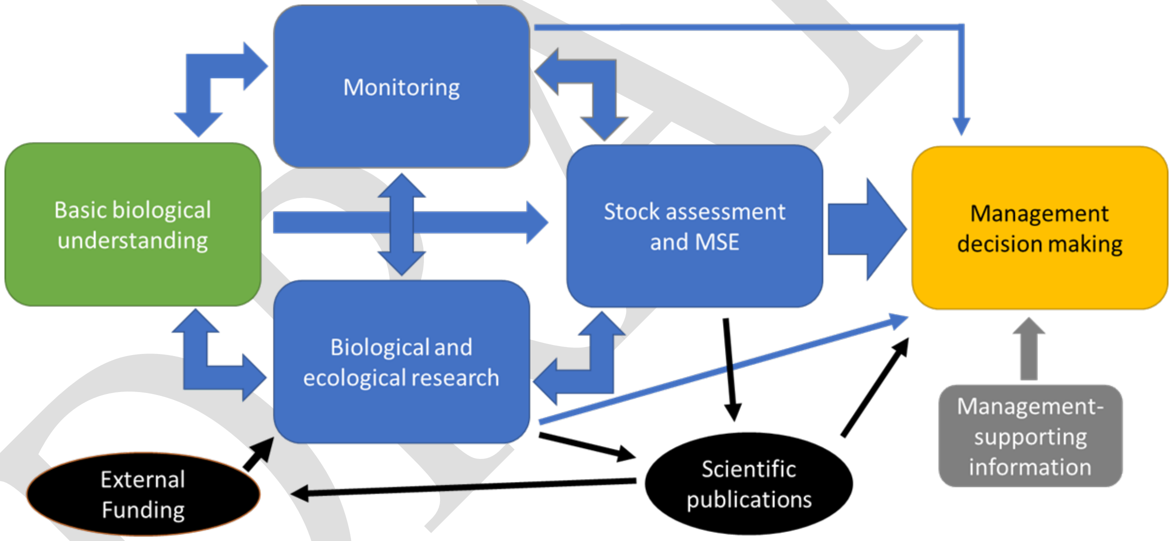

Figure 4. Flow of information from basic biological understanding of the Pacific halibut resource, through IPHC research components (monitoring, biological and ecological research, stock assessment, and MSE) to management decision-making. Management-supporting information (grey) constitute a range of additional decision-making drivers within and beyond IPHC's current research and monitoring programs. Arrows indicate the strength (size of the arow) and direction of information exchange. Also identified (in black) are the external links from funding and scientific publications which supplement the IPHC's internal process.

5.1 Research

5.1.1 Stock Assessment

Focal Area Objective	To improve accuracy and reduce uncertainty in the current stock assessment and the resultant stock management advice provided to the Commission.
IPHC Website portal	https://www.iphc.int/management/science-and-research/stock-assessment

The IPHC conducts an annual stock assessment, using data from the fishery-independent setline survey (FISS), the commercial Pacific halibut and other fisheries, as well biological information from its research program. The assessment includes the Pacific halibut resource in the IPHC Convention Area, covering the Exclusive Economic Zones of Canada and the United States of America. Data sources are updated each year to reflect the most recent scientific information available for use in management decision making.

The 2021 stock assessment relied on an ensemble of four population dynamics models to estimate the probability distributions describing the current stock size, trend, and demographics. The ensemble is designed to capture both uncertainty related to the data and stock dynamics (due to estimation) as well as uncertainty related to our understanding of the way in which the Pacific halibut stock functions and is best approximated by a statistical model (structural uncertainty).

Stock assessment results are used as inputs for harvest strategy calculations, including mortality projection tables for the upcoming year that reflect the IPHC's harvest strategy policy and other considerations, as well as the harvest decision table which provides a direct tool for the management process. The harvest decision table uses the probability distributions from short-term (three year) assessment projections to evaluate the trade-offs between alternative levels of potential yield (catch) and the associated risks to the stock and fishery.

The stock assessment research priorities have been subdivided into four categories:

1) Assessment data collection and processing;
2) technical development;
3) biological inputs; and
4) fishery yield.

It is important to note that ongoing monitoring, including the annual FISS and directed commercial landings sampling programs is not considered research and is therefore not included in this research priority list despite the critical importance of these collections. These are described in the sections below.

5.1.2 Management Strategy Evaluation (MSE)

Focal Area Objective	To provide inputs that inform the MSE process, which will evaluate the consequences of alternative management options, known as harvest strategies.
IPHC Website portal	https://www.iphc.int/management/science-and-research/management-strategy-evaluation

Management Strategy Evaluation (MSE) is a process to evaluate the consequences of alternative management options, known as harvest strategies. MSE uses a simulation tool to determine how alternative harvest strategies perform given a set of pre-defined fishery and conservation objectives, taking into account the uncertainties in the system and how likely candidate harvest strategies are to achieve the chosen management objectives.

MSE is a simulation technique based on modelling each part of a management cycle. The MSE uses an operating model to simulate the entire population and all fisheries, factoring in management decisions, the monitoring program, the estimation model, and potential ecosystem effects using a closed-loop simulation.

Undertaking an MSE has the advantage of being able to reveal the trade-offs among a range of possible management decisions. Specifically, to provide the information on which to base a rational decision, given harvest strategies, preferences, and attitudes to risk. The MSE is an essential part of the process of developing, evaluating and agreeing to a harvest strategy.

The MSE process involves:

- Defining fishery and conservation objectives with the involvement of stakeholders and managers;
- Identifying harvest strategies (a.k.a. management procedures) to evaluate;
- Simulating a Pacific halibut population using those harvest strategies;
- Evaluating and presenting the results in a way that examines trade-offs between objectives;
- Applying a chosen harvest strategy for the management of Pacific halibut;
- Repeating this process in the future in case of changes in objectives, assumptions, or expectations.

There are many tasks that would improve the MSE framework and the presentation of future results to the Commission. The tasks can be divided into five general categories, which are common to MSE in general:

1. **Objectives**: The goals and objectives that are used in the evaluation.
2. **Management Procedures (MPs)**: Specific, well-defined management procedures that can be coded in the MSE framework to produce simulated TCEYs for each IPHC Regulatory Area.
3. **Framework**: The specifications and computer code for the closed-loop simulations including the operating model and how it interacts with the MP.
4. **Evaluation**: The performance metrics and presentation of results. This includes how the performance metrics are evaluated (e.g. tables, figures, and rankings), presented to the Commission and its subsidiary bodies, and disseminated for outreach.
5. **Application**: Specifications of how an MP may be applied in practice and re-evaluated in the future, including responses to exceptional circumstances.

All of these categories provide inputs and outputs of the MSE process, but the Framework category benefits most from the integration of biological and ecosystem research because the operating model, the simulation of the monitoring program, the estimation model, and potential ecosystem effects are determined from this knowledge.

Outcomes of the MSE process will not only inform the Commission on trade-offs between harvest strategies and assist in choosing an optimal strategy for management of the Pacific halibut resource, but will inform the prioritization of research activities related to fisheries monitoring, biological and ecological research, stock assessment, and fishery socio-economics.

5.1.3 Biology and Ecology

Focal Area Objective	To identify and assess critical knowledge gaps in the biology and ecology of Pacific halibut within its known range, including the influence of environmental conditions on population and fishery dynamics.
IPHC Website portal	https://www.iphc.int/management/science-and-research/biological-and-ecosystem-science-research-program-bandesrp

Since its inception, the IPHC has had a long history of research activities devoted to describe and understand the biology of the Pacific halibut. At present, the main objectives of the Biological and Ecosystem Science Research Program at IPHC are to: 1) identify and assess critical knowledge gaps in the biology of the Pacific halibut; 2) understand the influence of environmental conditions in the biology of the Pacific halibut and its fishery; and 3) apply the resulting knowledge to reduce uncertainty in current stock assessment models.

The primary biological research activities at the IPHC that follow Commission objectives and selected for their important management implications are identified and described in the proposed 5-Year Research Plan for the period 2022-2026. An overarching goal of the 5-Year Research Plan is to promote integration and synergies among the various research activities led by the IPHC in order to improve our knowledge of key biological inputs that feed into the stock assessment and MSE process. The goals of the main research activities of the 5-Year Research Plan are therefore aligned and integrated with the IPHC stock assessment and MSE processes. The IPHC Secretariat conducts research activities to address key biological issues based on the IPHC Secretariat's own input as well as input from the IPHC Commissioners, stakeholders and particularly from specific subsidiary bodies to the IPHC such, including the Scientific Review Board (SRB) and the Research Advisory Board (RAB).

The biological research activities contemplated in the 5-Year Research Plan and their specific aims are detailed in Section 6. Overall, the biological research activities at IPHC aim at providing information on factors that influence the biomass of the Pacific halibut population (e.g. distribution and movement of fish among IPHC Regulatory Areas, growth patterns and environmental influences on growth in larval, juvenile and adult fish, drivers of changes in size-at-age) and, specifically, of the spawning (female) population (e.g. reproductive maturity, skipped spawning, reproductive migrations) and resulting changes in population dynamics. Furthermore, the research activities of IPHC also aim, on one hand, at providing information on the survival of regulatory-discarded Pacific halibut in the directed fisheries with the objective to refine current estimates of discard mortality rates and develop best handling practices, and, on the other hand, at reducing whale depredation and Pacific halibut bycatch through gear modifications and through a better understanding of behavioral and physiological responses of Pacific halibut to fishing gear.

5.2 Monitoring

Focal Area Objective	To collect fishery-dependent and fishery-independent data on the distribution, abundance, and demographics of Pacific halibut, as well as other key biological data, through ongoing monitoring activities.
IPHC Website portal	***Fishery-dependent data:*** • https://www.iphc.int/datatest/commercial-fisheries • https://www.iphc.int/data/datatest/non-directed-commercial-discard-mortality-fisheries • https://www.iphc.int/data/datatest/pacific-halibut-recreational-fisheries-data • https://www.iphc.int/datatest/subsistence-fisheries • https://www.iphc.int/data/time-series-datasets

	Fishery-independent data: • https://www.iphc.int/management/science-and-research/fishery-independent-setline-survey-fiss • https://www.iphc.int/data/datatest/fishery-independent-setline-survey-fiss

5.2.1 Fishery-dependent data.

The IPHC estimates all Pacific halibut removals taken in the IPHC Convention Area and uses this information in its yearly stock assessment and other analyses. The data are compiled by the IPHC Secretariat and include data from Federal and State agencies of each Contracting Party. Specific activities in this area include the following.

5.2.1.1 Directed commercial fisheries data

The IPHC Secretariat collects logbooks, otoliths, tissue samples, and associated sex-length-weight data from directed commercial landings coastwide (Fig. 5). A sampling rate is determined for each port by IPHC Regulatory Area. The applicable rate is calculated from the current year's mortality limits and estimated percentages of weight of fish landed, and estimated percentages of weight sampled in that port to allow for collection of the target number of biological samples by IPHC Regulatory Area. An example of the data collected and the methods used are provided in the annually updated directed commercial sampling manual (e.g. IPHC Directed Commercial Landings Sampling Manual 2021). Directed commercial fishery landings are recorded by the Federal and State agencies of each Contracting Party and summarized each year by the IPHC. Discard mortality for the directed commercial fishery is currently estimated using a combination of research survey (USA) and observer data (Canada).

5.2.1.2 Non-directed commercial discard mortality data

The IPHC accounts for non-directed commercial discard mortality by IPHC Regulatory Area and sector. Non-directed commercial discard mortality estimates are provided by State and Federal agencies of each Contracting Party, and compiled annually for use in the stock assessment and other analysis. https://www.iphc.int/data/datatest/non-directed-commercial-discard-mortality-fisheries.

Non-directed commercial discard mortality of Pacific halibut is estimated because not all fisheries have 100% monitoring and not all Pacific halibut that are discarded are assumed to die. The IPHC relies upon information supplied by observer programs run by Contracting Party agencies for non-directed commercial discard mortality estimates in most fisheries. Non-IPHC research survey information or other sources are used to generate estimates of non-directed commercial discard mortality in the few cases where fishery observations are unavailable. Non-directed fisheries off Canada British Columbia are monitored and discard mortality information is provided to IPHC by DFO. NOAA Fisheries operates observer programs off the USA West Coast and Alaska, which monitor the major groundfish fisheries. Data collected by those programs are used to estimate non-directed commercial discard mortality.

5.2.1.3 Subsistence fisheries data

Subsistence fisheries are non-commercial, customary, and traditional use of Pacific halibut for direct personal, family, or community consumption or sharing as food, or customary trade. The primary subsistence fisheries are the treaty Indian Ceremonial and Subsistence fishery in IPHC Regulatory Area 2A off northwest Washington State (USA), the First Nations Food, Social, and Ceremonial (FSC) fishery in British Columbia (Canada), and the subsistence fishery by rural residents and federally-recognized native tribes in Alaska (USA) documented via Subsistence Halibut Registration Certificates (SHARC). Subsistence fishery removals of Pacific halibut, including estimated subsistence discard mortality, are provided by State and Federal agencies of each Contracting

Party, estimated, and compiled annually for use in the stock assessment and other analysis. https://www.iphc.int/datatest/subsistence-fisheries.

5.2.1.4 Recreational fisheries data

Recreational removals of Pacific halibut, including estimated recreational discard mortality, are provided by National/State agencies of each Contracting Party, estimated, and compiled annually for use in the stock assessment and other analysis. https://www.iphc.int/data/datatest/pacific-halibut-recreational-fisheries-data.

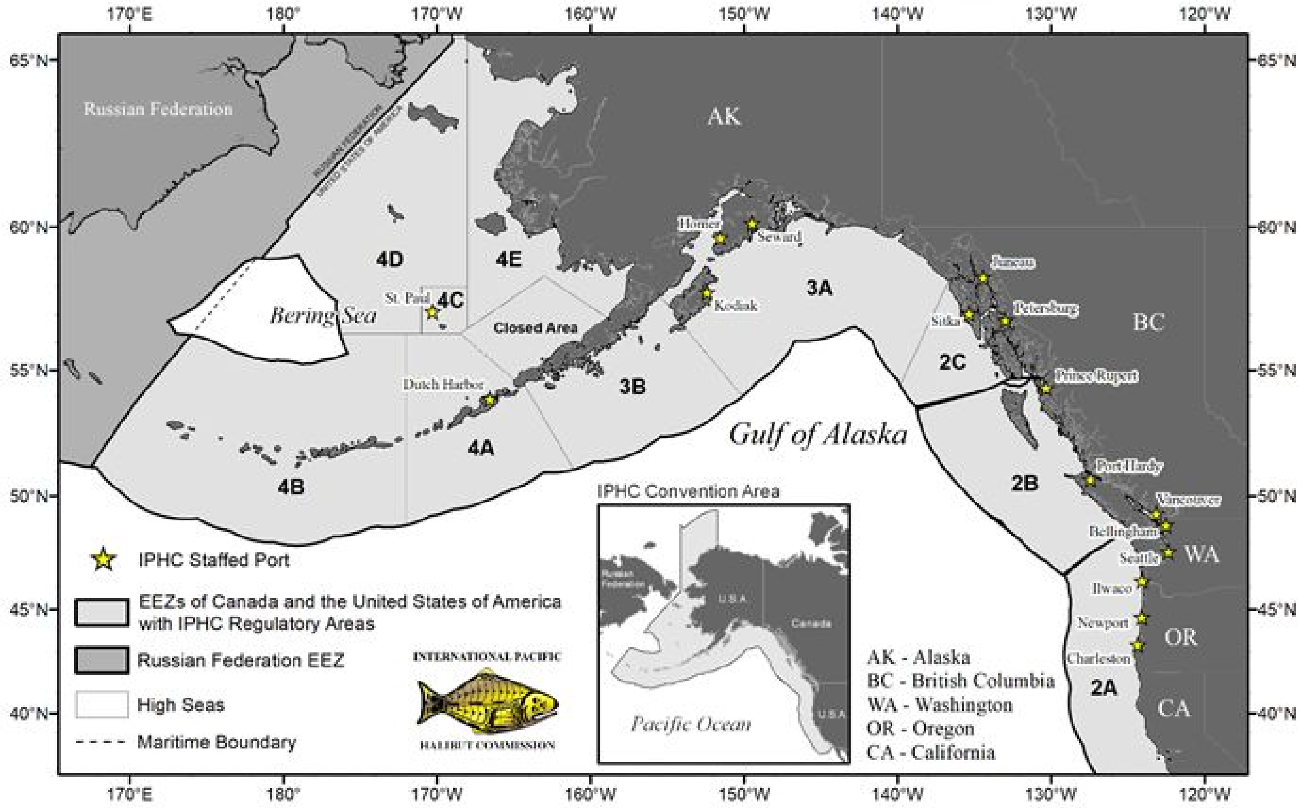

Figure 5. Ports where the IPHC has sampled directed commercial landings throughout the fishing period in recent years (note: ports sampled in a given year may change for operational reasons).

5.2.2 Fishery-independent data.

Data collection and monitoring activities aimed at providing a standardised time-series of biological and ecological data that is independent of the fishing fleet.

5.2.2.1 Fishery-independent setline survey (FISS)

The IPHC Fishery-Independent Setline Survey (FISS) provides catch-rate information and biological data on Pacific halibut that are independent of the fishery. These data, collected using standardized methods, bait, and gear, are used to estimate the primary index of population abundance used in the stock assessment. The FISS is restricted to the summer months, but encompasses the commercial fishing grounds in the Pacific halibut fishery, and almost all known Pacific halibut habitat in Convention waters outside the Bering Sea. The standard FISS grid totals 1,890 stations (Fig. 6). Biological data collected on the FISS (e.g. the length, weight, age, and sex of Pacific halibut) are used to monitor changes in biomass, growth, and mortality. In addition, records of non-target species caught during FISS operations provide insight into bait competition, and serve as an index of abundance over time, making them valuable to the potential management and avoidance of non-target species. An example of the data collected and the methods used are provided in the annually updated FISS sampling manual (e.g. IPHC FISS Sampling Manual 2021).

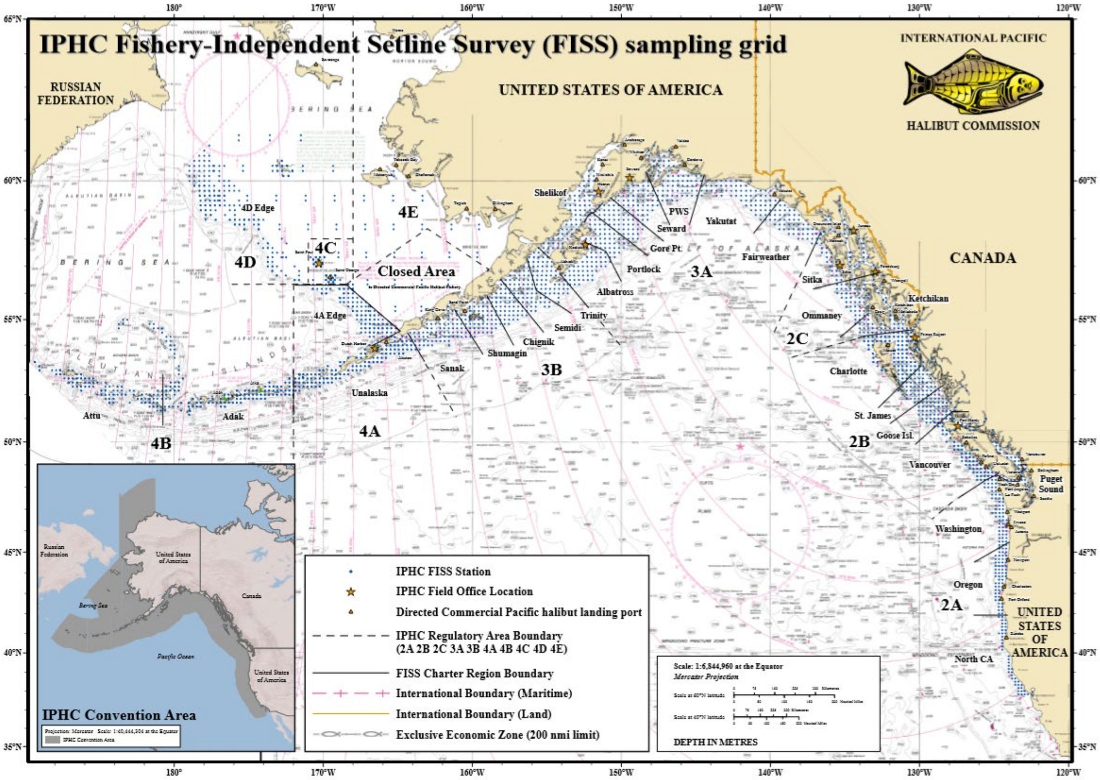

Figure 6. IPHC Fishery-Independent Setline Survey (FISS) with full sampling grid shown.

Quality control and sampling rate estimations: Following a program of planned FISS expansions from 2014-19, a process of rationialisation of the FISS was undertaken. The goal was to ensure that, given constraints on resources available for implementing the FISS, station selection was such that density indices would be estimated with high precision and low potential for bias. An annual design review process has been developed during which potential FISS designs for the subsequent three years are evaluated according to precision and bias criteria. The resulting proposed designs and their evaluation are presented for review at the June Scientific Review Board meetings and potentially modified following SRB input before presentation to the Commissioners at the Work Meeting and Interim Meeting. Annual biological sampling rates for each IPHC Regulatory Area are calculated based on the previous year's catch rates and an annual target of 2000 sampled fish (with 100 additional archive samples).

5.2.2.2 *Fishery-independent Trawl Survey (FITS)*

Since 1996, the IPHC has participated annually in the NOAA Fisheries trawl surveys operating in the Bering Sea (Fig. 7) and Aleutian Islands (Fig. 8) and Gulf of Alaska (Fig. 9). The information collected from Pacific halibut caught on these surveys, together with data from the IPHC Fishery-Independent Setline Survey (FISS) and commercial Pacific halibut data, are used directly in estimating indices of abundance and in the stock assessment and to monitor population trends, growth/size, and to supplement understanding of recruitment, and age composition of young Pacific halibut.

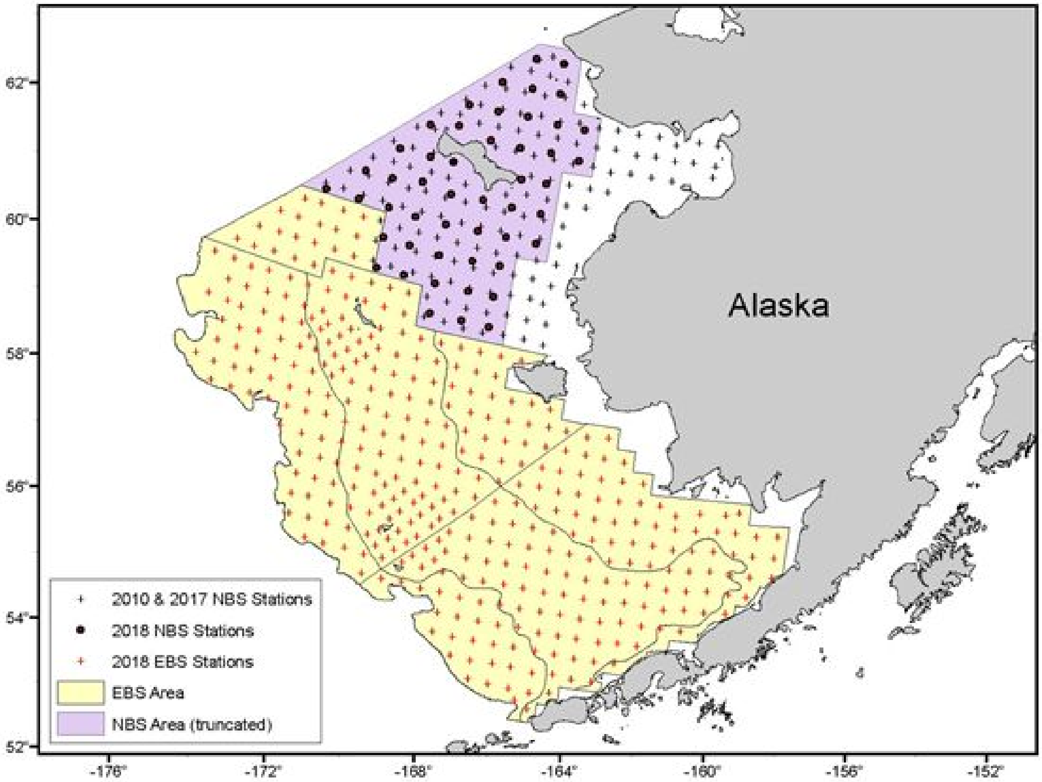

Figure 7. Sampling station design for the 2018 NOAA Bering Sea bottom trawl survey. Black dots are stations sampled in the 2018 "rapid-response" NBS trawl survey and black plus signs are stations sampled in the 2010 and 2017 standard NBS trawl surveys.

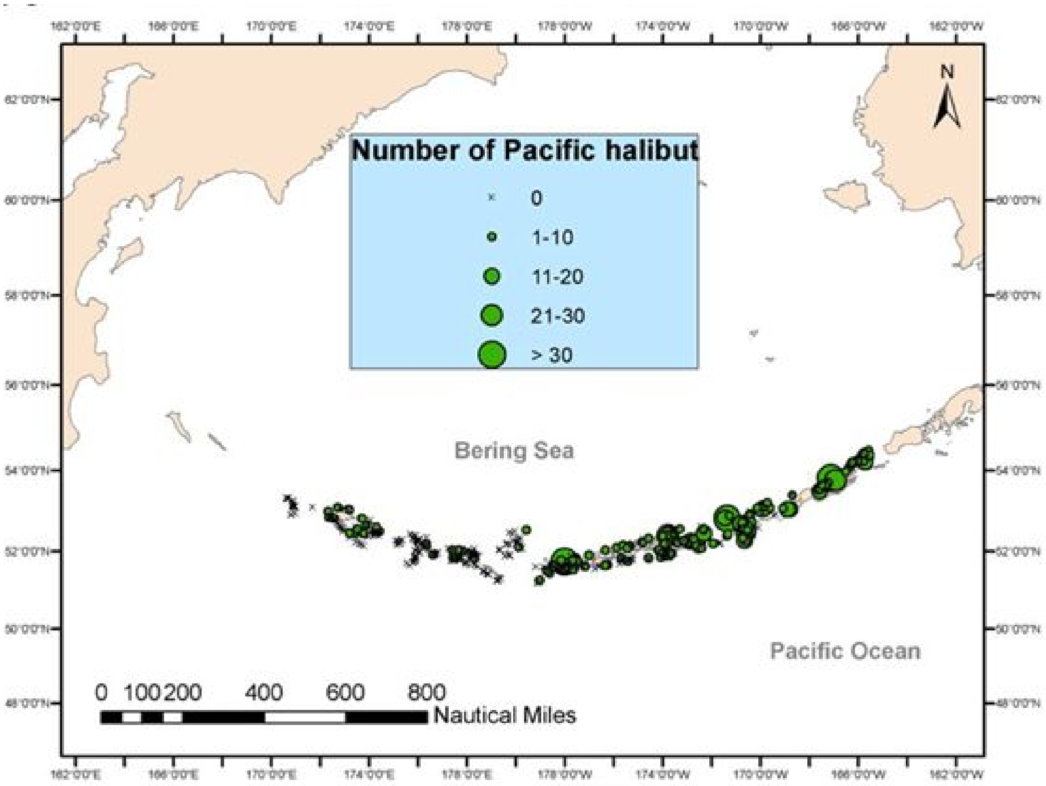

Figure 8. Sampling stations and catch for the 2018 NOAA-Fisheries Aleutian Islands bottom trawl survey.

[2021 Map to be added]

Figure 9. Sampling stations and catch for the yyyy NOAA-Fisheries Gulf of Alaska bottom trawl survey.

5.3 Management-supporting information

Successful fisheries management requires rigorous application of the scientific method of problem solving in the development of strategic alternatives and their evaluation on the basis of objectives that integrate ecosystem and human dynamics across space and time into management decision making (Lane and Stephenson, 1995). This points to the importance of understanding a broad range of factors in order to deliver on Commission's objective to develop the stocks of Pacific halibut to the levels that permit the optimum yield from the fishery over time. Management-supporting information beyond IPHC's current research and monitoring programs relate to, among others, socioeconomic considerations, community development, political constraints, and operational limitations.

Responding to the Commission's "*desire for more comprehensive economic information to support the overall management of the Pacific halibut resource in fulfillment of its mandate*" (economic study terms of reference adopted at FAC095 and endorsed at AM095 in 2019), between 2019 and 2021 the IPHC conducted a socioeconomic study. The study's core product, Pacific halibut multiregional economic impact assessment (PHMEIA) model, describes economic interdependencies between sectors and regions to bring a better understanding of the role and importance of Pacific halibut resource to regional economies of Canada and the United States of America (see project report). The model details the within-region production structure of the Pacific halibut sectors (fishing, processing, charter) and cross-regional flows of economic benefits, and accounts for economic activity generated through sectors that supply fishing vessels, processing plants, and charter businesses with inputs to production, by embedding Pacific halibut sectors into the model of the entire economy of Canada and the USA. The PHMEIA model fosters stakeholders' better understanding of a broad scope of regional impacts of the Pacific halibut resource. The results highlight that the harvest stage accounts for only a fraction of economic activity that would be forgone if the resource was not available to fishers in the Pacific Northwest. Moreover, the study informs on the vulnerability of communities to changes in the state of the Pacific halibut stock throughout its range, highlighting regions particularly dependent on economic activities that rely on Pacific halibut. Leveraging multiple sources of socioeconomic data, the project provides complementary input for designing policies with desired effects depending on regulators' priorities which may involve balancing multiple conflicting objectives. A good understanding of the localized effects is pivotal to policymakers who are often concerned about community impacts, particularly in terms of impact on employment opportunities and households' welfare. Fisheries policies have a long history of disproportionally hurting smaller communities, often because potential adverse effects were not sufficiently assessed.

The economic impact assessment is supplemented by an analysis of the formation of the price paid for Pacific halibut products by final consumers (end-users) that is intended to provide a better picture of Pacific halibut contribution to the gross domestic product (GDP) along the entire value chain, from the hook-to-plate. This supplemental material is available in IPHC's Pacific halibut market analysis.

6. *Core focal areas – Planned and opportunistic activities (2022-2026)*

[In development – addition of the IPHC Scientific process – meeting schedule/linkages figures]

Research at IPHC can be classified as "use-inspired basic research" (Stokes 1997) which combines knowledge building with the application of existing and emerging knowledge to provide for the management of Pacific halibut. The four core focal areas: stock assessment, management strategy evaluation, management supporting information, and biology & ecology, all interact with each other as well as with fisheries monitoring activities in the IPHC integrated program of research and monitoring. Progress and knowledge building in one focal area influences and informs application in other core focal areas, also providing insight into future research priorities. The circular feedback loop is similar to the scientific method of observing a problem, creating a hypothesis, testing that hypothesis through research and analysis, drawing conclusions, and refining the hypothesis.

The IPHC Secretariat has been working with IPHC advisory bodies, such as the Scientific Review Board (SRB), and the Commission to conduct scientific research in a way that utilizes the scientific method. Problems are often identified by an advisory body or Commission and hypotheses are developed by the IPHC Secretariat. Research is reviewed by the SRB and refined hypotheses are presented to advisory bodies and the Commission. This process occurs via an annual schedule of meetings, as shown in Fig. 10. In May, an MSE informational session may be held if there is significant progress in the MSE such that it would be useful to prepare stakeholders for the Management Strategy Advisory Board (MSAB) meeting in October. Recommendations related to the MSE and development of a harvest strategy directed to the Commission are a result of the MSAB meeting. The SRB holds two meetings each year: one in June where requests are typically directed to IPHC Secretariat, and one in September where recommendations are made to the Commission. The June SRB meeting has a focus on research; the September meeting represents a final check of science products to be presented to the Commission for use in management. The Research Advisory Board (RAB) meets in November to discuss ongoing research, provide guidance and recommend new research projects. The Work Meeting (WM) is held in September and is a working session with IPHC Secretariat and the Commission to prepare for the Interim Meeting (IM) held in November and the Annual Meeting (AM) held in January. Outcomes from the AM include mortality limits (coastwide and by IPHC Regulatory Area), directed fishery season dates, domestic regulations, and requests and recommendations for the IPHC Secretariat. In conjunction with the AM are meetings of the Finance and Administration Committee (FAC), the Conference Board (CB), and the Processor Advisory Board (PAB). The Commission may also hold Special Sessions (SS) throughout the year to take up and make decisions on specific topics.

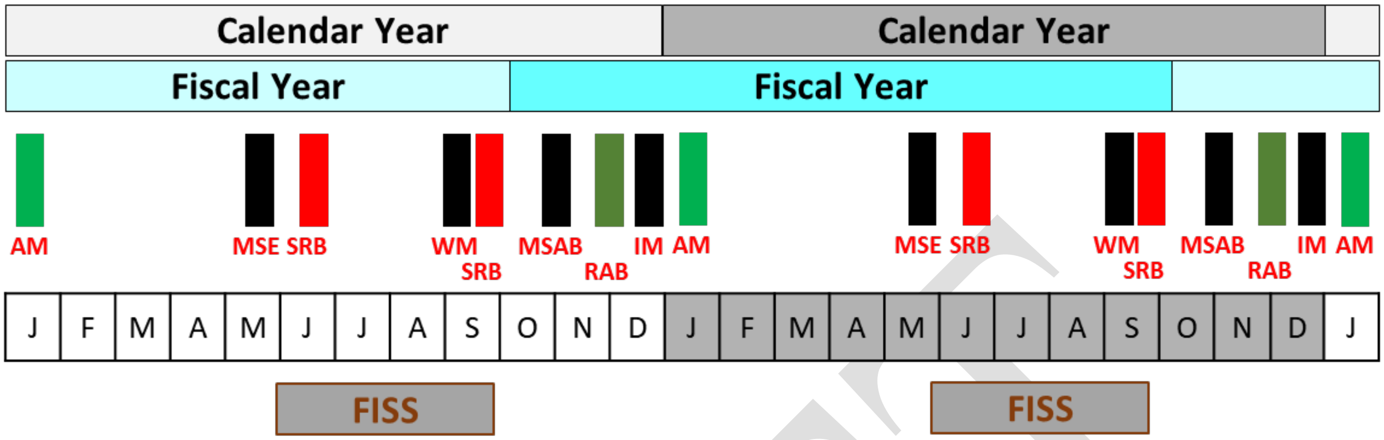

Figure 10. The typical IPHC annual meeting schedule with the calendar year and fiscal year shown. The meetings, shown in the middle row are: Annual Meeting where the Commission makes many final decisions for that year (AM), an MSE informational session (MSE), Scientific Review Board meetings (SRB), the Commission Work Meeting (WM), the Management Strategy Advisory Board meeting (MSAB), the Research Advisory Board Meeting (RAB), and the Interim Meeting (IM). The annual FISS schedule is also shown.

In addition to the annual meeting process at IPHC, individual core focal areas of research may identify and prioritize research for other core focal areas. For example, stock assessment research often identifies gaps in the knowledge of Pacific halibut biology and ecology, which then identifies priority research for the Biology and Ecology core area. Vice versa, basic biological and ecological research can identify concepts that could be better understood and result in improved implementation in any of the core areas. Furthermore, Management Strategy Evaluation can often be used to identify priority research topics for any core areas by simulation testing to identify research that may have the largest benefit to improving the management of Pacific halibut.

The top priorities of research for various categories in each of the core focal areas are provided below. The top priorities are a subset of the potential research topics in each core focal area. More exhaustive and up-to-date lists of research topics, that may extend beyond a five-year time-frame, can be found in recent meeting documents related each core focal area.

6.1 Research

6.1.1 Stock Assessment

Within the four assessment research categories, the following topics have been identified as top priorities in order to focus attention on their importance for the stock assessment and management of Pacific halibut. A brief narrative is provided here to highlight the specific use of products from these studies in the stock assessment.

6.1.1.1 Stock Assessment data collection and processing:

6.1.1.1.1 Commercial fishery sex-ratio-at-age via genetics

Commercial fishery sex-ratio information has been found to be closely correlated with the absolute scale of the population estimates in the stock assessment, and has been identified as the greatest source of uncertainty since 2013. With only four years (2017-20) of commercial sex-ratio-at-age information available for the 2021 stock assessment, the annual genetic assay of fin clips sampled from the landings remains critically important. When the time series grows longer, it may be advantageous to determine the ideal frequency at which these assays need to be conducted. Development of approaches to use archived otoliths, scales or other samples to derive historical estimates (if possible) could provide valuable information on earlier time-periods (with differing fishery and biological properties), and therefore potentially reconcile some of the considerable historical uncertainty in the present stock assessment. This assessment priority directly informs *6.1.3.2 Reproduction* as described below.

6.1.1.1.2 Whale depredation accounting and tools for avoidance

Whale depredation currently represents a source of unobserved and unaccounted-for mortality in the assessment and management of Pacific halibut. A logbook program has been phased in over the last several years, in order to record whale interactions observed by commercial fishermen. Estimation of depredation mortality, from logbook records and supplemented with more detailed data and analysis from the FISS represents a first step in accounting for this source of mortality; however, such estimates will likely come with considerable uncertainty. Reduction of depredation mortality through improved fishery avoidance and/or catch protection would be a preferable extension and/or solution to basic estimation. As such, research to provide the fishery with tools to reduce depredation is considered a closely-related high priority. This assessment priority directly informs *6.1.3.4 Mortality and Survival Assessment* as described below.

6.1.1.2 Stock Assessment technical development:

6.1.1.2.1 Maintaining coordination with the MSE

The stock assessment and MSE operating models have been developed in close coordination, in order to identify plausible hypotheses regarding the processes governing Pacific halibut population dynamics. Important aspects of Pacific halibut dynamics include recruitment (possibly related to extrinsic environmental factors in addition to spawning biomass), size-at-age, movement/migration and spatial patterns in fishery catchability and selectivity. Many approaches developed as part of the tactical stock assessment have been explored in the MSE operating model, and conversely, the MSE operating model has highlighted areas of data uncertainty or alternative hypotheses for exploration in the assessment (e.g., movement rates). Although these two modelling efforts target differing objectives (tactical vs. strategic) continued coordination is essential to ensure that the stock assessment and the MSE represent the Pacific halibut similarly and provide consistent and useful advice for tactical and strategic decision making.

6.1.1.2.2 Data weighting

The stock assessment currently relies on iterative “Francis” weighting of the age compositional data using a multinomial likelihood formulation (Francis 2011) based on the number of samples available in each year. Exploration of a stronger basis for input sample sizes through analysis of sampling design, estimation of sample weighting and alternative likelihoods may all provide for a more stable approach and a better description of the associated uncertainty.

6.1.1.2.3 Environmental covariates to recruitment

The two long time-series models included in the stock assessment ensemble allow for the Pacific Decadal Oscillation (PDO; Mantua et al. 1997) to be a binary covariate indicating periods of higher or lower average recruitment. This relationship has been observed to be consistent since its development over 20 years ago (Clark et al 1999) and is re-estimated in each year’s stock assessment models. With additional years of data, evaluation of the strength of this relationship, as compared to other metrics of the PDO (e.g., annual deviations, running averages) or other indicators of NE Pacific Ocean productivity should be undertaken in order to provide the best estimates and projections of Pacific halibut recruitment and to provide for alternative hypotheses for use in the MSE. This assessment priority partially informs *6.1.3.2 Reproduction* as described below.

6.1.1.2.4 'Leading' parameter estimation

Stock assessments are generally very sensitive to the estimates of leading parameters (stock-recruitment parameters, natural mortality, sex-specific dynamics, etc.). For Pacific halibut some of these are fully integrated into the estimation uncertainty (average unexploited recruitment), or partially integrated (e.g., estimation of natural mortality in two of the four models). As time-series of critically informative data sources like the FISS and the sex-ratio of the commercial landings grow longer it may be possible to integrate additional leading parameters directly in the assessment models and/or include them as nested models within the ensemble.

6.1.1.3 Stock Assessment biological inputs:

6.1.1.3.1 Maturity, skip-spawning and fecundity

Management of Pacific halibut is currently based on reference points that rely on relative female spawning biomass. Therefore, any changes to the understanding of reproductive output – either across age/size (maturity), over time (skip spawning) or as a function of body mass (fecundity) are crucially important. Each of these components directly affects the annual reproductive output estimated in the assessment. Ideally, the IPHC would have a program in place to monitor each of these three reproductive processes over time and use that information in the estimation of the stock-recruitment relationship, and the annual reproductive output relative to reference points. This would reduce the potential for biased time-series estimates created by non-stationarity in these traits (illustrated via sensitivity analyses in several of the recent assessments). However, at present we have only historical time-aggregated estimates of maturity and fecundity schedules. Therefore, the current research priority is to first update our estimates for each of these traits to reflect current environmental and biological conditions. After current stock-wide estimates have been achieved, a program for extending this information to a time-series via transition from research to monitoring can be developed. This assessment priority directly informs *6.1.3.2 Reproduction* as described below.

6.1.1.3.2 Stock structure of IPHC Regulatory Area 4B relative to the rest of the convention area

The current stock assessment and management of Pacific halibut assume that IPHC Regulatory Area 4B is functionally connected with the rest of the stock, i.e., that recruitment from other areas can support harvest in Area 4B and that biomass in Area 4B can produce recruits that may contribute to other Areas. Tagging (Webster et al. 2013) and genetic (Drinan et al. 2016) analyses have indicated the potential for Area 4B to be demographically isolated. An alternative to current assessment and management structure would be to treat Area 4B separately from the rest of the coast. This would not likely have a large effect on the coastwide stock assessment as Area 4B represents only approximately 5% of the surveyed stock (Stewart and Webster 2022). However, it would imply that the specific mortality limits for Area 4B could be very important to local dynamics and should be separated from stock-wide trends. Therefore, information on the stock structure for Area 4B has been identified as a top priority. This assessment priority directly informs *6.1.3.1 Migration and Population Dynamics* as described below.

6.1.1.3.3 Meta-population dynamics (connectivity) of larvae, juveniles and adults

The stock assessment and current management procedure treat spawning output, juvenile Pacific halibut abundance, and fish contributing to the fishery yield as equivalent across all parts of the Convention Area. Information on the connectivity of these life-history stages could be used for a variety of improvements to the assessment and current management procedure, including: investigating recruitment covariates, structuring spatial assessment models, identifying minimum or target spawning biomass levels in each Biological Region, refining the stock-recruitment relationship to better reflect source-sink dynamics and many others. Spatial dynamics have been highlighted as a major source of uncertainty in the Pacific halibut assessment for decades, and will continue to be of high priority until they are better understood. This assessment priority directly informs

6.1.3.1 Migration and Population Dynamics as described below.

6.1.1.4 Stock Assessment fishery yield:

6.1.1.4.1 Biological interactions with fishing gear

In 2020, 16% of the total fishing mortality of Pacific halibut was discarded (Stewart et al. 2021). Discard mortality rates can vary from less than 5% to 100% depending on the fishery, treatment of the catch and other factors (Leaman and Stewart 2017). A better understanding of the biological underpinnings for discard mortality could lead to increased precision in these estimates, avoiding potential bias in the stock assessment. Further, improved biological understanding of discard mortality mechanisms could allow for reductions in this source of fishing mortality, and thereby increased yield available to the fisheries. This assessment priority directly informs *6.1.3.4 Mortality and Survival Assessment* as described below.

6.1.1.4.2 Guidelines for reducing discard mortality

Much is already known about methods to reduce discard mortality, in non-directed fisheries as well as the directed commercial and recreational sectors. Promotion and adoption of best handling practices could reduce discard mortality, lead to greater retained yield, and reduce the potential uncertainty associated with large quantities of estimated mortality due to discarding. This assessment priority directly informs *6.1.3.4 Mortality and Survival Assessment* as described below.

Outside of the four general assessment categories, the IPHC has recently considered adding close-kin genetics (e.g., Bravington et al. 2016) to its ongoing research program (see section 6.1.3.1). Close-kin mark-recapture can potentially provide estimates of the absolute scale of the spawning output from the Pacific halibut population. This type of information can be fit directly in the stock assessment, and if estimated with a reasonable amount of precision, even a single data point could substantially reduce the uncertainty in the scale of total population estimates. Further, close-kin genetics may provide independent estimates of total mortality (and therefore natural mortality conditioned on catch-at-age), relative fecundity-at-age, and the spatial dynamics of spawning and recruitment. All of these quantities could substantially improve the structure of the current assessment and reduce uncertainty. Data collection of genetic samples from 100% of the sampled commercial landings has been in place since 2017 (as part of the sex-ratio monitoring) and from the FISS since 2021. The genetic analysis required to produce data allowing the estimation of reproductive output and other population parameters from close-kin mark-recapture modelling is both complex and expensive, and it could take several years for this project to get fully underway. This five-year plan should consider a pilot evaluation, such that a broader study could be undertaken in the future, providing the likely results would meet the Commission's objectives and prove possible given financial constraints. Research related to close-kin genetics would be pursued under *6.1.3.1 Migration and Population Dynamics* as described below.

6.1.2 Management Strategy Evaluation

MSE priorities have been subdivided into three categories: 1) biological parameterisation, 2) fishery parameterization, and 3) technical development. Research provides specifications for the MSE simulations, such as inputs to the Operating Model (OM), but another important outcome of the research is to define the range of plausibility to include in the MSE simulations as a measure of uncertainty. The following topics have been identified as top priorities.

6.1.2.1 MSE Biological and population parameterization

6.1.2.1.1 Distribution of life stages and stock connectivity

Research topics in this category will mainly inform parameterization of movement in the OM, but will also provide further understanding of Pacific halibut movement, connectivity, and the temporal variability. This knowledge may also be used to refine specific MSE objectives to reflect reality and plausible outcomes. Research under Section 6.1.3.1 will inform this MSE priority.

This research includes examining larval and juvenile distribution which is a main source of uncertainty in the OM that is currently not fully incorporated. Outcomes will assist with conditioning the OM, verify patterns simulated from the OM, and provide information to develop reasonable sensitivity scenarios to test the robustness of MPs.

Also included in this number one priority is stock structure research, especially with regard to IPHC Regulatory Area 4B. The dynamics of this IPHC Regulatory Area are not fully understood and it is useful to continue research on the connectivity of IPHC Regulatory Area 4B with other IPHC Regulatory Areas.

Finally, genomic analysis of population size is also included in this ranked category because that would help inform development of the OM as well as the biological sustainability objective related to maintaining a minimum spawning biomass in each IPHC Regulatory Area. An understanding of the spatial distribution of population size will help to inform this objective as well as the OM conditioning process.

6.1.2.1.2 Spatial spawning patterns and connectivity between spawning populations

An important parameter that can influence simulation outcomes is the distribution of recruitment across Biological Regions. Continued research in this area will improve the OM and provide justification for parameterising temporal variability. Research includes assigning individuals to spawning areas and establishing temporal and spatial spawning patterns. Outcomes may also provide information on recruitment strength and the relationship with environmental factors. For example, recent work by Sadorus et al (2020) used a biophysical and spatio-temporal models to examine connectivity across the Bering Sea and Gulf of Alaska. Furthermore, close-kin mark-recapture (Bravington et al. 2016) may provide insights into spatial relationships between juveniles and adults as well as abundance in specific regions. Research under Sections 6.1.3.1 and 6.1.3.2 will inform this MSE priority.

6.1.2.1.3 Understanding growth variation

Changes in the average weight-at-age of Pacific halibut is one of the major drivers of changes in biomass over time. The OM currently simulates temporal changes in weight-at-age via a random autocorrelated process which is unrelated to population size or environmental factors. Ongoing research in drivers related to growth in Pacific halibut will help to improve the simulation of weight-at-age. Research under Section 6.1.3.3 will inform this MSE priority.

6.1.2.1.4 MSE fishery parameterization

The specifications of fisheries and their parameterizations involved consultation with Pacific halibut stakeholders but some aspects of those parameterizations benefit from targeted research. One specific example is knowledge of discarding and discard mortality rates in directed and non-directed fisheries. Discard mortality can be a significant source of fishing mortality in some IPHC Regulatory Areas and appropriately modelling that mortality will provide a more robust evaluation of MPs. Research under Sections 6.1.3.4 and 6.1.3.5 will inform this MSE priority.

6.1.2.2 MSE technical development

Technical improvements to the MSE framework will allow for rapid development of alternative operating models and efficient simulation of management strategies for future evaluation. Coordination with the technical development of the stock assessment (Section 6.1.1.2.1) is necessary to ensure consistent assumptions and hypotheses for tactical (i.e. stock assessment) and strategic (i.e. MSE) models. Investigations done in the stock assessment will inform the stock assessment, which will then be informed by investigations using the closed-loop simulation framework. Multi-year assessments may allow for additional opportunity to coordinate between stock assessment and MSE.

6.1.2.2.1 Alternative migration scenarios

Including alternative migration hypotheses in the MSE simulations will assist in identifying management procedures that are robust to this uncertainty. This exploration will draw on general research on the movement and migration of Pacific halibut, observations from FISS and fisheries data, and outcomes of the stock assessment. Identification of reasonable hypotheses for the movement of Pacific halibut is essential to the robust investigation of management procedures. Research under Section 6.1.3.1 will inform this MSE priority.

6.1.2.2.2 Realistic simulations of estimation error

Closed loop simulation uses feedback from the management procedure to update the population in the projections. The management procedure consists of data collection, an estimation model, and harvest rules;currently IPHC uses a stock assessment as the estimation model. Future development of an efficient simulation process to mimic the stock assessment will more realistically represent the current management process. This involves using multiple estimation models to represent the ensemble and appropriately adding data and updating those models in the simulated projections. Improvements to the current MSE framework include adding additional estimation models to better represent the ensemble stock assessment, ensuring that the simulated estimation accurately represent the stock assessment now and in the future, and speeding up the simulation process.

6.1.2.2.3 Incorporate additional sources of implementation uncertainty

Implementation uncertainty consists of three subcategories: 1) decision-making uncertainty, 2) realized uncertainty, and 3) perceived uncertainty. Decision-making uncertainty is the difference between mortality limits determined from the management procedure and those adopted by the Commission. This uncertainty is currently not implemented in the MSE framework, but has been requested by the SRB and the independent peer review of the MSE. Realized uncertainty is the difference between the mortality limit set by the Commission and the actual mortality realized by the various fisheries. This type of uncertainty is currently partially implemented in the MSE framework. Finally, perceived uncertainty is the difference between the realized mortality and the estimated mortality limits from the various fisheries, which would be used in the estimation model. This third type of implementation uncertainty has not been implemented in the MSE framework. Implementing decision-making uncertainty is a priority for the MSE and will assist in understanding the performance of management procedures when they may not be followed exactly.

6.1.2.3 MSE Program of Work for 2021–2023

Following the 11th Special Session of the IPHC, an MSE program of work for 2021–2023 was developed. Seven tasks were identified that pertained to further developments of the MSE framework, evaluation of alternative MPs, and improvements in evaluation and presentation of results. Table 1 lists these tasks and provides a brief description. Additional details can be found in the program of work available on the MSE webpage.

Table 1. Tasks recommended by the Commission at SS011 (IPHC-2021-SS011-R para 7) for inclusion in the IPHC Secretariat MSE Program of Work for 2021–23.

ID	**Category**	**Task**	**Deliverable**
F.1	Framework	Develop migration scenarios	Develop OMs with alternative migration scenarios
F.2	Framework	Implementation variability	Incorporate additional sources of implementation variability in the framework
F.3	Framework	Develop more realistic simulations of estimation error	Improve the estimation model to more adequately mimic the ensemble stock assessment
F.5	Framework	Develop alternative OMs	Code alternative OMs in addition to the one already under evaluation.
M.1	MPs	Size limits	Identification, evaluation of size limits
M.3	MPs	Multi-year assessments	Evaluation of multi-year assessments
E.3	Evaluation	Presentation of results	Develop methods and outputs that are useful for presenting outcomes to stakeholders and Commissioners

6.1.2.4 Potential Future MSE projects

Management Strategy Evaluation is an iterative process where new management procedures may be evaluated, current management procedures may be re-evaluated under different assumptions, and the understanding of the population, environment, and fisheries may be updated with new information stemming from the stock assessment and biological/ecological research. The current Program of Work (Table 1) focuses on two elements of Management Procedures, but in the future other elements may be of interest, such as distribution procedures. The research being done now will inform the development of the MSE in the future to ensure a robust evaluation of any management procedure.

6.1.3 Biology and Ecology

Capitalizing on the outcomes of the previous 5-year plan (IPHC–2019–BESRP-5YP) (Appendix II), the IPHC Secretariat has identified five research areas that will provide key inputs for stock assessment and the MSE process. In addition to linking genetics and genomics with migration and distribution studies in the newly-coined area of Migration and Population Dynamics, the IPHC Secretariat has incorporated a novel research area on Fishing Technology. A series of key objectives for each the five research areas have been identified:

6.1.3.1 Migration and Population Dynamics

Genetic and genomic studies aimed at improving current knowledge of Pacific halibut migration and population dynamics throughout all life stages in order to achieve a complete understanding of stock structure and distribution across the entire distribution range of Pacific halibut in the North Pacific Ocean and the biotic and abiotic factors that influence it (specifically excluding satellite tagging). Specific objectives in this area include:

- Improve current knowledge of the genetic structure of the Pacific halibut population through the use of state-of-the-art low-coverage whole genome resequencing approaches. Establishment of genetic signatures of spawning sites.
- Improve our understanding of the mechanisms and magnitude of larval connectivity in the North Pacific

Ocean. Identification of environmental and biological predictors of larval abundance and recruitment.

- Improve our understanding of spawning site contributions to nursery/settlement areas in relation to year-class, recruit survival and strength, and environmental conditions in the North Pacific Ocean. Measure of genetic diversity of Pacific halibut juveniles from the eastern Bering Sea and the Gulf of Alaska.
- Improve our understanding of the relationship between nursery/settlement origin and adult distribution and abundance over temporal and spatial scales. Genomic assignment of individuals to source populations and assessment of distribution changes.
- Integrate analyses of Pacific halibut connectivity and distribution changes by incorporating genomic approaches.
- Improve estimates of population size, migration rates among geographical regions, and demographic parameters (e.g. fecundity-at-age, survival rate), through the application of close-kin mark-recapture-based approaches.
- Improve our understanding of the influences of oceanographic and environmental variation on connectivity, population structure and adaptation at a genomic level using seascape genomics approaches.
- Exploration and development of alternative methods for aging Pacific halibut based on genetic analyses of DNA methylation patterns in tissues (fin clips).
- Exploration of methods for individual identification based on computer-assisted tail image matching systems as an alternative for traditional mark and recapture tagging.

6.1.3.2 Reproduction

Studies aimed primarily at addressing two critical issues for stock assessment analysis based on estimates of female spawning biomass: 1) the sex ratio of the commercial catch and 2) maturity estimations. Specific objectives in this area include:

- Continued improvement of genetic methods for accurate sex identification of commercial landings from fin clips and otoliths in order to incorporate recent and historical sex-at-age information into the stock assessment process.
- Improve our understanding of the temporal progression of reproductive development and gamete production during an entire annual reproductive cycle in female and male Pacific halibut.
- Update current maturity-at-age estimates.
- Provide estimates of fecundity-at-age and fecundity-at-size.
- Investigate the possible presence of skip spawning in Pacific halibut females.
- Improve accuracy in current staging criteria of maturity status used in the field.
- Investigate possible environmental effects on the ontogenetic establishment of the phenotypic sex and their influence on sex ratios in the adult Pacific halibut population.
- Improve our understanding of potential temporal and spatial changes in maturity schedules and spawning patterns in female Pacific halibut and possible environmental influences.
- Improve our understanding of the genetic basis of variation in age and/or size-at-maturity, fecundity, and spawning timing, by conducting genome-wide association studies.

6.1.3.3 Growth

Studies aimed at describing the role of factors responsible for the observed changes in size-at-age and at evaluating growth and physiological condition in Pacific halibut. Specific objectives in this area include:

- Evaluate possible variation in somatic growth patterns in Pacific halibut as informed by physiological growth markers, physiological condition, energy content and dietary influences.
- Investigate the effects of environmental and ecological conditions that may influence somatic growth in Pacific halibut. Evaluate the relationship between somatic growth and temperature and trophic histories in Pacific halibut through the integrated use of physiological growth markers.
- Improve our understanding of the genetic basis of variation in somatic growth and size-at-age by conducting genome-wide association studies.

6.1.3.4 Mortality and Survival Assessment.

Studies aimed at providing updated estimates of discard mortality rates (DMRs) for Pacific halibut in the guided recreational fisheries and at evaluating methods for reducing mortality of Pacific halibut. Specific objectives in this area include:

- Provide information on the types of fishing gear and fish handling practices used in the Pacific halibut recreational (charter) fishery as well as on the number and size composition of discarded Pacific halibut in this fishery.
- Establish best handling practices for reducing discard mortality of Pacific halibut in recreational fisheries.
- Investigate new methods for improved estimation of depredation mortality from marine mammals.

6.1.3.5 Fishing Technology.

Studies aimed at developing methods that involve modifications of fishing gear with the purpose of reducing Pacific halibut depredation and bycatch. Specific objectives in this area include:

- Investigate new methods for whale avoidance and/or deterrence for the reduction of Pacific halibut depredation by whales (e.g. catch protection methods).
- Investigate physiological and behavioral responses of Pacific halibut to fishing gear in order to reduce bycatch.

<<In development>>>

6.2 Monitoring

The Commission's extensive monitoring programs provide the basis for stock assessment and MSE analysis, many biological research studies and some inputs directly to the decision-making process (Figure 4). While not the primary focus of this 5-year plan, a basic summary of the components led by the IPHC and those that are provided by domestic agencies is provided below.

6.2.1 Fishery-dependent data.

Data collection and monitoring activities aimed at providing standardised time-series of mortality, fishery, and biological data from both direct target fisheries as well as fisheries that incidentally catch P. halibut. Directed commercial fisheries data are managed by IPHC. Non-directed commercial discard mortality data, subsistence fisheries data, and recreational fisheries data are managed by Contracting Party domestic agencies.

6.2.1.1 Directed commercial fisheries data:

Annually review the spatial distribution of sampling effort among ports, data collection methods, sampling rates, and QAQC processes, including in-season review of port sampling activities. Ensure current data collection efforts meet current and future needs of stock assessment, MSE and management. Collaborate and coordinate with other Secretariat functions to develop methods and procedures for incorporating promising research results into long-term monitoring program. The IPHC relies on domestic agency programs to report annual mortality

6.2.1.2 Non-directed commercial discard mortality data

Annually collaborate with observer programs and other partners to ensure robust data collection and sampling, QAQC processes, and reporting of incidental catch and mortality, as well as biological sampling.

6.2.1.3 Subsistence fisheries data

Annually collaborate with Tribal, State and Federal agencies of each Contracting Party to ensure high quality data collection, sampling and reporting in the subsistence fisheries in the U.S. and Canada.

6.2.1.4 Recreational fisheries data

Annually collaborate with National/State agencies of each Contracting Party to ensure and validate high quality data and reporting of recreational fishery mortality estimates and biological data.

6.2.2 Fishery-independent data

Data collection and monitoring activities aimed at providing a standardised time-series of biological and ecological data that is independent of the fishing fleet.

6.2.2.1 Fishery-independent setline survey (FISS)

An annual review process for the FISS station design has been developed (Figure 10) and is expected to continue in coming years. This process involves scientific review of proposed FISS designs by the Scientific Review Board and includes input from stakeholders prior to review and approval of designs by the Commissioners.

Direct weighing of Pacific halibut has been integrated into the annual FISS sampling since 2019 and will continue into the future to ensure accurate estimation of WPUE and other weight-derived quantities. Sample rates for genetic monitoring will need to be determined for future sampling. Sampling rates of otoliths for aging, archive otoliths and tagged fish will continue to be reviewed annually to ensure the data needs of the IPHC stock assessment and research program are met. Annual FISS sampler training and data QAQC (including at point of data collection and during post-sampling review) will ensure high quality data from the FISS program. Procedures are reviewed annually.Fishery-independent Trawl Survey (FITS): The IPHC will continue to collaborate with NMFS on sampling procedures for Pacific halibut on the placement of an IPHC sampler onboard a survey vessel for the collection of biological data.

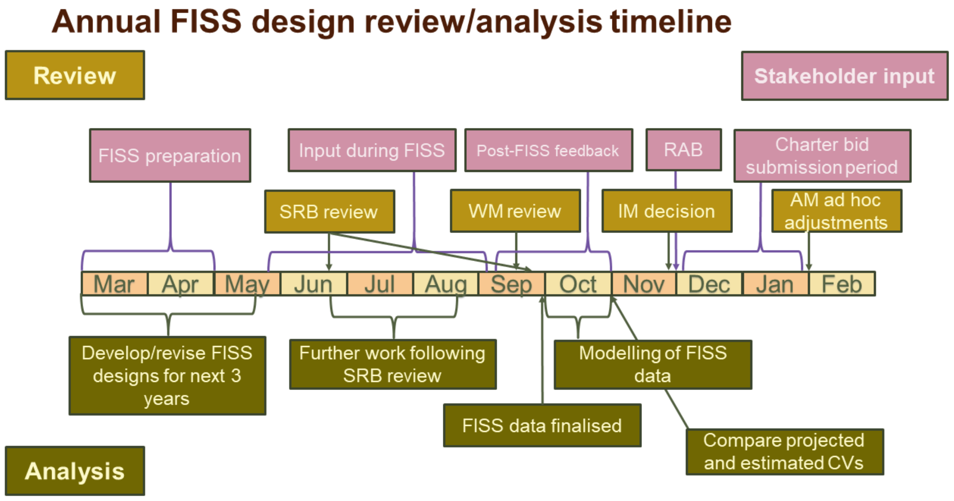

Figure 10. Timeline of annual FISS design review process.

6.2.2.2 Fishery-independent Trawl Survey (FITS)

6.3 Potential of integrating human dynamics into management decision making

Understanding the complexity of human dimension of the fisheries sectors is becoming increasingly important in the context of globalization. Local products compete on the market with a large variety of imported seafood. High exposure to international markets makes seafood accessibility fragile to perturbations, as shown by the covid-19 outbreak (OECD, 2020). Seafood production is also highly dependent on the production and price of imports. The IPHC's socioeconomic study showed that Pacific halibut contribution to households' income dropped by a quarter throughout the pandemic. While signs of strong recovery were present in 2021 (Fry, 2021), the study called attention to Pacific halibut sectors' exposure to external factors beyond stock condition and the need for expanding the scope of management-supporting information the IPHC provides.

It is also unclear how small remote communities can capitalize on the high prices that the final customers are paying for premium seafood products. In 2021, fresh Alaskan Pacific halibut fillets routinely sold for USD 24-28 a pound, and often more, in downtown Seattle (e.g. USD 38 at Pike Place Market). Pacific halibut dishes at the restaurants typically sell for USD 37-43 for a dish including a 6oz fish portion. The IPHC's socioeconomic study detailed the geography of impacts of the Pacific halibut fisheries, providing a coherent picture of the exposure of fisheries-dependent households by location to changes in resource availability, but paying closer attention to quantifying leakage of economic benefits from communities strongly involved in fisheries highlighted that the local earnings often do not align with how much fishing occurs within the community. This suggests the need for research focused on how to operationalize social equity in the context of the globalized market dynamics and the pursuit of stock sustainability.

In addition, fisheries are at the forefront of exposure to the accelerating impacts of climate change. For example, a rapid increase in water temperature off the coast of Alaska in 2014-16, termed *the blob*, affected fisheries (Cheung and Frölicher, 2020) and may have a long-term impact on Pacific halibut distribution. The consequences may include shifts in the distribution of benefits, but possibly go further, affecting the stability of agreements over allocation of a shared resource. Research on decision quality under fast-progressing climate-induced changes to stock distribution may be warranted.

Conflicting objectives among stakeholders regarding the use of limited resource in the context of globalization, calls for social equity and climate change are a major challenge of decision-making in fisheries management. Integrating approaches aimed at understanding the human dynamics and external factors with stock assessment and MSE can assist fisheries in bridging the gap between the current and the optimal performance without compromising the stock biological sustainability. For example, socioeconomic performance metrics presented alongside already developed biological/ecological performance metrics would supplement IPHC's portfolio of tools for assessing policy-oriented issues (as requested by the Commission, IPHC-2021-AM097-R, AM097-Req.02) and support decision making. Moreover, continuing investment in understanding the human dimension of Pacific halibut fishing can also inform on other drivers such as human behavior or human organization that affect the dynamics of fisheries, and thus contribute to improved accuracy of the stock assessment and the MSE (Lynch, Methot and Link, 2018). As such, it can contribute to research integration at the IPHC and provide a complementary resource for the development of harvest control rules.

Lastly, Pacific halibut's value is also in its contribution to the diet through subsistence fisheries and importance to the traditional users of the resource. To native people, traditional fisheries constitute a vital aspect of local identity and a major factor in cohesion. One can also consider the Pacific halibut's existence value as an iconic fish of the Pacific Northwest. Recognizing and adopting such an all-encompassing definition of the Pacific halibut resource contribution, the IPHC echoes a broader call to include the human dimension into the research on the impact of management decisions, as well as changes in environmental or stock conditions.

7. Conclusion and future review/amendments

<<In development>>>

This document represents a substantial expansion from the previous 5-year plan, which focused primarily on the IPHC's research program. All of the programs described here are closely linked and planning for each accounts for the interactions between all of monitoring, assessment, MSE and other management supporting information It is expected that this document will be available and periodically updated on the IPHC's website during the current period to respond to emerging needs and opportunities.

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APPENDICES

Appendix I:	Multi-year tactical activity matrix
Appendix II:	Outcomes of the IPHC 5-Year Biological and Ecosystem Science Research Plan (2017-21)
Appendix III:	Proposed schedule of outputs
Appendix IV:	Proposed schedule with funding and staffing indicators

APPENDIX I

Multi-year tactical activity matrix

<<Info. Graphic in development>>

APPENDIX II

Outcomes of the IPHC 5-Year Biological and Ecosystem Science Research Plan (2017-21) (IPHC–2019–BESRP-5YP)

A. Outcomes by Research Area:

1. Migration and Distribution.

1.1. Larval and juvenile connectivity and early life history studies. Planned research outcomes: improved understanding of larval and juvenile distribution.

Main results:

- Larval connectivity between the Gulf of Alaska and the Bering Sea occurs through large island passes across the Aleutian Island chain.
- The degree of larval connectivity between the Gulf of Alaska and the Bering Sea is influenced by spawning location.
- Spawning locations in the western Gulf of Alaska significantly contribute Pacific halibut larvae to the Bering Sea.
- Pacific halibut juveniles counter-migrate from inshore settlement areas in the eastern Bering Sea into the Gulf of Alaska through Unimak Pass.
- Elemental signatures of otoliths from juvenile Pacific halibut vary geographically at a scale equivalent to IPHC regulatory areas.

Publications:

Sadorus, L.; Goldstein, E.; Webster, R.; Stockhausen, W.; Planas, J.V.; Duffy-Anderson, J. Multiple life-stage connectivity of Pacific halibut (*Hippoglossus stenolepis*) across the Bering Sea and Gulf of Alaska. *Fisheries Oceanography*. 2021. 30:174-193. doi: https://doi.org/10.1111/fog.12512.

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Links to 5-Year Research Plan (2022-2026):

- Evaluate the level of genetic diversity among juvenile Pacific halibut in the Gulf of Alaska and the Bering sea due to admixture.
- Assignment of individual juvenile Pacific halibut to source populations.

Integration with Stock Assessment and MSE: The relevance of research outcomes from activities in this research area for stock assessment is in the improvement of estimates of productivity. Research outcomes will be used to generate potential recruitment covariates and to inform minimum spawning biomass targets by Biological Region and represent one of the top three biological inputs into stock assessment. The relevance of these research outcomes for MSE is in the improvement of the parametrization of the Operating Model and represent the top ranked biological input into the MSE.

2. **Reproduction**.

2.1 Sex ratio of commercial landings. Planned research outcomes: sex ratio information.

Main results:

- Establishment of TaqMan-based genetic assays for genotyping Pacific halibut in the IPHC Biological Laboratory.
- Sex ratio information for the 2017-2020 commercial landings.
- Transfer of genotyping efforts for sex identification to IPHC monitoring program.

Links to 5-Year Research Plan (2022-2026):

- Monitoring effort.

2.2 Histological maturity assessment. Planned research outcomes: updated maturity schedule.

Main results:

- Oocyte developmental stages have been characterized and fully described in female Pacific halibut for the first time.
- Oocyte developmental stages have been used for the classification of female developmental stages and to be able to characterize female Pacific halibut as group synchronous with determinate fecundity.
- Female developmental stages have been used for the classification of female reproductive phases and to be able to characterize female Pacific halibut as following an annual reproductive cycle with spawning in January and February.
- Female developmental stages and reproductive phases of females collected in the central Gulf of Alaska have been used to identify the month of August as the time of the transition between the Vtg2 and Vtg3 developmental stages marking the beginning of the spawning capable reproductive phase.
- Future gonad collections for revising maturity schedules and estimating fecundity can be conducted in August during the FISS.

Publications:

Fish, T., Wolf, N., Harris, B.P., Planas, J.V. A comprehensive description of oocyte developmental stages in Pacific halibut, *Hippoglossus stenolepis*. *Journal of Fish Biology* 2020. 97: 1880-1885. doi: 10.1111/jfb.14551.

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Links to 5-Year Research Plan (2022-2026):

- Revision of maturity schedule by gonad collection during the FISS, as informed by previous studies on reproductive development.
- Estimation of fecundity by age and size, as informed by previous studies demonstrating determinate fecundity.

Integration with Stock Assessment and MSE: Research activities in this Research Area aim at providing information on key biological processes related to reproduction in Pacific halibut (maturity and fecundity) and to provide sex ratio information of Pacific halibut commercial landings. The relevance of research outcomes from these activities for stock assessment is in the scaling of Pacific halibut biomass and in the estimation of reference points and fishing intensity. These research outputs will result in a revision of current maturity schedules and will be included as inputs into the stock assessment, and represent the most important biological inputs for stock assessment. The relevance of these research outcomes for MSE is in the improvement of the simulation of spawning biomass in the Operating Model.

3. Growth.

3.1 Identification of physiological growth markers and their application for growth pattern evaluation. Planned research outcomes: informative physiological growth markers.

Main results:

- Transcriptomic profiling by RNAseq of white skeletal muscle from juvenile Pacific halibut subjected to growth suppression and to growth stimulation resulted in the identification of a number of genes that change their expression levels in response to growth manipulations.
- Proteomic profiling by LC-MS/MS of white skeletal muscle from juvenile Pacific halibut subjected to growth suppression and to growth stimulation resulted in the identification of a number of proteins that change their abundance in response to growth manipulations.
- Genes and proteins that changed their expression levels in accordance to changes in the growth rate in juvenile Pacific halibut were selected as putative growth markers for future studies on growth pattern evaluation.

Publications:

Planas et al. 2022. In Preparation.

Links to 5-Year Research Plan (2022-2026):

- Application of identified growth markers in studies aiming at investigating environmental influences on growth patterns and at investigating dietary influences on growth patterns and physiological condition.

3.2 Environmental influences on growth patterns. Planned research outcomes: information on growth responses to temperature variation.

Main results:

- Laboratory experiments under controlled temperature conditions have shown that temperature affects the growth rate of juvenile Pacific halibut through changes in the expression of genes that regulate growth processes.

Publications:

Planas et al. 2022. In Preparation.

Links to 5-Year Research Plan (2022-2026):

- Identification of temperature-specific responses in skeletal muscle through comparison between transcriptomic responses to temperature-induced growth changes and to density- and stress-induced growth changes.
- Application of growth markers for additional studies investigating the link between environmental variability and growth patterns and the effects of diet (prey quality and abundance) on growth and physiological condition.

Integration with Stock Assessment and MSE: Research activities conducted in this Research Area aim at providing information on somatic growth processes driving size-at-age in Pacific halibut. The relevance of research outcomes from these activities for stock assessment resides, first, in their ability to inform yield-per-recruit and other spatial evaluations for productivity that support mortality limit-setting, and, second, in that they may provide covariates for projecting short-term size-at-age and may help delineate between fishery and environmental effects, thereby informing appropriate management responses. The relevance of these research outcomes for MSE is in the improvement of the simulation of variability and to allow for scenarios investigating climate change.

4. **Mortality and Survival Assessment**.

4.1 Discard mortality rate estimation in the longline Pacific halibut fishery. Planned research outcomes: experimentally-derived DMR.

Main results:

- Different hook release methods used in the longline fishery result in specific injury profiles and viability classification.
- Plasma lactate levels are high in Pacific halibut with the lowest viability classification.
- Mortality of discarded fish with the highest viability classification is estimated to be between 4.2 and 8.4%.

Publications:

Kroska, A.C., Wolf, N., Planas, J.V., Baker, M.R., Smeltz, T.S., Harris, B.P. Controlled experiments to explore the use of a multi-tissue approach to characterizing stress in wild-caught Pacific halibut (*Hippoglossus stenolepis*). *Conservation Physiology* 2021. 9(1):coab001; doi:10.1093/conphys/coab001.

Loher, T., Dykstra, C.L., Hicks, A., Stewart, I.J., Wolf, N., Harris, B.P., Planas, J.V. Estimation of postrelease longline mortality in Pacific halibut using acceleration-logging tags. *North American Journal of Fisheries Management*. 2022. 42: 37-49. DOI: **https://doi.org/10.1002/nafm.10711**.

Links to 5-Year Research Plan (2022-2026):

- Integration of information on capture and handling conditions, injury and viability assessment and physiological condition will lead to establishing a set of best handling practices in the longline fishery.

4.2 Discard mortality rate estimation in the guided recreational Pacific halibut fishery. Planned research outcomes: experimentally-derived DMR.

Main results:

- Field experiments testing two different types of gear types (i.e. 12/0 and 16/0 circle hooks) resulted in the capture, sampling and tagging of 243 Pacific halibut in IPHC Regulatory Area 2C (Sitka, AK) and 118 in IPHC Regulatory Area 3A (Seward, AK).
- The distributions of fish lengths by regulatory area and by hook size were similar.

Links to 5-Year Research Plan (2022-2026):

- Estimation of discard mortality rate in the guided recreational fishery.
- Integration of information on capture and handling conditions, injury and viability assessment and physiological condition linked to survival.
- Establishment of a set of best handling practices in the guided recreational fishery.

Integration with Stock Assessment and MSE: The relevance of research outcomes from these activities for stock assessment resides in their ability to improve trends in unobserved mortality in order to improve estimates of stock productivity and represent the most important inputs in fishery yield for stock assessment. The relevance of these research outcomes for MSE is in fishery parametrization

5. Genetics and genomics.

5.1 Generation of genomic resources for Pacific halibut. Planned research outcomes: sequenced genome and reference transcriptome.

Main results:

- A first draft of the chromosome-level assembly of the Pacific halibut genome has been generated.
- The Pacific halibut genome has a size of 602 Mb and contains 24 chromosome-size scaffolds covering 99.8% of the complete assembly with a N50 scaffold length of 27 Mb at a coverage of 91x.
- The Pacific halibut genome has been annotated by NCBI and is available as NCBI Hippoglossus stenolepis Annotation Release 101 (https://www.ncbi.nlm.nih.gov/assembly/GCA_022539355.2/).
- Transcriptome (i.e. RNA) sequencing has been conducted in twelve tissues in Pacific halibut and the raw sequence data have been deposited in NCBI's Sequence Read Archive (SRA) under the bioproject number PRJNA634339 (https://www.ncbi.nlm.nih.gov/bioproject/PRJNA634339) and with SRA accession numbers SAMN14989915 - SAMN14989926.

Publications:

Jasonowicz, A.C., Simeon, A., Zahm, M., Cabau, C., Klopp, C., Roques, C., Iampietro, C., Lluch, J., Donnadieu, C., Parrinello, H., Drinan, D.P., Hauser, L., Guiguen, Y., Planas, J.V. Generation of a chromosome-level genome assembly for Pacific halibut (*Hippoglossus stenolepis*) and characterization of its sex-determining genomic region. *Molecular Ecology Resources. 2022. In Press*.

Jasonowicz et al. 2022. In Preparation.

Links to 5-Year Research Plan (2022-2026):

- Genome-wide analysis of stock structure and composition.

5.2 Determine the genetic structure of the Pacific halibut population in the Convention Area. Planned research outcomes: genetic population structure.

Main results:

- The collection of winter genetic samples in the Aleutian Islands completed the winter sample collection needed to conduct studies on the genetic population structure of Pacific halibut in the Convention Area.
- Initial results of low coverage whole genome resequencing of winter samples indicate that an average of 26.5 million raw sequencing reads per obtained per sample that provided average individual genomic coverages for quality filtered alignments of 3.2x.

Links to 5-Year Research Plan (2022-2026):

- Fine-scale delineation of population structure, with particular emphasis on IPHC Regulatory 4B structure.

Integration with Stock Assessment and MSE: The relevance of research outcomes from these activities for stock assessment resides in the introduction of possible changes in the structure of future stock assessments, as separate assessments may be constructed if functionally isolated components of the population are found (e.g. IPHC Regulatory Area 4B), and in the improvement of productivity estimates, as this information may be used to define management targets for minimum spawning biomass by Biological Region. These research outcomes provide the second and third top ranked biological inputs into stock assessment. Furthermore, the relevance of these research outcomes for MSE is in biological parametization and validation of movement estimates and of recruitment distribution.

B. List of ranked biological uncertainties and parameters for stock assessment (SA) and their links to research areas and activities contemplated in the IPHC 5-Year Biological and Ecosystem Science Research Plan (2017-21)

SA Rank	Research outcomes	Relevance for stock assessment	Specific analysis input	Research Area	Research activities
1. Biological input	Updated maturity schedule	Scale biomass and reference point estimates	Will be included in the stock assessment, replacing the current schedule last updated in 2006	Reproduction	Histological maturity assessment
	Incidence of skip spawning		Will be used to adjust the asymptote of the maturity schedule, if/when a time-series is available this will be used as a direct input to the stock assessment		Examination of potential skip spawning
	Fecundity-at-age and -size information		Will be used to move from spawning biomass to egg-output as the metric of reproductive capability in the stock assessment and management reference points		Fecundity assessment
	Revised field maturity classification		Revised time-series of historical (and future) maturity for input to the stock assessment		Examination of accuracy of current field macroscopic maturity classification
2. Biological input	Stock structure of IPHC Regulatory Area 4B relative to the rest of the Convention Area	Altered structure of future stock assessments	If 4B is found to be functionally isolated, a separate assessment may be constructed for that IPHC Regulatory Area	Genetics and Genomics	Population structure
3. Biological input	Assignment of individuals to source populations and assessment of distribution changes	Improve estimates of productivity	Will be used to define management targets for minimum spawning biomass by Biological Region		Distribution
	Improved understanding of larval and juvenile distribution		Will be used to generate potential recruitment covariates and to inform minimum spawning biomass targets by Biological Region	Migration	Larval and juvenile connectivity studies
1. Assessment data collection and processing	Sex ratio-at-age	Scale biomass and fishing intensity	Annual sex-ratio at age for the commercial fishery fit by the stock assessment	Reproduction	Sex ratio of current commercial landings
	Historical sex ratio-at-age		Annual sex-ratio at age for the commercial fishery fit by the stock assessment		Historical sex ratios based on archived otolith DNA analyses
2. Assessment data collection and processing	New tools for fishery avoidance/deterence; improved estimation of depredation mortality	Improve mortality accounting	May reduce depredation mortality, thereby increasing available yield for directed fisheries. May also be included as another explicit source of mortality in the stock assessment and mortality limit setting process depending on the estimated magnitude	Mortality and survival assessment	Whale depredation accounting and tools for avoidance
1. Fishery yield	Physiological and behavioral responses to fishing gear	Reduce incidental mortality	May increase yield available to directed fisheries	Mortality and survival assessment	Biological interactions with fishing gear
2. Fishery yield	Guidelines for reducing discard mortality	Improve estimates of unobserved mortality	May reduce discard mortality, thereby increasing available yield for directed fisheries	Mortality and survival assessment	Best handling practices: recreational fishery

C. List of ranked biological uncertainties and parameters for management strategy evaluation (MSE) and their links to research areas and activities contemplated in the IPHC 5-Year Biological and Ecosystem Science Research Plan (2017-21)

MSE Rank	Research outcomes	Relevance for MSE	Research Area	Research activities
1. Biological parameterization and validation of movement estimates	Improved understanding of larval and juvenile distribution	Improve parametization of the Operating Model	Migration	Larval and juvenile connectivity studies
	Stock structure of IPHC Regulatory Area 4B relative to the rest of the Convention Area		Genetics and Genomics	Population structure
2. Biological parameterization and validation of recruitment variability and distribution	Assignment of individuals to source populations and assessment of distribution changes	Improve simulation of recruitment variability and parametization of recruitment distribution in the Operating Model		Distribution
	Establishment of temporal and spatial maturity and spawning patterns	Improve simulation of recruitment variability and parametization of recruitment distribution in the Operating Model	Reproduction	Recruitment strength and variability
3. Biological parameterization and validation for growth projections	Identification and application of markers for growth pattern evaluation	Improve simulation of variability and allow for scenarios investigating climate change	Growth	Evaluation of somatic growth variation as a driver for changes in size-at-age
	Environmental influences on growth patterns			
	Dietary influences on growth patterns and physiological condition			
1. Fishery parameterization	Experimentally-derived DMRs	Improve estimates of stock productivity	Mortality and survival assessment	Discard mortality rate estimate: recreational fishery

D. External funding received during the IPHC 5-Year Biological and Ecosystem Science Research Plan (2017-21):

Project #	Grant agency	Project name	PI	Partners	IPHC Budget ($US)	Management implications	Grant period
1	**Saltonstall-Kennedy NOAA**	Improving discard mortality rate estimates in the Pacific halibut by integrating handling practices, physiological condition and post-release survival (NOAA Award No. NA17NMF4270240)	IPHC	Alaska Pacific University	$286,121	Bycatch estimates	September 2017 – August 2020
2	**North Pacific Research Board**	Somatic growth processes in the Pacific halibut (*Hippoglossus stenolepis*) and their response to temperature, density and stress manipulation effects (NPRB Award No. 1704)	IPHC	AFSC-NOAA-Newport, OR	$131,891	Changes in biomass/size-at-age	September 2017 – February 2020
3	**Bycatch Reduction Engineering Program - NOAA**	Adapting Towed Array Hydrophones to Support Information Sharing Networks to Reduce Interactions Between Sperm Whales and Longline Gear in Alaska	Alaska Longline Fishing Association	IPHC, University of Alaska Southeast, AFSC-NOAA	-	Whale Depredation	September 2018 – August 2019
4	**Bycatch Reduction Engineering Program - NOAA**	Use of LEDs to reduce Pacific halibut catches before trawl entrainment	Pacific States Marine Fisheries Commission	IPHC, NMFS	-	Bycatch reduction	September 2018 – August 2019
5	**National Fish & Wildlife Foundation**	Improving the characterization of discard mortality of Pacific halibut in the recreational fisheries (NFWF Award No. 61484)	IPHC	Alaska Pacific University, U of A Fairbanks, charter industry	$98,902	Bycatch estimates	April 2019 – November 2021
6	**North Pacific Research Board**	Pacific halibut discard mortality rates (NPRB Award No. 2009)	IPHC	Alaska Pacific University,	$210,502	Bycatch estimates	January 2021 –March 2022
7	**Bycatch Reduction Engineering Program - NOAA**	Gear-based approaches to catch protection as a means for minimizing whale depredation in longline fisheries (NA21NMF4720534)	IPHC	Deep Sea Fishermen's Union, Alaska Fisheries Science Center-NOAA, industry representatives	$99,700	Mortality estimations due to whale depredation	November 2021 – October 2022
8	**North Pacific Research Board**	Pacific halibut population genomics (NPRB Award No. 2110)	IPHC	Alaska Fisheries Science Center-NOAA	$193,685	Stock structure	December 2021- January 2024
				Total awarded ($)	**$1,020,801**		

E. Publications in the peer-reviewed literature resulting from the IPHC 5-Year Biological and Ecosystem Science Research Plan (2017-21):

2020:

Fish, T., Wolf, N., Harris, B.P., Planas, J.V. A comprehensive description of oocyte developmental stages in Pacific halibut, *Hippoglossus stenolepis*. *Journal of Fish Biology*. 2020. 97: 1880-1885. https://doi: 10.1111/jfb.14551.

2021:

Carpi, P., Loher, T., Sadorus, L., Forsberg, J., Webster, R., Planas, J.V., Jasonowicz, A., Stewart, I. J., Hicks, A. C. Ontogenetic and spawning migration of Pacific halibut: a review. *Rev Fish Biol Fisheries*. 2021. https://doi.org/10.1007/s11160-021-09672-w.

Kroska, A.C., Wolf, N., Planas, J.V., Baker, M.R., Smeltz, T.S., Harris, B.P. Controlled experiments to explore the use of a multi-tissue approach to characterizing stress in wild-caught Pacific halibut (*Hippoglossus stenolepis*). *Conservation Physiology* 2021. 9(1):coab001. https://doi:10.1093/conphys/coab001.

Loher, T., Bath, G. E., Wischniowsky, S. The potential utility of otolith microchemistry as an indicator of nursery origins in Pacific halibut (*Hippoglossus stenolepis*) in the eastern Pacific: the importance of scale and geographic trending. *Fisheries Research*. 2021. 243: 106072. https://doi.org/10.1016/j.fishres.2021.106072.

Lomeli, M.J.M., Wakefield, W.W., Herrmann, B., Dykstra, C.L., Simeon, A., Rudy, D.M., Planas, J.V. Use of Artificial Illumination to Reduce Pacific Halibut Bycatch in a U.S. West Coast Groundfish Bottom Trawl. *Fisheries Research*. 2021. 233: 105737. doi: 10.1016/j.fishres.2020.105737.

Sadorus, L.; Goldstein, E.; Webster, R.; Stockhausen, W.; Planas, J.V.; Duffy-Anderson, J. Multiple life-stage connectivity of Pacific halibut (*Hippoglossus stenolepis*) across the Bering Sea and Gulf of Alaska. *Fisheries Oceanography*. 2021. 30:174-193. doi: https://doi.org/10.1111/fog.12512.

2022:

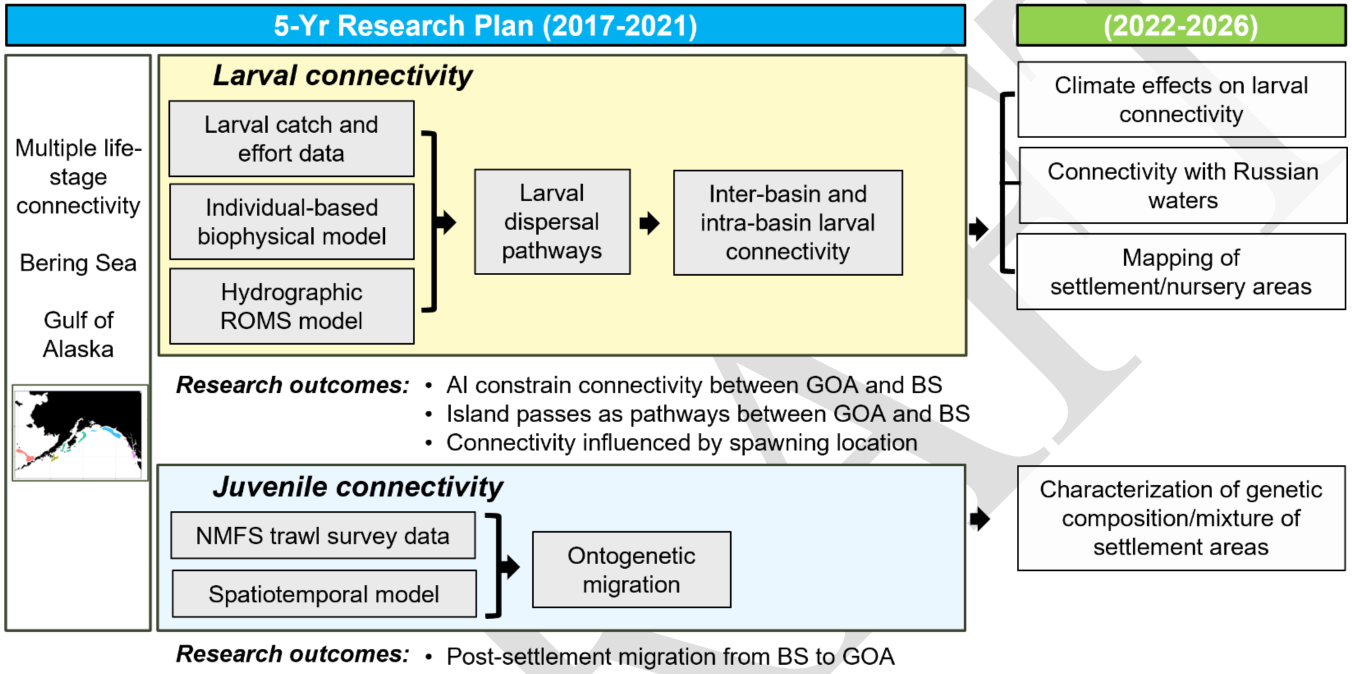
Fish, T., Wolf, N., Smeltz, T. S., Harris, B. P., and Planas, J. V. Reproductive Biology of Female Pacific Halibut (*Hippoglossus stenolepis*) in the Gulf of Alaska. *Frontiers in Marine Science* 2022. 9:801759. doi: 10.3389/fmars.2022.801759.

Jasonowicz, A.C., Simeon, A., Zahm, M., Cabau, C., Klopp, C., Roques, C., Iampietro, C., Lluch, J., Donnadieu, C., Parrinello, H., Drinan, D.P., Hauser, L., Guiguen, Y., Planas, J.V. Generation of a chromosome-level genome assembly for Pacific halibut (*Hippoglossus stenolepis*) and characterization of its sex-determining genomic region. *Molecular Ecology Resources*. 2022. In Press.

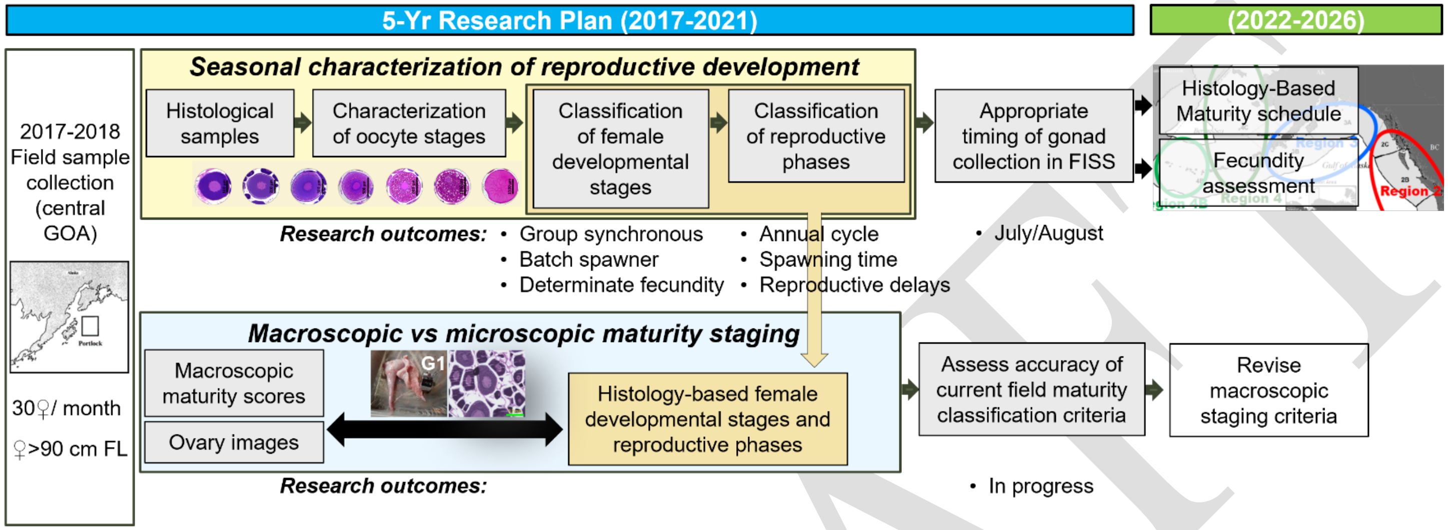
Loher, T., Dykstra, C.L., Hicks, A., Stewart, I.J., Wolf, N., Harris, B.P., Planas, J.V. Estimation of postrelease longline mortality in Pacific halibut using acceleration-logging tags. *North American Journal of Fisheries Management*. 2022. 42: 37-49. DOI: http://dx.doi.org/10.1002/nafm.10711

F. Flow chart of progress resulting from the IPHC 5-Year Biological and Ecosystem Science Research Plan (2017-21) by research area leading to the IPHC 5-Year Program of Integrated Research and Monitoring (2022-2026)

1. Migration and Distribution



2. Reproduction



5-Yr Research Plan (2017-2021)

(2022-2026)

2017-2018 Field sample collection (central GOA)

30♀/ month

♀>90 cm FL

Seasonal characterization of reproductive development

Histological samples

Characterization of oocyte stages

Classification of female developmental stages

Classification of reproductive phases

Appropriate timing of gonad collection in FISS

Histology-Based Maturity schedule

Fecundity assessment

Research outcomes:
- Group synchronous
- Batch spawner
- Determinate fecundity
- Annual cycle
- Spawning time
- Reproductive delays
- July/August

Macroscopic vs microscopic maturity staging

Macroscopic maturity scores

Ovary images

Histology-based female developmental stages and reproductive phases

Assess accuracy of current field maturity classification criteria

Revise macroscopic staging criteria

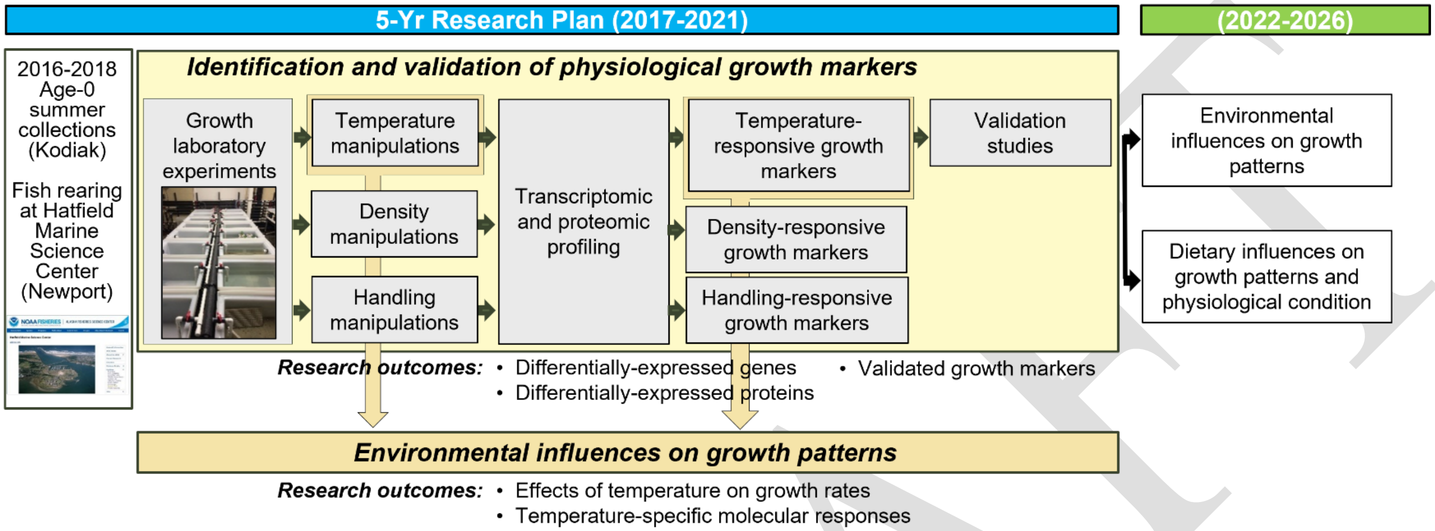
Research outcomes:
- In progress

Staff involved: Teresa Fish, MSc APU (2018-2020), Crystal Simchick, Ian Stewart, Allan Hicks, Josep Planas

Funding: IPHC (2018-2020)

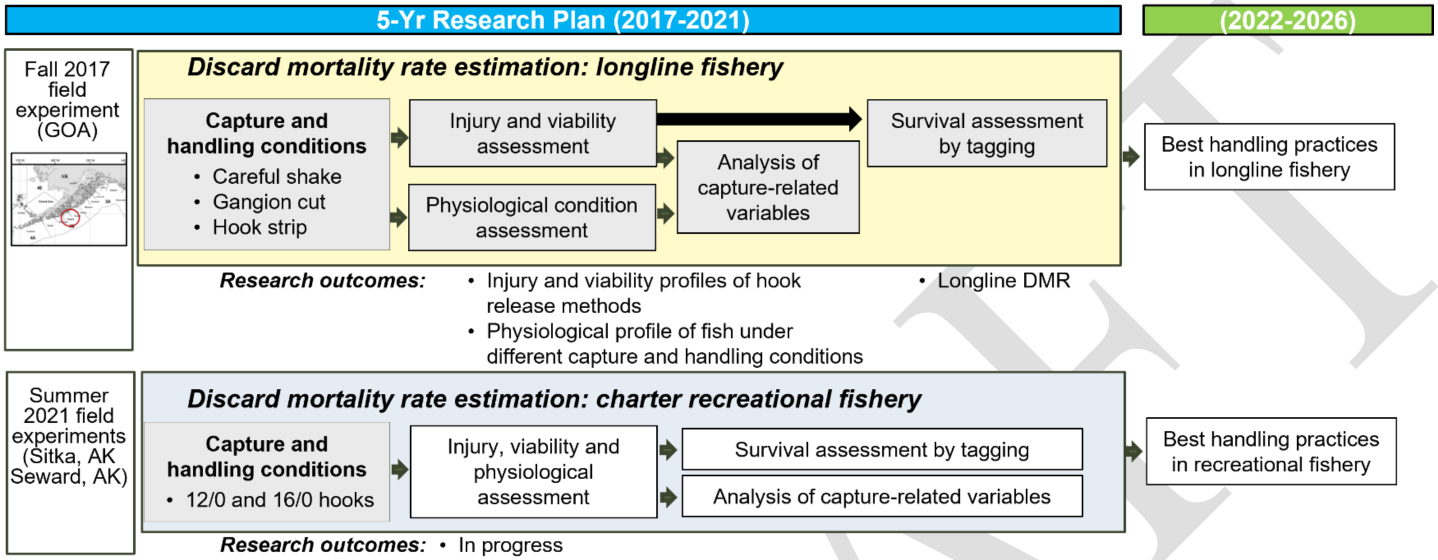
Publications (2): Fish et al. (2020) *J. Fish Biol*. **97**: 1880–1885 ; Fish et al. (2022) Front. Mar. Sci. 9:801759

3. Growth



Staff involved: Andy Jasonowicz, Crystal Simchick, Josep Planas
Funding: NPRB Grant#1704 (Sept. 2017-Feb. 2020)
Publications: Planas et al. (in preparation)

4. Mortality and SurvivalAssessment



5-Yr Research Plan (2017-2021)

(2022-2026)

Fall 2017 field experiment (GOA)

Discard mortality rate estimation: longline fishery

Capture and handling conditions
- Careful shake
- Gangion cut
- Hook strip

Injury and viability assessment

Physiological condition assessment

Analysis of capture-related variables

Survival assessment by tagging

Best handling practices in longline fishery

Research outcomes:
- Injury and viability profiles of hook release methods
- Physiological profile of fish under different capture and handling conditions
- Longline DMR

Summer 2021 field experiments (Sitka, AK Seward, AK)

Discard mortality rate estimation: charter recreational fishery

Capture and handling conditions
- 12/0 and 16/0 hooks

Injury, viability and physiological assessment

Survival assessment by tagging

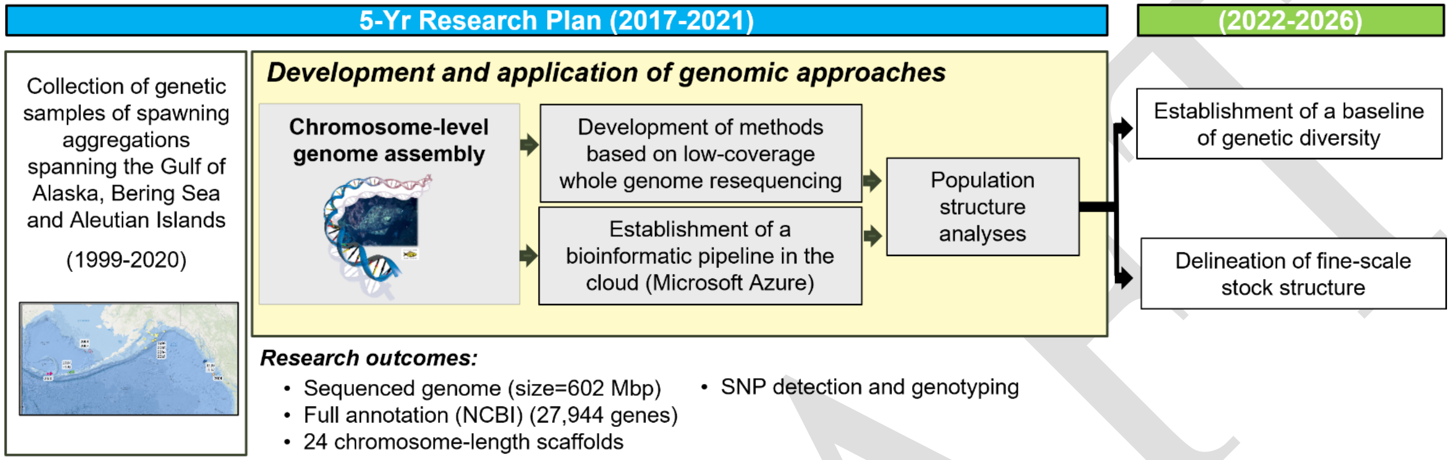
Analysis of capture-related variables

Best handling practices in recreational fishery

Research outcomes:
- In progress

Staff involved: Claude Dykstra, Allan Hicks, Ian Stewart, Josep Planas
Funding (3): Saltonstall-Kennedy NOAA (Sept. 2017-Aug. 2020); NFWF (Apr. 2019-Nov. 2021); NPRB#2009 (Jan. 2021-Mar. 2022)
Publications (2): Kroska et al. (2021) *Conserv. Physiol.*; Loher et al. (2022) *North Amer. J. Fish. Manag. 42: 37-49*

5. Genetics and Genomics



5-Yr Research Plan (2017-2021)

(2022-2026)

Collection of genetic samples of spawning aggregations spanning the Gulf of Alaska, Bering Sea and Aleutian Islands

(1999-2020)

Development and application of genomic approaches

Chromosome-level genome assembly

Development of methods based on low-coverage whole genome resequencing

Establishment of a bioinformatic pipeline in the cloud (Microsoft Azure)

Population structure analyses

Establishment of a baseline of genetic diversity

Delineation of fine-scale stock structure

Research outcomes:

- Sequenced genome (size=602 Mbp)
- Full annotation (NCBI) (27,944 genes)
- 24 chromosome-length scaffolds
- SNP detection and genotyping

Staff involved: Andy Jasonowicz, Josep Planas
Funding: IPHC, NPRB#2110
Publications: Jasonowicz et al. (2022) *Mol. Ecol. Resour. (In Review)*

APPENDIX III

Proposed schedule of outputs

	2022		2023		2024		2025		2026	
Biology and Ecology										
Migration and population dynamics	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Reproduction		▨	▨	▨	▨	▨	▨	▨	▨	▨
Growth			▨	▨	▨	▨	▨			
Mortality and survival assessment	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Fishing technology	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Stock Assessment										
Management Strategy Evaluation										
Monitoring										
Other?										

APPENDIX IV

Proposed schedule of funding and staffing indicators: Biology and Ecology

Research areas	Research activities	Required FTEs/Year	IPHC FTEs/Year	2022				2023				2024				2025				2026				IPHC Funds	Grant Funds
Migration and Population Dynamics	Larval and juvenile connectivity and early life history studies	0.45	0.45	▨	▨	▨	▨	▨	RB1	▨	▨	RB2	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	Yes	NPRB #2100
	Population structure	0.4	0.8	▨	▨	▨	▨	RB1	▨	▨	▨	▨												No	NPRB #2110
	Adult migration and distribution	0.4		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	No	NPRB #2110
	Close-kin mark-recapture studies	1	0									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	No	Planned
	Seascape genomics	1	0									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	No	Planned
	Genome-wide association analyses	1	0									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	No	Planned
	Genomic-based aging methods	1	1				▨	▨	RS 1	▨	▨	▨	▨	▨										Yes	No
Reproduction	Maturity-at-age estimations	0.75	0				▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	Yes	No
	Fecundity assessment	0.5	0.25				▨	▨	▨	▨	▨	RB4	▨	▨	▨	▨	▨	RS 2	▨	▨	▨	▨	▨	Yes	No
	Examination of accuracy of current field macroscopic maturity classification	0.25								▨	▨	▨	▨											Yes	No
	Sex ratio of current commercial landings	0.5	0.75	LT	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	Yes	No
	Recruitment strength and variability	0.5	0												▨	▨	RS 2	▨	▨	▨	▨	▨	▨	Yes	Planned
Growth	Environmental influences on growth patterns	0.5	0.5					▨	▨	▨	MSc student	▨	▨	▨	▨	▨	▨							No	Planned
	Dietary influences on growth patterns and physiological condition	0.5	0.2					▨	▨	▨	RB3	▨	▨	▨	▨	▨	▨							No	Planned
Mortality and survival assessment	Discard mortality rate estimate: recreational fishery	0.5	1	▨	▨	▨	▨																	No	NPRB #2009
	Best handling practices: recreational fishery	0.5		▨	▨	RB 3	▨	▨	▨															No	NPRB #2009
	Whale depredation accounting and tools for avoidance	0.5		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	No	BREP
	Biological interactions with fishing gear	0.5		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	No	BREP

IPHC staff (Planned):

RS1: Research Scientist 1(PhD; Life History Modeler I). Full time temporary position (100% research;

RS2: Research Scientist 1(PhD; Life History Modeler II). Full time temporary position (100% research;

RB1: Research Biologist 1 (Geneticist; MSc). Full time temporary position (until April 2022; 1 FTE). 55% of salary covered by Grant NPRB#2110.

RB2: Research Biologist 2 (Early Life History; MSc). Full time permanent position (40% research; 0.4 FTE)

RB3: Research Biologist 3 (DMR; MSc). Full time permanent position (100% research; 1 FTE)

RB4: Research Biologist 4 (Maturity and Fecundity; MSc). Full time permanent position (100% research; 1 FTE)

LT: Laboratory Technician (MSc). Full time temporary position (100% research; 1 FTE)

Proposed schedule of funding and staffing indicators: Others