IPHC–2020–SRB017–00

17th Session of the IPHC Scientific Review Board (SRB017) – *Compendium of meeting documents*

22 – 24 September 2020, Seattle, WA, USA

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IPHC–2020–SRB017–R

Report of the 17th Session of the IPHC Scientific Review Board (SRB017)

Meeting held electronically, 22-24 September 2020

Commissioners

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ACRONYMS

AM	Annual Meeting
COVID-19	Novel Coronavirus 2019
DMR	Discard Mortality Rate
FISS	Fishery-Independent Setline Survey
IPHC	International Pacific Halibut Commission
MSAB	Management Strategy Advisory Board
MSE	Management Strategy Evaluation
NPUE	Number-Per-Unit-Effort
SA	Stock Assessment
SRB	Scientific Review Board
TCEY	Total Constant Exploitable Yield
U.S.A.	United States of America
WPUE	Weight-Per-Unit-Effort

DEFINITIONS

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

HOW TO INTERPRET TERMINOLOGY CONTAINED IN THIS REPORT

This report has been written using the following terms and associated definitions so as to remove ambiguity surrounding how particular paragraphs should be interpreted.

Level 1: **RECOMMENDED**; **RECOMMENDATION; ADOPTED** (formal); **REQUESTED; ENDORSED** (informal): A conclusion for an action to be undertaken, by a Contracting Party, a subsidiary (advisory) body of the Commission and/or the IPHC Secretariat.

Level 2: **AGREED**: Any point of discussion from a meeting which the Commission considers to be an agreed course of action covered by its mandate, which has not already been dealt with under Level 1 above; a general point of agreement among delegations/participants of a meeting which does not need to be elevated in the Commission's reporting structure.

Level 3: **NOTED/NOTING**; **CONSIDERED**; **URGED**; **ACKNOWLEDGED**: General terms to be used for consistency. Any point of discussion from a meeting which the Commission considers to be important enough to record in a meeting report for future reference. Any other term may be used to highlight to the reader of an IPHC report, the importance of the relevant paragraph. Other terms may be used but will be considered for explanatory/informational purposes only and shall have no higher rating within the reporting terminology hierarchy than Level 3.

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EXECUTIVE SUMMARY

The 17th Session of the International Pacific Halibut Commission (IPHC) Scientific Review Board (SRB017) was held electronically from 22 to 24 September 2020. The meeting was opened by the Chairperson, Dr Sean Cox (Canada).

The following are a subset of the complete recommendations/requests for action from the SRB017, which are provided in full at Appendix V.

RECOMMENDATIONS

IPHC Fishery-independent setline survey (FISS)

SRB017–Rec.01 (para. 14) The SRB **RECOMMENDED** that the Commission endorse the final 2021 FISS design as proposed by IPHC Secretariat, and provided at Appendix IVa.

Biological and ecosystem science program research updates

SRB017–Rec.02 (para. 31) **NOTING** the improved presentation of the research integration plan, the SRB **RECOMMENDED** that the research planning table shown in the meeting presentation for paper IPHC-2020-SRB017-08, be improved by adding clear prioritization of biological research needs for addressing uncertainties in the stock assessment and MSE programs. Ideally, this would be in the form of ranked biological uncertainties/parameters for the stock assessment and MSE operating model along with an explanation for deviations from this ranked list.

Management Strategy Evaluation

SRB017–Rec.06 (para. 57) The SRB **NOTED** three options for estimation error are available and currently the option of simulating estimation is the most appropriate option to evaluate results in 2020, but **RECOMMENDED** continuing work to incorporate actual estimation models, as in the third option, because that method would best mimic the current assessment process.

SRB017–Rec.07 (para. 59) The SRB **RECOMMENDED** using the current MSE results to compare and contrast management procedures incorporating scale and distribution elements, but **NOTED** that, current results are conditional on some parameters and processes that remain uncertain. The uncertainty in applying the untested current approach potentially creates greater risk than adopting a repeatable management procedure that has been simulation tested under a wide range of uncertainties.

REQUESTS

Biological and ecosystem science program research updates

SRB017–Req.07 (para. 33) The SRB **REQUESTED** that the IPHC Secretariat further develop planning for the remainder of the current 5-year planning period and to revise and submit a comparable synthesis planning document for review at SRB018. In terms of the current research activities and research outcomes, further detail is needed in several areas, including:

a) further detail for (i) specific research outcomes, (ii) specific relevance for stock assessment relevance, (iii) specific relevance for MSE (see Section 8.1 for examples);

b) prioritize research activities and research outcomes.

SRB017–Req.09 (para. 37) The SRB **REQUESTED** that the IPHC Secretariat include explicit statements describing how research activities and research outcomes for each of the five IPHC research areas have relevance to stock assessment and the MSE in all future SRB meeting briefing documents beginning with SRB018.

1. OPENING OF THE SESSION

1. The 17th Session of the International Pacific Halibut Commission (IPHC) Scientific Review Board (SRB017) was held electronically from 22 to 24 September 2020. The list of participants is provided at Appendix I. The meeting was opened by the Chairperson, Dr Sean Cox (Canada).

2. The SRB **RECALLED** its mandate, as detailed in Appendix VIII, Sect. I, para. 1-3 of the IPHC Rules of Procedure (2020):

   1. *The Scientific Review Board (SRB) shall provide an independent scientific peer review of Commission science/research proposals, programs, and products, including but not limited to:*
      - a. *Data collection;*
      - b. *Historical data sets;*
      - c. *Stock assessment;*
      - d. *Management Strategy Evaluation;*
      - e. *Migration;*
      - f. *Reproduction;*
      - g. *Growth;*
      - h. *Discard survival;*
      - i. *Genetics and Genomics.*
   2. *Undertake periodic reviews of science/research strategy, progress, and overall performance.*
   3. *Review the recommendations arising from the MSAB and the RAB.*

2. ADOPTION OF THE AGENDA AND ARRANGEMENTS FOR THE SESSION

3. The SRB **ADOPTED** the Agenda as provided at Appendix II. The documents provided to the SRB are listed in Appendix III. Participants were reminded that all documents for the meeting were published on the IPHC website, 30 days prior to the Session: https://www.iphc.int/venues/details/17th-session-of-the-iphc-scientific-review-board-srb017.

3. IPHC PROCESS

3.1 SRB annual workflow

4. The SRB **RECALLED** that the core purpose of the SRB017 is to review progress on the IPHC science and research program, including specific products, and to provide guidance for the delivery of products to the Commission at its Interim Meeting in November 2020, and Annual Meeting in January 2021.

3.2 Update on the actions arising from the 16th Session of the SRB (SRB016)

5. The SRB **NOTED** paper IPHC-2020-SRB017-03, which provided the SRB with an opportunity to consider the progress made during the intersessional period, on the recommendations/requests arising from the SRB016.

6. The SRB **NOTED** that most actions from SRB016 remain either ‘In Progress’ or ‘Pending’.

7. The SRB **AGREED** to consider and revise the actions as necessary, and to combine them with any new actions arising from SRB017 into a consolidated list for future reporting.

3.3 Outcomes of the 96th Session of the IPHC Annual Meeting (AM096)

8. The SRB **NOTED** paper IPHC-2020-SRB017-04 which detailed the outcomes of the 96th Session of the IPHC Annual Meeting (AM096), relevant to the mandate of the SRB, and **AGREED** to consider how best to provide the Commission with the information it has requested, throughout the course of the current SRB meeting.

3.4 Observer updates

9. The SRB **NOTED** updates from the two science advisors, who provided brief overviews of some of the points of clarification being sought from the present SRB meeting. These included, but were not limited to: 1) potential differences between estimated movement rates (i.e. via previous research, tagging estimates, and assumptions for young fish) and MSE operating model values and the potential implications for MSE results; 2) ongoing challenges communicating MSE analyses and encouraged SRB input on approaches to improving this process.

10. The SRB **NOTED** valuable contributions by scientific observers to both the SRB and MSAB processes.

4. IPHC FISHERY-INDEPENDENT SETLINE SURVEY (FISS)

4.1 Preliminary results from the 2020 FISS

11. The SRB **NOTED** paper IPHC-2020-SRB017-05, which provides an update on space-time modelling data inputs for 2020 and preliminary results of 2020 FISS modelling, recognizing that FISS data are not yet finalized and therefore space-time modelling of IPHC Regulatory Areas surveyed in 2020 has not been undertaken at present.

12. The SRB **NOTED** and applauded the IPHC Secretariat, field staff (Fisheries Data Specialists; Setline Survey Specialists), and contracted vessels for successfully executing the 2020 FISS under the potentially overwhelming circumstances of the COVID-19 pandemic. Despite such challenges, the FISS was still able to achieve the intended range of precision set in the FISS Objectives. This achievement speaks to both the dedication of the entire IPHC Secretariat and the flexibility of the spatio-temporal analysis framework to accommodate changes in FISS design.

4.2 Review: Rationalisation of the FISS following the 2014-19 expansion series

13. The SRB **NOTED** paper IPHC-2020-SRB017-06, which provided background on and review the methods for the IPHC's Fishery-Independent Setline Survey (FISS) rationalisation following the 2014-19 expansion series, along with discussion of the resulting FISS design proposals for the 2020-22 period and presentation of the proposed designs for 2021-23.

14. The SRB **RECOMMENDED** that the Commission endorse the final 2021 FISS design as proposed by IPHC Secretariat, and provided at Appendix IVa.

15. The SRB provisionally **ENDORSED** the 2022 and 2023 FISS design proposals provided at Appendix IVb and IVc, recognizing that these will be reviewed again at subsequent SRB meetings.

16. The SRB **REQUESTED** clarification of the FISS design workflow and timeline to make it clear that when FISS design proposals are presented to the SRB, the current year's FISS data will not be available, and therefore evaluation of design proposals for the subsequent three years will be based on past years' data only.

17. The SRB **REQUESTED** that at SRB018, the IPHC Secretariat present information on changes in space-time model parameters and output over time:
    a) covariate parameter estimates over several years should be provided in order to assess their sensitivity to the addition of each year's new data;
    b) comparison maps of estimates of WPUE or NPUE at each FISS station for the same calendar year based on models fitted in different years to determine how station estimates are affected by the addition of new data;
    c) estimates of the relative contributions of covariates vs. spatio-temporal interpolations in predictions at unsampled locations.

18. The SRB **REQUESTED** that the IPHC Secretariat present at SRB018, a review of the methods used for adjusting WPUE and NPUE indices for the effects of hook competition in the FISS, given the SRB's interest in the following:

a) the potential benefits of further analysis and/or hook timer experiments to better inform bait mortality rates used in FISS hook competition adjustments;

b) an evaluation of hook competition incorporated into the space-time model to account for potential spatio-temporal patterns in hook competition and linking the hook competition adjustment to covariates of competitor (e.g. dogfish) abundance;

c) a quantitative evaluation of the assumptions that the same hook competition adjustment factor can be applied to both NPUE and WPUE, as well as uniformly across regions, because the biomass to numbers (i.e. the mean weight) apparently changes over time.

5. PACIFIC HALIBUT STOCK ASSESSMENT: 2020

5.1 Updates on the development of the 2020 stock assessment

19. The SRB **NOTED** paper IPHC-2020-SRB017-07, which provided a summary of stock assessment development, including responses to previous SRB requests and an update on data sources and planning for the final 2020 stock assessment.

20. The SRB **AGREED** that the final 2020 stock assessment would include new data on recreational and commercial sex-ratios at age as well as updates to all standard data sources, including:

    a) 2020 FISS results: modelled trends and biological data;

    b) 2020 Commercial fishery logbook and biological sampling;

    c) Biological information from other sources (non-directed commercial and recreational);

    d) Mortality estimates for 2020 and updates to 2019 where necessary.

21. The SRB **REQUESTED** that the IPHC Secretariat continue to update data weighting on an annual basis, even for updated stock assessments (such as 2020), in order to maintain internal model consistency and to best reflect changes in existing and new data as they arise.

22. The SRB **NOTED** the IPHC Secretariat's review of the use of the logistic-normal likelihood for composition data in stock assessment, including the development challenges associated with treatment of a two-dimensional correlation structure (age and sex) and the associated resource requirement that are needed.

23. The SRB **REQUESTED** that the IPHC Secretariat first investigate the consequences of implementing a logistic-normal likelihood for composition data assuming no correlation structure. This would provide an initial estimate of the benefits of self-weighting fairly quickly compared to developing a full age/sex correlated version.

24. The SRB **REQUESTED** that the IPHC Secretariat continue to evaluate whether the Stock Synthesis modelling framework is the most efficient for Commission needs, and to coordinate future development with the MSE framework as features and technical needs evolve together for the two efforts.

6. PEER REVIEW OF THE IPHC MANAGEMENT STRATEGY EVALUATION PROCESS

25. The SRB **NOTED** the presentation provided by Dr Trevor Branch, the independent peer reviewer of the IPHC MSE process. Dr Branch presented his draft report, with the intention of seeking additional feedback from the SRB before finalising the report. The following is a summary of the report findings, as provided by Dr Branch:

> "*The management strategy evaluation (MSE) of IPHC is intended to simulation test rules for setting allowable catch for Pacific halibut and the allocation of catch and bycatch among IPHC Regulatory Areas. In my judgment the MSE is technically sound. Furthermore, the MSE team led by Allan Hicks was praised by all interviewed participants involved in the process for their technical work, collaboration with stakeholders in developing harvest control rules, and*

> *communication of results to stakeholders. However, the following issues need to be resolved to ensure the continued success and accuracy of MSE simulation for IPHC: (1) decide soon on the future of the MSE process beyond January 2021 and allocate necessary funding; (2) treat the MSE framework as an ongoing process that will be used over many years alongside the stock assessment, to test the effectiveness of data gathering, stock assessment assumptions, and catch - setting in IPHC; (3) require the Commission to codify the rules they used to adjust catch levels within each Regulatory Area after the harvest control rule is applied, so that the MSE framework accurately evaluates risk to the stock and catches within each such Area.*"

26. The SRB **AGREED** that the peer review was a thorough analysis, and met the desired objectives of providing a fully independent external review of the IPHC's Management Strategy Evaluation work undertaken to date.

27. The SRB **AGREED** with conclusions of the independent peer reviewer that:
    a) the MSE framework establishes a valuable new tool for formally evaluating and prioritizing research objectives;
    b) uncertainty regarding staffing for MSE work is inconsistent with the long-term role of MSE in addressing critical strategic needs of the Commission in setting and distributing Pacific halibut yield among regulatory areas;
    c) the IPHC Secretariat continue to improve and develop communication tools and participation in the MSE process;
    d) the IPHC Secretariat establish a formal process for determining whether Exceptional Circumstances exist in a given year that would justify deviating from the harvest control rule.

28. The SRB **NOTED** that the independent peer review suggested a further round of development may be necessary on the spatial allocation of TCEY.

7. BIOLOGICAL AND ECOSYSTEM SCIENCE PROGRAM RESEARCH UPDATES

7.1 Report on current and future biological research activities

29. The SRB **NOTED** paper IPHC-2020-SRB017-08 which provided the SRB with an update on progress on IPHC's five-year Biological and Ecosystem Sciences Research Plan (2017-21).

30. The SRB **NOTED** the efforts made by the IPHC Secretariat to address requests made by the SRB during the SRB016 meeting. Addressing remarks made during the Secretariat's presentation pertaining to each request.

31. **NOTING** the improved presentation of the research integration plan, the SRB **RECOMMENDED** that the research planning table shown in the meeting presentation for paper IPHC-2020-SRB017-08, be improved by adding clear prioritization of biological research needs for addressing uncertainties in the stock assessment and MSE programs. Ideally, this would be in the form of ranked biological uncertainties/parameters for the stock assessment and MSE operating model along with an explanation for deviations from this ranked list.

32. The SRB **RECALLED** the request from SRB016–Req.17, and that strides made by the IPHC Secretariat to better integrate the IPHC Biological and Ecosystem Sciences Research program to meet stock assessment and MSE needs. Placing the Research Activities and Research Outcomes for each of the five IPHC Research Areas into contexts of relevance to stock assessment and MSE was viewed positively by the SRB. However, such information was only presented in the oral presentation and not in paper IPHC-2020-SRB017-08. The brief description of species analysis input to stock assessment and MSE needs was also a useful step forward.

33. The SRB **REQUESTED** that the IPHC Secretariat further develop planning for the remainder of the current 5-year planning period and to revise and submit a comparable synthesis planning document for

review at SRB018. In terms of the current research activities and research outcomes, further detail is needed in several areas, including:

a) further detail for (i) specific research outcomes, (ii) specific relevance for stock assessment relevance, (iii) specific relevance for MSE (see Section 8.1 for examples);

b) prioritize research activities and research outcomes.

34. **NOTING** that a time line was presented by the IPHC Secretariat that provided information on likely periods in future years when research outcomes would be available for use by the Secretariat, the SRB **REQUESTED** further clarification on funding and staffing needs required to meet self-imposed deadlines.

35. The SRB **NOTED** the progress on ongoing research projects contemplated within the IPHC's five-year biological and ecosystem sciences research plan (2017-21) in each of five research areas.

36. The SRB **THANKED** the IPHC Secretariat for the presentation on progress in these studies, but **NOTED** that it was not always possible to discern the relevance of the findings in relation to the management process, because detail in the sampling design evaluation, hypotheses to be tested, and the potential scale of impact on the stock assessment and MSE processes were not usually included in the presentation. In some cases at least such information appeared to have been available and should have been included.

37. The SRB **REQUESTED** that the IPHC Secretariat include explicit statements describing how research activities and research outcomes for each of the five IPHC research areas have relevance to stock assessment and the MSE in all future SRB meeting briefing documents beginning with SRB018.

38. The SRB **NOTED** that this is the final opportunity for the SRB to input into the prioritisation of the new research plan prior to finalisation while the necessary information on use prioritization, methodological information and cost which would have allowed the SRB to assess the risks and benefits of the research plan, were not available. The SRB therefore **NOTED** that feedback on the five-year biological and ecosystem sciences research plan would be provided.

39. The SRB **NOTED** the progress on ongoing research projects contemplated within the IPHC's five-year biological and ecosystem sciences research plan (2017-21).

7.1.1 Migration and Distribution

40. The SRB **NOTED** the studies aimed at further understanding reproductive migration and identification of spawning times and locations as well as larval and juvenile dispersal.

41. The SRB **NOTED** and congratulated authors Sadorus et al. (2020) on acceptance for publication of their paper in Fisheries Oceanography pertaining to larval and juvenile dispersal in the Gulf of Alaska and the Bering Sea.

7.1.2 Reproduction

42. The SRB **NOTED** the studies aimed at providing information on the sex ratio of the commercial catch and to improve current estimates of maturity.

43. The SRB **REQUESTED** that the Secretariat should clarify how skip-spawning research contributes to stock assessment and MSE functions. In particular, future research should develop and present:

i. models for forecasting or estimating skip-spawning for Pacific halibut taking into account the timing of the sample collection, size / age and potentially condition factor of females;

ii. estimates of the potential impact of skip-spawning scenarios on management procedure performance;

iii. clear plans for analyses of histological data, including incorporation of age variation and locational variation;

iv. details of experimental and sampling designs, as well as expected analyses for "measures of fecundity".

7.1.3 Growth and Physiological Condition

44. The SRB **NOTED** ongoing studies 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. Studies in this research area would benefit from greater integration with the genomics area. The SRB **REQUESTED** that the Secretariat provide a plan for integration of research outcomes in this research area with outcomes in the genetics and genomics research area.

7.1.4 Discard Mortality Rates (DMRs) and Survival

45. The SRB **NOTED** ongoing studies aimed at providing updated estimates of DMRs in both the commercial longline and recreational fisheries.

46. The SRB **NOTED** the new IPHC project pertaining to handling practices and stress within the recreational fishery, but that summary materials presented in paper IPHC-2020-SRB017-08 and in the meeting presentation were brief and did not provide sufficient detail for the SRB to comment on the efficacy of experimental methods or of the likelihood of achieving desired research outcomes.

47. The SRB **REQUESTED** that IPHC Secretariat provide the grant proposal funding the DMR work, and provide a more detailed presentation at SRB018.

7.1.5 Genetics and Genomics

48. The SRB **NOTED** ongoing studies 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.

49. **NOTING** IPHC Secretariat responses to SRB016-Req. 15 that requested additional methodological detail pertaining to ongoing genomics research, the SRB **RECOMMENDED** that the IPHC Secretariat work with collectors to develop a series of benchmark summary statistics that characterize the quality of the Pacific halibut genome developed.

50. The SRB **NOTED** that IPHC Secretariat comments on SRB016-Req. 18 to annotate the genome. A URL was provided.

51. **NOTING** SRB016-Req. 18 was addressed and that the Pacific halibut genome has been annotated, the SRB **REQUESTED** that the IPHC Secretariat prepare a research plan for describing and justifying how the knowledge (and all the resources expended in getting it) of the genome will be used to inform SA and MSE information needs (i.e. as per above request to further elaborate the research plan for this research area). This will likely require some form of interaction (e.g. collaborations, workshops) with outside researchers and/or agencies.

7.2 Research integration

52. The SRB **NOTED** that the IPHC Secretariat have embraced past SRB recommendations to integrate the research program with stock assessment and MSE information needs.

53. The SRB **RECOMMENDED** that the IPHC Secretariat incorporate prioritization of research activities, as well as the timeline of available research outputs as inputs into the stock assessment and MSE processes.

54. 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.

8. MANAGEMENT STRATEGY EVALUATION: UPDATE

8.1 An update on the IPHC Management Strategy Evaluation (MSE) process

55. The SRB **NOTED** paper IPHC-2020-SRB017-09 which provided the SRB with a description of the IPHC MSE framework, a description of the specifications of the multi-area operating model, results from conditioning the multi-area operating model, and an overview of the implementation of management procedures.

56. The SRB **NOTED** the MSE Explorer tool available online to present and evaluate MSE results. The SRB was impressed by the flexibility of the tool to facilitate stakeholder education of fishery management and MSE concepts, as well as the power to analyze complex outputs from the simulations.

57. The SRB **NOTED** three options for estimation error are available and currently the option of simulating estimation is the most appropriate option to evaluate results in 2020, but **RECOMMENDED** continuing work to incorporate actual estimation models, as in the third option, because that method would best mimic the current assessment process.

58. The SRB **NOTED** that results from the multi-region simulations showed a higher average TCEY and lower probabilities of low stock status for a given SPR than the previous coastwide MSE results, but average stock status was similar. This is consistent with the lower variability incorporated in the multi-region approach due to the use of a single operating model as opposed to the 2 used in the coast-wide operating model. Low biomass regionally and the need for the model to maintain all populations means the parameter space may be more restrictive resulting in greater stability.

59. The SRB **RECOMMENDED** using the current MSE results to compare and contrast management procedures incorporating scale and distribution elements, but **NOTED** that, current results are conditional on some parameters and processes that remain uncertain. The uncertainty in applying the untested current approach potentially creates greater risk than adopting a repeatable management procedure that has been simulation tested under a wide range of uncertainties.

60. The SRB **RECOMMENDED** that Exceptional Circumstances be defined to determine whether monitoring information has potentially departed from their expected distributions generated by the MSE. Declaration of Exceptional Circumstances may warrant re-opening and revising the operating models and testing procedures used to justify a particular management procedure.

61. The SRB **REQUESTED** that the IPHC Secretariat include plotting function in the MSE Explorer to visualize among-Regulatory Area trade-offs in various yield statistics.

9. REVIEW OF THE DRAFT AND ADOPTION OF THE REPORT OF THE 17TH SESSION OF THE IPHC SCIENTIFIC REVIEW BOARD (SRB017)

62. The report of the 17th Session of the IPHC Scientific Review Board (IPHC-2020-SRB017-R) was **ADOPTED** on 24 September 2020, including the consolidated set of recommendations and/or requests arising from SRB017, provided at Appendix V.

APPENDIX I
LIST OF PARTICIPANTS FOR THE 17TH SESSION OF THE IPHC SCIENTIFIC REVIEW BOARD (SRB017)

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Dr Ian **Stewart**	Quantitative Scientist, ian.stewart@iphc.int
Dr Ray **Webster**	Quantitative Scientist, ray.webster@iphc.int

APPENDIX II

AGENDA FOR THE 17TH SESSION OF THE IPHC SCIENTIFIC REVIEW BOARD (SRB017)

Date: 22-24 September 2020
Location: Electronic Meeting
Venue: Go-To-Meeting
Time: 12:00-17:00 (22nd), 09:00-16:00 (23rd), 09:00-12:00 (24th)
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

3. IPHC PROCESS

3.1. SRB annual workflow (D. Wilson)
3.2. Update on the actions arising from the 16th Session of the SRB (SRB016) (D. Wilson)
3.3. Outcomes of the 96th Session of the IPHC Annual Meeting (AM096) (D. Wilson)
3.4. Observer updates (e.g. Science Advisors)

4. IPHC FISHERY-INDEPENDENT SETLINE SURVEY (FISS)

4.1. Preliminary results from the 2020 FISS (R. Webster)
4.2. Review: Rationalisation of the FISS following the 2014-19 expansion series (R. Webster)

5. PACIFIC HALIBUT STOCK ASSESSMENT: 2020

5.1. Updates on the development of the 2020 stock assessment (I. Stewart)

6. PEER REVIEW OF THE IPHC MANAGEMENT STRATEGY EVALUATION PROCESS

6.1. Report on the peer review of the IPHC Management Strategy Evaluation process (T. Branch)

7. BIOLOGICAL AND ECOSYSTEM SCIENCE RESEARCH UPDATES

7.1. Report on current and future biological research activities (J. Planas)

8. MANAGEMENT STRATEGY EVALUATION: UPDATE

8.1. An update on the IPHC Management Strategy Evaluation (MSE) process (A. Hicks, P. Carpi, S. Berukoff, I. Stewart)

9. REVIEW OF THE DRAFT AND ADOPTION OF THE REPORT OF THE 17TH SESSION OF THE IPHC SCIENTIFIC REVIEW BOARD (SRB017)

APPENDIX III
LIST OF DOCUMENTS FOR THE 17TH SESSION OF THE IPHC SCIENTIFIC REVIEW BOARD (SRB017)

Document	Title	Availability
IPHC-2020-SRB017-01	Agenda & Schedule for the 17th Session of the Scientific Review Board (SRB017)	✓ 26 Jun 2020 ✓ 20 Aug 2020 ✓ 22 Sep 2020
IPHC-2020-SRB017-02	List of Documents for the 17th Session of the Scientific Review Board (SRB017)	✓ 16 Aug 2020 ✓ 21 Aug 2020
IPHC-2020-SRB017-03	Update on the actions arising from the 16th Session of the SRB (SRB016) (IPHC Secretariat)	✓ 21 Aug 2020
IPHC-2020-SRB017-04	Outcomes of the 96th Session of the IPHC Annual Meeting (AM096) (D. Wilson)	✓ 20 Aug 2020
IPHC-2020-SRB017-05	Preliminary results of the 2020 FISS (R. Webster)	✓ 21 Aug 2020
IPHC-2020-SRB017-06	Review: Rationalisation of the FISS following the 2014-19 expansion series (R. Webster)	✓ 20 Aug 2020
IPHC-2020-SRB017-07	Updates on the development of the 2020 stock assessment (I. Stewart, A. Hicks)	✓ 20 Aug 2020
IPHC-2020-SRB017-08	Report on current and future biological research activities (J. Planas)	✓ 20 Aug 2020
IPHC-2020-SRB017-09	An update on the IPHC Management Strategy Evaluation (MSE) process for SRB017 (A. Hicks, P. Carpi, S. Berukoff, I. Stewart)	✓ 21 Aug 2020
IPHC-2020-SRB017-10	Technical details of the IPHC MSE framework (A. Hicks, P. Carpi, S. Berukoff)	✓ 21 Aug 2020
Information papers		
IPHC-2020-SRB017-INF01	Nil	-

APPENDIX IV

IPHC FISHERY-INDEPENDENT SETLINE SURVEY (FISS) DESIGN PROPOSED FOR 2021, AND TENTATIVELY PROPOSED FOR 2022-23

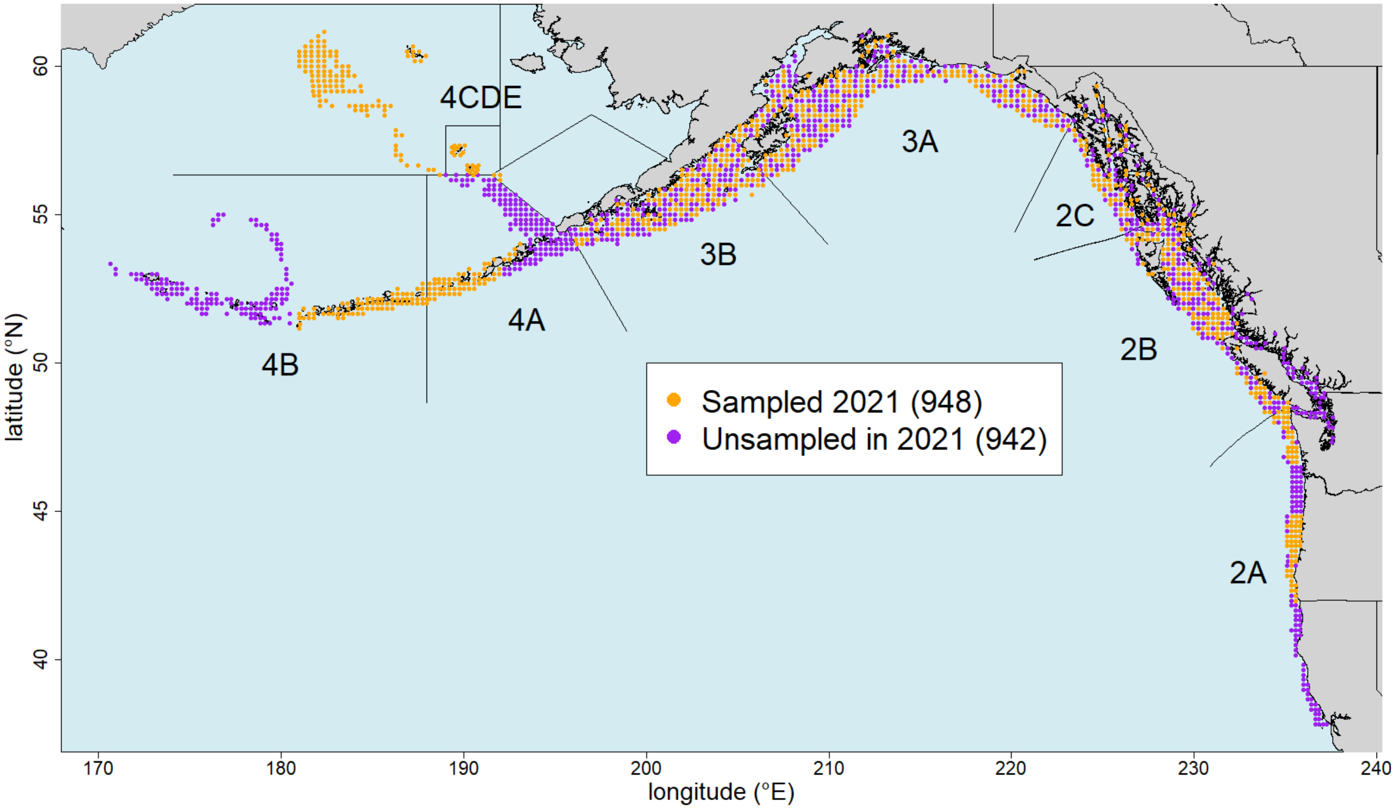


Figure a. Proposed minimum FISS design in 2021 (orange circles) based on randomized sampling in 2B-3B, and a subarea design elsewhere. Purple circles are optional for meeting data quality criteria.

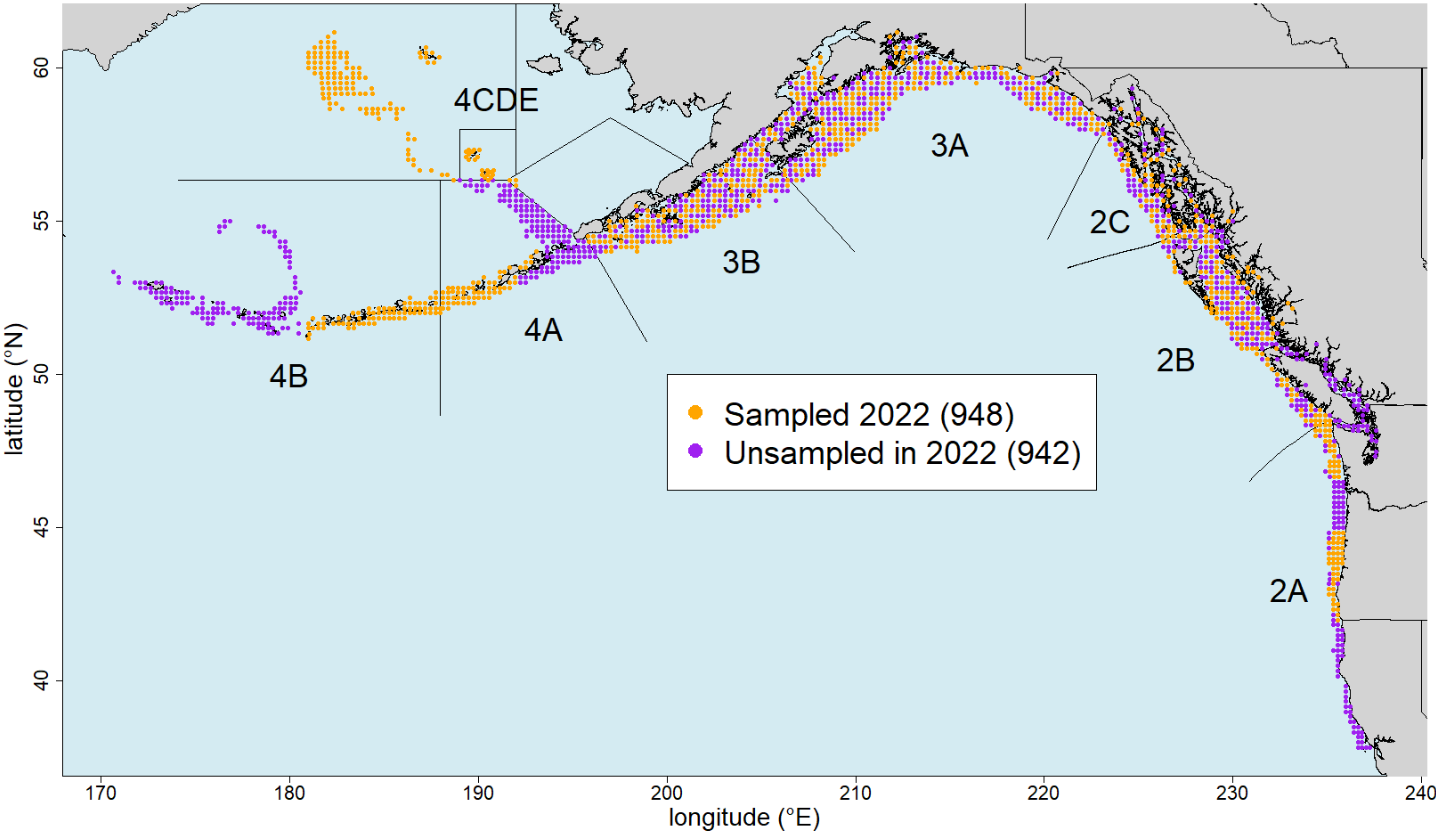


Figure b. Proposed minimum FISS design in 2022 (orange circles) based on randomized sampling in 2B-3B, and a subarea design elsewhere. Purple circles are optional for meeting data quality criteria. The proposed design for 2022 is subject to revision following analysis of data from the 2021 FISS.

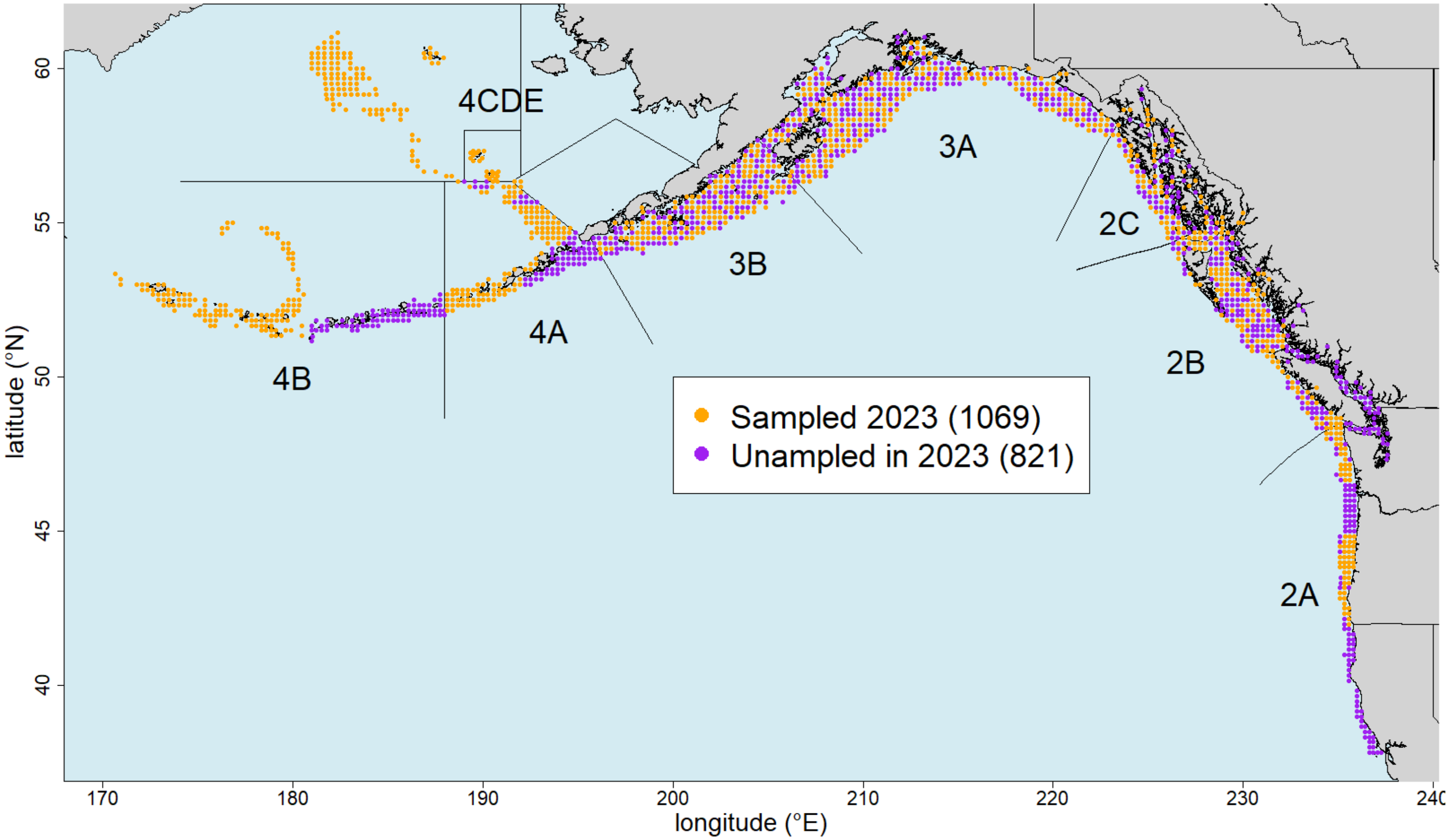


Figure c. Proposed minimum FISS design in 2023 (orange circles) based on randomized sampling in 2B-3B, and a subarea design elsewhere. Purple circles are optional for meeting data quality criteria. The proposed design for 2023 is subject to revision following analysis of data from the 2021 and 2022 FISS.

APPENDIX V

CONSOLIDATED SET OF RECOMMENDATIONS AND REQUESTS OF THE 17TH SESSION OF THE IPHC SCIENTIFIC REVIEW BOARD (SRB017)

RECOMMENDATIONS

IPHC Fishery-independent setline survey (FISS)

SRB017–Rec.01 (para. 14) The SRB **RECOMMENDED** that the Commission endorse the final 2021 FISS design as proposed by IPHC Secretariat, and provided at Appendix IVa.

Biological and ecosystem science program research updates

SRB017–Rec.02 (para. 31) **NOTING** the improved presentation of the research integration plan, the SRB **RECOMMENDED** that the research planning table shown in the meeting presentation for paper IPHC-2020-SRB017-08, be improved by adding clear prioritization of biological research needs for addressing uncertainties in the stock assessment and MSE programs. Ideally, this would be in the form of ranked biological uncertainties/parameters for the stock assessment and MSE operating model along with an explanation for deviations from this ranked list.

Genetics and Genomics

SRB017–Rec.03 (para. 49) **NOTING** IPHC Secretariat responses to SRB016-Req. 15 that requested additional methodological detail pertaining to ongoing genomics research, the SRB **RECOMMENDED** that the IPHC Secretariat work with collectors to develop a series of benchmark summary statistics that characterize the quality of the Pacific halibut genome developed.

Research integration

SRB017–Rec.04 (para. 53) The SRB **RECOMMENDED** that the IPHC Secretariat incorporate prioritization of research activities, as well as the timeline of available research outputs as inputs into the stock assessment and MSE processes.

SRB017–Rec.05 (para. 54) 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.

Management Strategy Evaluation

SRB017–Rec.06 (para. 57) The SRB **NOTED** three options for estimation error are available and currently the option of simulating estimation is the most appropriate option to evaluate results in 2020, but **RECOMMENDED** continuing work to incorporate actual estimation models, as in the third option, because that method would best mimic the current assessment process.

SRB017–Rec.07 (para. 59) The SRB **RECOMMENDED** using the current MSE results to compare and contrast management procedures incorporating scale and distribution elements, but **NOTED** that, current results are conditional on some parameters and processes that remain uncertain. The uncertainty in applying the untested current approach potentially creates greater risk than adopting a repeatable management procedure that has been simulation tested under a wide range of uncertainties.

SRB017–Rec.08 (para. 60) The SRB **RECOMMENDED** that Exceptional Circumstances be defined to determine whether monitoring information has potentially departed from their expected distributions generated by the MSE. Declaration of Exceptional Circumstances may warrant re-opening and revising the operating models and testing procedures used to justify a particular management procedure.

REQUESTS

IPHC Fishery-independent setline survey (FISS)

SRB017–Req.01 (para. 16) The SRB **REQUESTED** clarification of the FISS design workflow and timeline to make it clear that when FISS design proposals are presented to the SRB, the current year's FISS data will not be available, and therefore evaluation of design proposals for the subsequent three years will be based on past years' data only.

SRB017–Req.02 (para. 17) The SRB **REQUESTED** that at SRB018, the IPHC Secretariat present information on changes in space-time model parameters and output over time:

a) covariate parameter estimates over several years should be provided in order to assess their sensitivity to the addition of each year's new data;

b) comparison maps of estimates of WPUE or NPUE at each FISS station for the same calendar year based on models fitted in different years to determine how station estimates are affected by the addition of new data;

c) estimates of the relative contributions of covariates vs. spatio-temporal interpolations in predictions at unsampled locations.

SRB017–Req.03 (para. 18) The SRB **REQUESTED** that the IPHC Secretariat present at SRB018, a review of the methods used for adjusting WPUE and NPUE indices for the effects of hook competition in the FISS, given the SRB's interest in the following:

a) the potential benefits of further analysis and/or hook timer experiments to better inform bait mortality rates used in FISS hook competition adjustments;

b) an evaluation of hook competition incorporated into the space-time model to account for potential spatio-temporal patterns in hook competition and linking the hook competition adjustment to covariates of competitor (e.g. dogfish) abundance;

c) a quantitative evaluation of the assumptions that the same hook competition adjustment factor can be applied to both NPUE and WPUE, as well as uniformly across regions, because the biomass to numbers (i.e. the mean weight) apparently changes over time.

Pacific halibut stock assessment: 2020

SRB017–Req.04 (para. 21) The SRB **REQUESTED** that the IPHC Secretariat continue to update data weighting on an annual basis, even for updated stock assessments (such as 2020), in order to maintain internal model consistency and to best reflect changes in existing and new data as they arise.

SRB017–Req.05 (para. 23) The SRB **REQUESTED** that the IPHC Secretariat first investigate the consequences of implementing a logistic-normal likelihood for composition data assuming no correlation structure. This would provide an initial estimate of the benefits of self-weighting fairly quickly compared to developing a full age/sex correlated version.

SRB017–Req.06 (para. 24) The SRB **REQUESTED** that the IPHC Secretariat continue to evaluate whether the Stock Synthesis modelling framework is the most efficient for Commission needs, and to coordinate future development with the MSE framework as features and technical needs evolve together for the two efforts.

Biological and ecosystem science program research updates

SRB017–Req.07 (para. 33) The SRB **REQUESTED** that the IPHC Secretariat further develop planning for the remainder of the current 5-year planning period and to revise and submit a comparable synthesis planning document for review at SRB018. In terms of the current research activities and research outcomes, further detail is needed in several areas, including:

a) further detail for (i) specific research outcomes, (ii) specific relevance for stock assessment relevance, (iii) specific relevance for MSE (see Section 8.1 for examples);

b) prioritize research activities and research outcomes.

SRB017–Req.08 (para. 34) **NOTING** that a time line was presented by the IPHC Secretariat that provided information on likely periods in future years when research outcomes would be available for use by the Secretariat, the SRB **REQUESTED** further clarification on funding and staffing needs required to meet self-imposed deadlines.

SRB017–Req.09 (para. 37) The SRB **REQUESTED** that the IPHC Secretariat include explicit statements describing how research activities and research outcomes for each of the five IPHC research areas have relevance to stock assessment and the MSE in all future SRB meeting briefing documents beginning with SRB018.

Reproduction

SRB017–Req.10 (para. 43) The SRB **REQUESTED** that the Secretariat should clarify how skip-spawning research contributes to stock assessment and MSE functions. In particular, future research should develop and present:

i. models for forecasting or estimating skip-spawning for Pacific halibut taking into account the timing of the sample collection, size / age and potentially condition factor of females;

ii. estimates of the potential impact of skip-spawning scenarios on management procedure performance;

iii. clear plans for analyses of histological data, including incorporation of age variation and locational variation;

iv. details of experimental and sampling designs, as well as expected analyses for "measures of fecundity"

Growth and Physiological Condition

SRB017–Req.11 (para. 44) The SRB **NOTED** ongoing studies 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. Studies in this research area would benefit from greater integration with the genomics area. The SRB **REQUESTED** that the Secretariat provide a plan for integration of research outcomes in this research area with outcomes in the genetics and genomics research area.

Discard Mortality Rates (DMRs) and Survival

SRB017–Req.12 (para. 47) The SRB **REQUESTED** that IPHC Secretariat provide the grant proposal funding the DMR work, and provide a more detailed presentation at SRB018.

Genetics and Genomics

SRB017–Req.13 (para. 51) **NOTING** SRB016-Req. 18 was addressed and that the Pacific halibut genome has been annotated, the SRB **REQUESTED** that the IPHC Secretariat prepare a research plan for describing and justifying how the knowledge (and all the resources expended in getting it) of the genome will be used to inform SA and MSE information needs (i.e. as per above request to further elaborate the research plan for this research area). This will likely require some form of interaction (e.g. collaborations, workshops) with outside researchers and/or agencies.

Management Strategy Evaluation

SRB017–Req.14 (para. 61) The SRB **REQUESTED** that the IPHC Secretariat include plotting function in the MSE Explorer to visualize among-Regulatory Area trade-offs in various yield statistics.

Last updated: 22 September 2020

AGENDA & SCHEDULE FOR THE 17th SESSION OF THE IPHC SCIENTIFIC REVIEW BOARD (SRB017)

Date: 22-24 September 2020
Location: Electronic Meeting
Venue: Go-To-Meeting
Time: 12:00-17:00 (22nd), 09:00-16:00 (23rd), 09:00-12:00 (24th)
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

3. IPHC PROCESS

3.1. SRB annual workflow (D. Wilson)
3.2. Update on the actions arising from the 16th Session of the SRB (SRB016) (D. Wilson)
3.3. Outcomes of the 96th Session of the IPHC Annual Meeting (AM096) (D. Wilson)
3.4. Observer updates (e.g. Science Advisors)

4. IPHC FISHERY-INDEPENDENT SETLINE SURVEY (FISS)

4.1. Preliminary results from the 2020 FISS (R. Webster)
4.2. Review: Rationalisation of the FISS following the 2014-19 expansion series (R. Webster)

5. PACIFIC HALIBUT STOCK ASSESSMENT: 2020

5.1. Updates on the development of the 2020 stock assessment (I. Stewart)

6. PEER REVIEW OF THE IPHC MANAGEMENT STRATEGY EVALUATION PROCESS

6.1. Report on the peer review of the IPHC Management Strategy Evaluation process (T. Branch)

7. BIOLOGICAL AND ECOSYSTEM SCIENCE RESEARCH UPDATES

7.1. Report on current and future biological research activities (J. Planas)

8. MANAGEMENT STRATEGY EVALUATION: UPDATE

8.1. An update on the IPHC Management Strategy Evaluation (MSE) process (A. Hicks, P. Carpi, S. Berukoff, I. Stewart)

9. REVIEW OF THE DRAFT AND ADOPTION OF THE REPORT OF THE 17TH SESSION OF THE IPHC SCIENTIFIC REVIEW BOARD (SRB017)

SCHEDULE FOR THE 17th SESSION OF THE IPHC SCIENTIFIC REVIEW BOARD (SRB017)

Tuesday, 22 September 2020

Time	**Agenda item**	**Lead**
12:00-12:30	Go-To-Meeting set-up. Participants encouraged to call in and test connection	
12:30-12:45	1. OPENING OF THE SESSION 2. ADOPTION OF THE AGENDA AND ARRANGEMENTS FOR THE SESSION	S. Cox & D. Wilson
12:45-13:30	3. IPHC PROCESS 3.1 SRB annual workflow 3.2 Update on the actions arising from the 16th Session of the SRB (SRB016) 3.3 Outcomes of the 96th Session of the IPHC Annual Meeting (AM096) 3.4 Observer updates (e.g. Science Advisors)	D. Wilson
13:30-14:45	4. IPHC FISHERY-INDEPENDENT SETLINE SURVEY (FISS) 4.1 Preliminary results from the 2020 FISS 4.2 Review: Rationalisation of the FISS following the 2014-19 expansion series (R. Webster)	R. Webster
14:45-15:30	5. PACIFIC HALIBUT STOCK ASSESSMENT: 2020 5.1 Updates on the development of the 2020 stock assessment	I. Stewart
15:30-15:45	Break	
15:45-16:30	5. PACIFIC HALIBUT STOCK ASSESSMENT: 2020 (cont.)	I. Stewart
16:30-17:00	SRB drafting session	SRB members

Wednesday, 23 September 2020

Time	**Agenda item**	**Lead**
09:00-10:00	Review of Day 1 and discussion of SRB Recommendations from Day 1	Chairperson
10:00-10:30	6. PEER REVIEW OF THE IPHC MANAGEMENT STRATEGY EVALUATION PROCESS 6.1. Report on the peer review of the IPHC Management Strategy Evaluation process	T. Branch

10:30-12:00	7. BIOLOGICAL AND ECOSYSTEM SCIENCE PROGRAM RESEARCH UPDATES 7.1. Report on current and future biological research activities	J. Planas
12:00-12:30	Break	
12:30-15:00	8. MANAGEMENT STRATEGY EVALUATION: UPDATE 8.1 An update on the IPHC Management Strategy Evaluation (MSE) process	A. Hicks
15:00-16:00	SRB drafting session	SRB members
16:00	Close	
Thursday, 24 September 2020		
Time	**Agenda item**	**Lead**
09:00-11:00	SRB drafting session	SRB members
11:00-12:00	9. REVIEW OF THE DRAFT AND ADOPTION OF THE REPORT OF THE 17th SESSION OF THE IPHC SCIENTIFIC REVIEW BOARD (SRB017)	S. Cox

INTERNATIONAL PACIFIC HALIBUT COMMISSION

IPHC-2020-SRB017-02

Last updated: 21 August 2020

DRAFT: LIST OF DOCUMENTS FOR THE 17th SESSION OF THE IPHC SCIENTIFIC REVIEW BOARD (SRB017)

Document	Title	Availability
IPHC-2020-SRB017-01	Agenda & Schedule for the 17th Session of the Scientific Review Board (SRB017)	✓ 26 Jun 2020 ✓ 20 Aug 2020
IPHC-2020-SRB017-02	List of Documents for the 17th Session of the Scientific Review Board (SRB017)	✓ 16 Aug 2020 ✓ 21 Aug 2020
IPHC-2020-SRB017-03	Update on the actions arising from the 16th Session of the SRB (SRB016) (IPHC Secretariat)	✓ 21 Aug 2020
IPHC-2020-SRB017-04	Outcomes of the 96th Session of the IPHC Annual Meeting (AM096) (D. Wilson)	✓ 20 Aug 2020
IPHC-2020-SRB017-05	Preliminary results of the 2020 FISS (R. Webster)	✓ 21 Aug 2020
IPHC-2020-SRB017-06	Review: Rationalisation of the FISS following the 2014-19 expansion series (R. Webster)	✓ 20 Aug 2020
IPHC-2020-SRB017-07	Updates on the development of the 2020 stock assessment (I. Stewart, A. Hicks)	✓ 20 Aug 2020
IPHC-2020-SRB017-08	Report on current and future biological research activities (J. Planas)	✓ 20 Aug 2020
IPHC-2020-SRB017-09	An update on the IPHC Management Strategy Evaluation (MSE) process for SRB017 (A. Hicks, P. Carpi, S. Berukoff, I. Stewart)	✓ 21 Aug 2020
IPHC-2020-SRB017-10	Technical details of the IPHC MSE framework (A. Hicks, P. Carpi, S. Berukoff)	✓ 21 Aug 2020
Information papers		
IPHC-2020-SRB017-INF01	Nil	-

UPDATE ON THE ACTIONS ARISING FROM THE 16TH SESSION OF THE IPHC SCIENTIFIC REVIEW BOARD (SRB016)

PREPARED BY: IPHC SECRETARIAT (21 AUGUST 2020)

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 SRB016.

BACKGROUND

At the SRB016, the members recommended/requested a series of actions to be taken by the IPHC Secretariat, as detailed in the SRB016 meeting report (IPHC-2020-SRB016-R) available from the IPHC website, and as provided in Appendix A.

DISCUSSION

During the 17th Session of the SRB (SRB017), 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-2020-SRB017-03, 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 (SRB016).
2) **AGREE** to consider and revise the actions as necessary, and to combine them with any new actions arising from SRB017.

APPENDICES

Appendix A: Update on actions arising from the 16th Session of the IPHC Scientific Review Board (SRB016)

APPENDIX A
Update on actions arising from the 16th Session of the IPHC Scientific Review Board (SRB016)

RECOMMENDATIONS

(para. 4) ***NOTING*** *that the core purpose of the SRB016 is to review progress on the IPHC science program, and to provide guidance for the delivery of products to the SRB017 in September 2020, the SRB* ***RECALLED*** *that formal recommendations to the Commission would not be developed at the present meeting, but rather, these would be developed at the SRB017.*

REQUESTS

Action No.	Description	Update
SRB016–Req.01 (para. 11)	***IPHC Fishery-independent setline survey (FISS)*** The SRB **NOTED** that many ecological processes that could be influencing the spatial distribution of the stock, and thus the performance of the FISS in providing a reliable index of relative abundance, are not adequately represented and uncertainty is underestimated when the spatial-temporal model is used to both simulate and analyse FISS data. One specific concern is that density-dependent habitat selection combined with preferential sampling of core habitat areas (to achieve cost goals) could lead to hyperstability in the index. As a first step, the SRB **REQUESTED** the IPHC Secretariat investigate the potential consequences and risk of FISS designs under density-dependent habitat selection (or other spatial processes) in future MSE work. Independent models could be developed for simulating FISS sampling data that could represent qualitatively different scenarios regarding ecological processes driving the spatial distribution of the stock.	**Pending**: MSE research will be done in the future after the delivery of the MSE results at AM097.
SRB016–Req.02 (para. 12)	The SRB **REQUESTED** that the IPHC Secretariat to develop a routine evaluation procedure following data collection to ensure that FISS designs adequately meet monitoring objectives (i.e. that projected FISS CVs represent realized future CVs).	**Pending**: Pending results of the 2020 FISS, projected CVs for sampled IPHC Regulatory Areas will be compared with CVs estimated from the 2020 space-time modelling."

Action No.	Description	Update
SRB016–Req.03 (para. 20)	***Pacific halibut stock assessment: 2020*** The SRB **REQUESTED** that the IPHC Secretariat continue to update data weighting on an annual basis, even for updated stock assessments, in order to maintain internal model consistency and to best reflect changes in existing and new data as they arise.	**In Progress**: Will be completed for the final 2020 stock assessment. See document **IPHC-2020-SRB017-07**.
SRB016–Req.04 (para. 21)	The SRB **AGREED** that data weighting approaches, including alternative error distributions (e.g. self-weighting), should be evaluated further in the context of the next full stock assessment, and should strive to make use of the best methods available, noting that there are a range of approaches in use for similar stock assessments. In particular, the SRB **REQUESTED** that the IPHC Secretariat investigate the feasibility of a logistic-normal distribution to incorporate correlated errors in age composition data (see Francis, R.I.C.C. 2014. Replacing the multinomial in stock assessment models: A first step. Fisheries Research 151: 70–84). This change may be technically challenging given the current assessment software, as well as having sexed age composition data, and could non-trivially affect the stock assessment estimates of biomass and recruitment. Therefore, the SRB does not expect new results until at least SRB018 in June 2021.	**In Progress**: See document **IPHC-2020-SRB017-07**.
SRB016–Req.05 (para. 22)	The SRB **REQUESTED** that the Secretariat staff continue to evaluate whether the Stock Synthesis modelling framework is the most efficient for Commission needs, and to coordinate future development with the MSE framework as features and technical needs evolve together for the two efforts.	**In Progress**: See document **IPHC-2020-SRB017-07**.
SRB016–Req.06 (para. 23)	The SRB **REQUESTED** an update at SRB017 on all data available at that time and any additional changes anticipated for the final 2020 stock assessment.	**Completed**: See document **IPHC-2020-SRB017-07**.

Action No.	Description	Update
SRB016–Req.07 (para. 26)	***Management Strategy Evaluation: update*** The SRB **REQUESTED** that the IPHC Secretariat carefully (i.e. narrowly) scope the MSE work for 2020 to questions that are reasonably determined given the rapid expansion of uncertainties in a more complex model. The MSE timelines for delivery is short; therefore, results will need to be presented conditional on some parameters and processes remaining highly uncertain. For example, processes that remain highly uncertain be collected in a "reference grid" of plausible scenarios and a "robustness grid" of processes that currently lack evidence based on historical data.	**In Progress**: The MSE is focused to meet the recommendations of the Commission and MSAB as outlined in document **IPHC-2020-SRB017-09**.
SRB016–Req.08 (para. 27)	The SRB **NOTED** that stochasticity in Pacific halibut productivity is driven substantially by extrinsic factors (i.e. processes independent of Pacific halibut population size, structure, distribution, etc.). While the current approach is reasonable at this early stage of operating model development, the SRB **REQUESTED** that the IPHC Secretariat investigate intrinsic drivers (e.g. compensatory and depensatory effect) for at least some of these processes. Further integration of the IPHC's biological and ecosystem sciences research plan into the MSE operating model development could be used to sensitivity-test such scenarios. Given the existing MSE timelines, however, more complex operating models could be delayed until SRB018 in June 2021.	**Pending**: The MSE framework is generalized and will be expanded to encompass additional questions after the first complete results are presented to the Commission.
SRB016–Req.09 (para. 28)	The SRB **NOTED** autocorrelation structure in projected Pacific halibut weight-at-age in the spatial operating model. While such a structure adequately captures the smoothness of historical patterns, it is not clear whether it captures the correlation structure among ages. Therefore, the SRB **REQUESTED** that a multivariate normal distribution be investigated (for SRB018 June 2021) for weight-at-age deviations in which these are correlated among ages. This would involve fitting a multivariate time-series model instead of	**Pending**: This will be investigated for SRB018

Action No.	Description	Update
	the ARIMA. Other forms of growth deviations (e.g. cohort-dependence) could also be used to better represent changes in weight-at-age over time.	
SRB016–Req.10 (para. 29)	The SRB **NOTED** that the operating model includes decision-making variability or implementation uncertainty. This is an important addition to the MSE because, while some management procedures may perform reasonably well if fully implemented, large inter-annual adjustments could be made in practice in response to anticipated economic and social disruptions to the fishery. Thus, the SRB **REQUESTED** further investigation of decision-making variability, including empirical analysis of the relationship between recommended and implemented harvest levels.	**In Progress**: A small amount of implementation variability is included, but is not related to the decision-making process. This will be investigated in 2021.
SRB016–Req.11 (para. 36)	***Migration and distribution*** **NOTING** that the genetic data may be complimentary to data collected using other methods, for example, stock structure at the genetic level could be reflected in individual differences in otolith chemistry (if primary otolith annuli are interrogated), the SRB **REQUESTED** that a portion of individuals that are selected for otolith chemistry also be used for whole genome sequencing.	**Pending**: Future planning of studies involving otolith chemistry will incorporate the collection of tissue (fin clip) samples for whole genome sequencing
SRB016–Req.12 (para. 37)	**NOTING** the issues of Gulf of Alaska (GOA) and Bering Sea (BS) connectivity relative to juvenile dispersal, the SRB **REQUESTED** that the IPHC Secretariat include individuals of different ages and locations in the GOA and BS in their whole genome sequencing analysis, including individuals from different places in GOA and BS.	**In Progress**: Tissue (fin clip) samples from juvenile Pacific halibut collected in the GOA and BS are currently being selected for age and capture location for whole genome sequencing analysis. A sample summary will be presented at the SRB017.

Action No.	Description	Update
SRB016–Req.13 (para. 38)	***Reproductive assessment*** The SRB **REQUESTED** a preliminary analysis of existing data on 'skipped spawning'.	**In Progress**: Representative histological characteristics of skipped spawning are being investigated. This information will be presented at the SRB017.
SRB016–Req.14 (para. 39)	The SRB **REQUESTED** that work on size- and age-specific fecundity be incorporated in the next 5-year research plan.	**In Progress**: Studies on size- and age-specific fecundity are being planned for execution in 2021. This information will be presented at the SRB017.
SRB016–Req.15 (para. 41)	***Genetics and genomics*** The SRB **NOTED** that the text in this section of paper IPHC-2020-SRB016-09 was not consistent. A high level of detail was provided in some areas and much less detail was provided in others. At one level, the SRB requires more information on (a) objectives and (b) methods to evaluate study design and the quality of data, however this was not possible given the information provided. For example in the first section on whole genome sequencing there was a major gap in methods. The SRB **REQUESTED** specific information on how the sequence data would be mapped to the reference genome.	**In Progress**: Methods similar to those used by Clucas et al. (2019) will be used to align raw sequence reads to the Pacific halibut reference genome. This information will be presented at the SRB017.

Action No.	Description	Update
SRB016–Req.16 (para. 42)	**NOTING** the importance of genetically determined sex information to stock assessment, the SRB **REQUESTED** that the IPHC Secretariat conduct a pilot study to determine whether DNA and PCR amplification of sex-linked SNP loci can be obtained from archived otoliths of different collection periods to demonstrate feasibility to develop a more comprehensive spatial and temporal sex ratio data base.	**In Progress**: The IPHC Secretariat is conducting studies to determine whether DNA can be extracted from otoliths and whether sex information can be generated. This information will be presented at the SRB017.
SRB016–Req.17 (para. 44)	***Research integration*** The SRB **REQUESTED** an updated presentation on the plan and timelines for integrating research and results from biological and ecosystem science research plan into specific functions and parameters of the assessment and MSE.	**In Progress**: The IPHC Secretariat is updating the plan and timelines of the integration between research activities and stock assessment and MSE needs. This information will be presented at the SRB017
SRB016–Req.18 (para. 49)	The SRB **REQUESTED** that the IPHC Secretariat contact the National Center for Biological Information to annotate the genome. Subsequently, existing and newly discovered SNPs be mapped onto the existing Pacific halibut genome.	**Completed**: The IPHC Secretariat requested genome annotation from NCBI and the annotation has now been completed and available as NCBI Hippoglossus stenolepis Annotation Release 100.
SRB016–Req.19 (para. 52)	**NOTING** that a common theme in programmatic studies is a need to understand growth, the maturation process and size and age at sexual maturity, and to incorporate this understanding into the assessment and MSE programs. The SRB reiterated its previous **REQUEST** that the IPHC Secretariat hire a PhD-level life history modeller with expertise in the areas that include life history and quantitative genetics. The SRB was advised	**Pending**: The IPHC does not intend on hiring a life-history modeller for the foreseeable future.

Action No.	Description	Update
	that at this point in time, the hiring of a life-history modeller is not financially feasible unless either 1) additional contributions were appropriated by the Contracting Parties, or 2) a current FTE was replaced with a life-history modeller.	

IPHC-2020-SRB017-04

OUTCOMES OF THE 96TH SESSION OF THE IPHC ANNUAL MEETING (AM096)

PREPARED BY: IPHC SECRETARIAT (D. WILSON, 20 AUGUST 2020)

PURPOSE

To provide the SRB with the outcomes of the 96th Session of the IPHC Annual Meeting (AM096) relevant to the mandate of the SRB.

BACKGROUND

The agenda of the Commission's Annual Meeting (AM096) included several agenda items relevant to the SRB:

6. *STOCK STATUS OF PACIFIC HALIBUT (2019) & HARVEST DECISION TABLE (2020)*
   - *6.1 IPHC Fishery-Independent Setline Survey (FISS) design and implementation in 2019*
   - *6.2 Space-time modelling of IPHC Fishery-Independent Setline Survey (FISS) data*
   - *6.3 Stock Assessment: Independent peer review of the Pacific halibut stock assessment*
   - *6.4 Stock Assessment: Data overview and stock assessment (2019), and harvest decision table (2020)*
   - *6.5 Pacific halibut mortality projections using the IPHC mortality projection tool*
7. *IPHC 5-YEAR RESEARCH PROGRAM*
   - *7.1 IPHC 5-year Biological & Ecosystem Science Research Plan: update*
8. *REPORT OF THE 20TH SESSION OF THE IPHC RESEARCH ADVISORY BOARD (RAB020)*
9. *REPORTS OF THE 14th AND 15TH SESSIONS OF THE IPHC SCIENTIFIC REVIEW BOARD (SRB014; SRB015)*
10. *MANAGEMENT STRATEGY EVALUATION*
    - *10.1 IPHC Management Strategy Evaluation: update*
    - *10.2 Reports of the 13th and 14th Sessions of the IPHC Management Strategy Advisory Board (MSAB013; MSAB014)*

DISCUSSION

During the course of the 96th Session of the IPHC Annual Meeting (AM096) 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-2020-SRB017-04 which details the outcomes of the 96th Session of the IPHC Annual Meeting (AM096) relevant to the mandate of the SRB.

APPENDICES

Appendix A: Excerpts from the 96th Session of the IPHC Annual Meeting (AM096) Report (IPHC-2020-AM096-R).

APPENDIX A
Excerpt from the 96th Session of the IPHC Annual Meeting (AM096) Report
(IPHC-2020-AM096-R)

RECOMMENDATIONS

Space-time modelling of IPHC Fishery-Independent Setline Survey (FISS) data

AM096–Rec.01 (para. 31) The Commission **RECOMMENDED** that for the 2020 FISS season, the IPHC Secretariat shall employ the proposed subarea design for Regulatory Areas 2A, 4A, 4B, 4CDE, and an enhanced randomised subsampling FISS design in Regulatory Areas 2B, 2C, 3A, and 3B to meet the primary design objective, while also considering secondary and tertiary objectives (Table 2). The IPHC Secretariat shall determine the number of skates at each FISS station with the secondary objective in mind (Table 2). A demonstration of this design is provided at Fig. 2.

AM096–Rec.02 (para. 32) The Commission **RECOMMENDED** the following specific additions to the new 2020 FISS design, on the basis of the tertiary objective specified in Table 2 on a cost recovery basis. Any other tertiary sampling objective shall be at the discretion of the IPHC Secretariat unless specifically directed by the Commission:

a) Regulatory Area 2A: Washington Department of Fish and Wildlife - rockfish sampling;

b) Regulatory Area 2B: DFO-Canada - rockfish sampling.

REQUESTS

Space-time modelling of IPHC Fishery-Independent Setline Survey (FISS) data

AM096–Req.01 (para. 33) The Commission **REQUESTED** the 2020 consultation process in preparation for the 2021 FISS and beyond be enhanced to include input from the IPHC subsidiary bodies, particularly the Research Advisory Board and the Scientific Review Board, as well as from stakeholders who have performed survey work for the IPHC, with a view to finalizing the FISS sampling design for the coming year as early as possible in the annual planning cycle.

Stock Assessment: Data overview and stock assessment (2019), and harvest decision table (2020)

AM096–Req.02 (para. 52) The Commission **REQUESTED** that the IPHC MSE process continue to evaluate status quo management related to discard mortality for non-directed fisheries (bycatch) under the current program of work for delivery of full MSE results at AM097 in 2021, noting that this source of mortality is currently modelled as a fixed component of the total (with variability).

Reports of the 13th and 14th Sessions of the IPHC Management Strategy Advisory Board (MSAB013 and MSAB014)

AM096–Req.03 (para. 89) The Commission **REQUESTED** the MSAB to confirm the proposed topics of work beyond the 2021 deliverables in time for the Interim Meeting (IM096), including work to investigate and provide advice on approaches for accounting for the impacts of bycatch in one Regulatory Area on harvesting opportunities in other Regulatory Areas.

Size limits

AM096–Req.08 (para. 158) The Commission **REQUESTED** that the IPHC Secretariat prepare an updated discussion of the costs and benefits of removing or adjusting the current minimum size limit and/or adding a maximum size limit. This analysis would be presented during the 2020 Work Meeting and IM096.

Preliminary results of the 2020 FISS

PREPARED BY: IPHC SECRETARIAT (R. WEBSTER; 21 AUGUST 2020)

PURPOSE

To update SRB members on space-time modelling data inputs and provide preliminary results of space-time modelling of FISS data for 2020.

BACKGROUND/INTRODUCTION

Since 2016, IPHC Secretariat staff has used a space-time modelling approach to estimate indices of density and biomass for use in stock assessment modelling and estimation of stock distribution. Among other advantages over the previous empirical method, the modelling allows easy integration of data from expansions of the IPHC fishery-independent setline survey (FISS), removing the need for computing ad-hoc adjustment scalars each time new regions are covered by the FISS. In 2019, the planned IPHC FISS expansion program was completed, resulting in 2020 being the first year in which the FISS was based on the full expanded grid. However, due to budgetary constraints and the impact of COVID-19, a reduced FISS was implemented, with coverage only in IPHC Regulatory Areas 2B, 2C, 3A and 3B. In addition to these expansions, a comparison of fixed and snap gear was conducted using a randomised design at FISS stations in Regulatory Area 2B, following a similar experiment in Regulatory Area 2C in 2019. At the time of writing, the FISS is currently nearing completion, and results (including modelling output) are in progress.

DATA INPUT CHANGES OR UPDATES

- The FISS timing adjustment will be updated using 2019 data (this adjustment has a one-year lag).
- The NMFS Bering Sea trawl survey was also not undertaken in 2020. However, the Alaska Department of Fish and Game trawl survey for Norton Sound was successfully completed, and will provide our only source of data in the Bering Sea in 2020.

- Routine weighing of Pacific halibut on the FISS was introduced in 2019 and continued in 2020. As in 2020, direct measurements of weights will be used in computing weight per unit effort (WPUE) indices for space-time modelling input.

SPACE-TIME MODELLING

Space-time modelling for IPHC Regulatory Areas 2A, 4B and 4A is currently in progress. As the FISS was not undertaken in these areas in 2020, estimates of WPUE and NPUE (numbers per unit effort) indices will depend on spatial and temporal correlation and covariate relationships estimated from previous years' data. Preliminary modelling for other IPHC Regulatory Areas will begin when data become available in coming weeks.

RECOMMENDATION

That the SRB:

1) **NOTE** paper IPHC-2020-SRB017-05 which provides an update on space-time modelling data inputs for 2020 and preliminary results of 2020 FISS modelling, noting a ppt will be presented in session with latest results.


L. Boitor

INTERNATIONAL PACIFIC HALIBUT COMMISSION

Preliminary results of the 2020 FISS

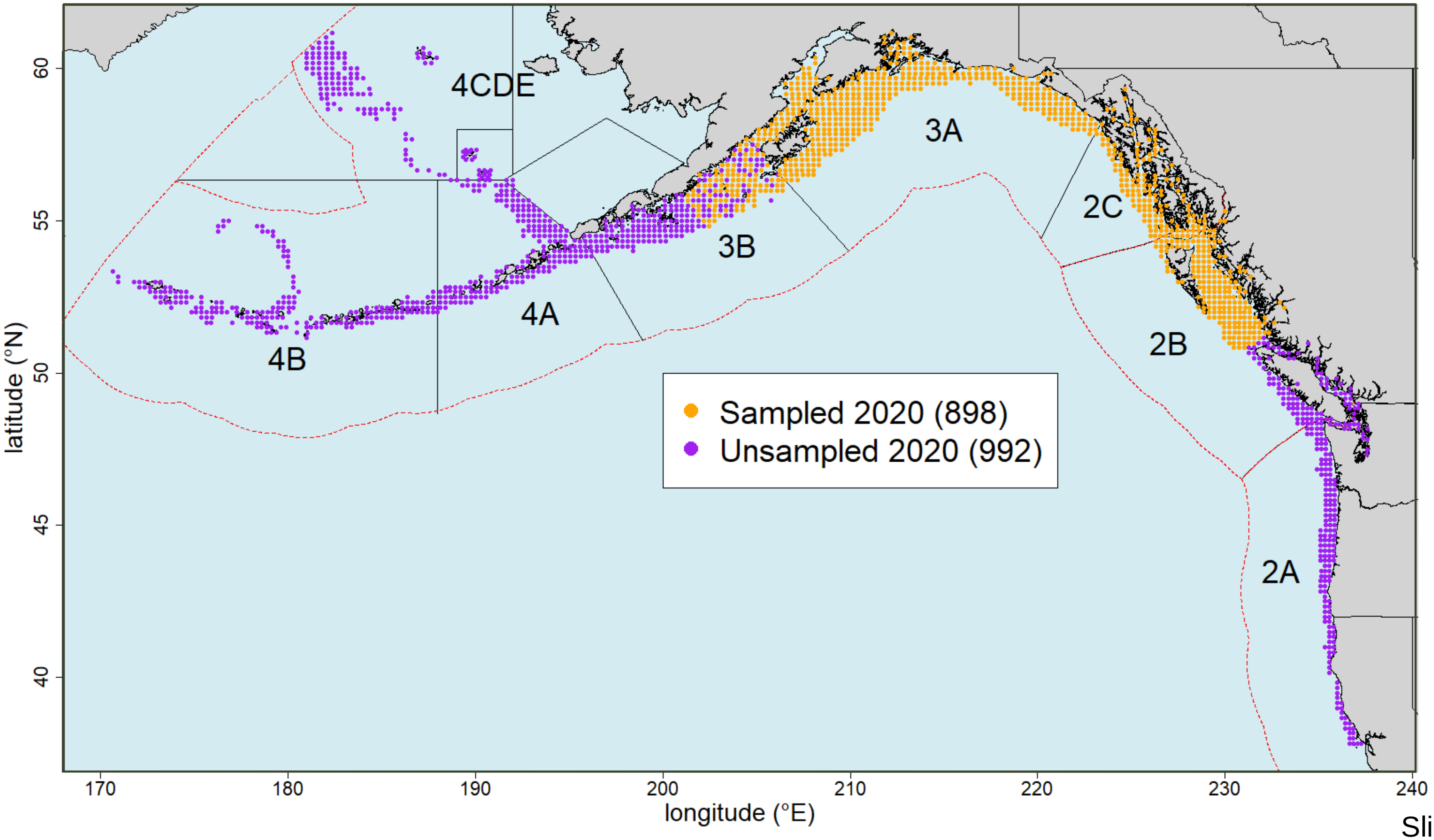
Agenda item: 4.1

IPHC-2020-SRB017-05

2020 FISS

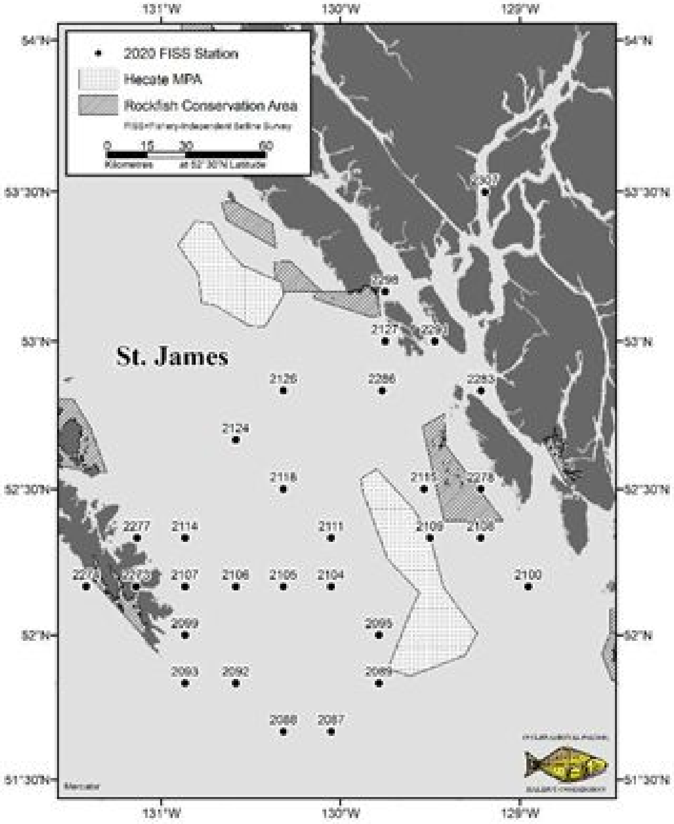
- First year in which the FISS design was based on the full grid of 1890 stations
  - 6-year planned expansion program completed in 2019
- Due to budgetary constraints and the impact of COVID-19, the implemented design was reduced in spatial extent from designs proposed by staff or approved at AM096

Implemented 2020 FISS design

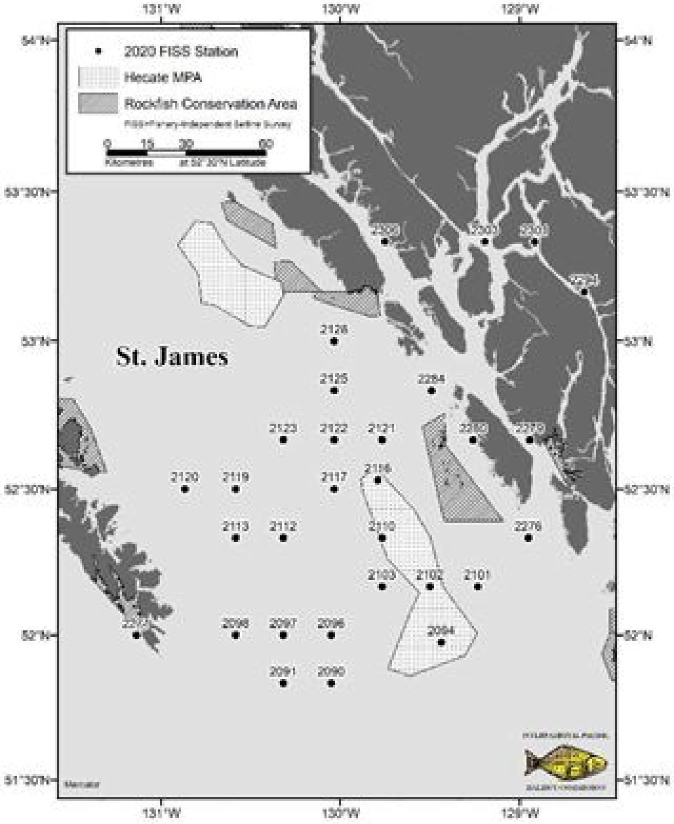


2020 FISS gear comparison in Reg. Area 2B

Fixed Hook Early



Fixed Hook Late



- Fixed hook vs snap gear
- All stations fished twice
- Random selection of gear order

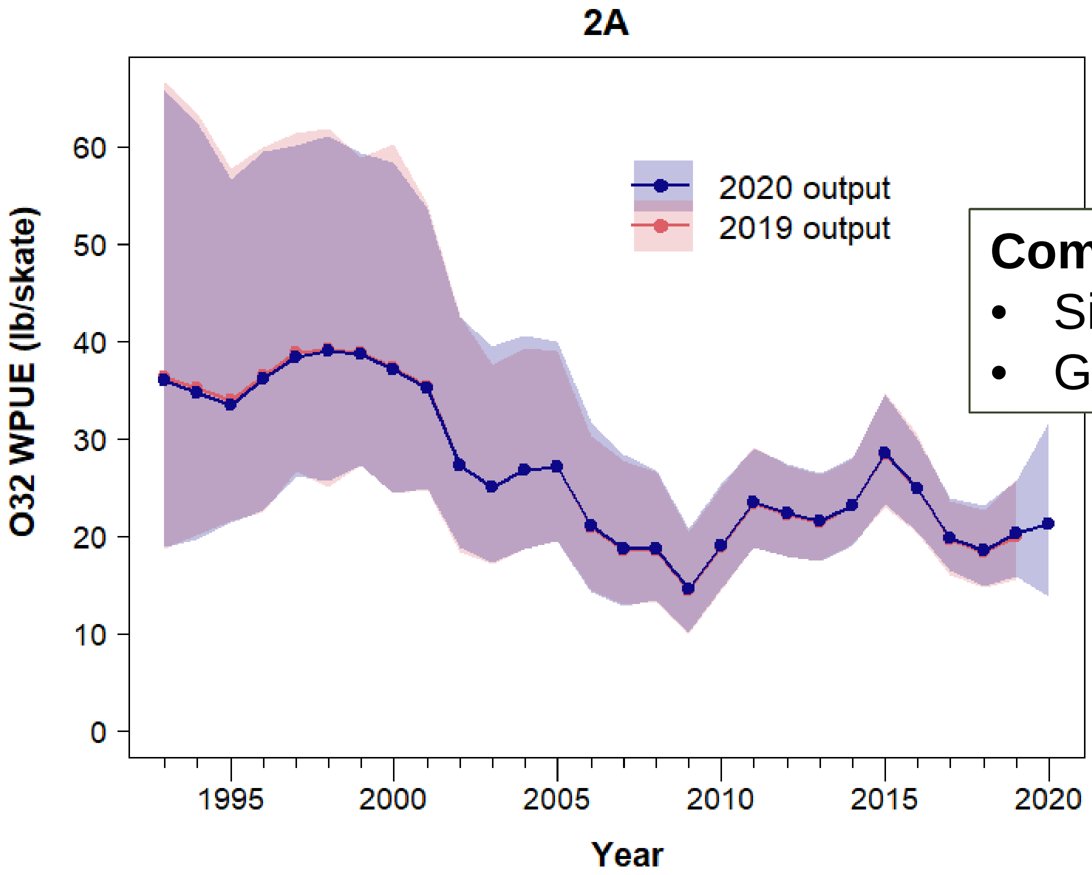
2020 data input updates

- The FISS timing adjustment is being updated using 2019 data (this adjustment has a one-year lag).
- The NMFS Bering Sea trawl survey was not undertaken in 2020.
    - Important data source for Reg. Area 4CDE
- However, the Alaska Department of Fish and Game trawl survey for Norton Sound was successfully completed:
    - Provides our only source of data in the Bering Sea in 2020
- As in 2019, direct measurements of weights will be used in computing weight per unit effort (WPUE) indices for space-time modelling input.

Results of 2020 FISS modelling

- FISS data are still in preparation, and no modelling results are yet available for areas sampled in 2020
- Raw data indicate that catch rates were generally stable in IPHC Regulatory Areas 2B, 2C and 3B, and up in 3A.
    - Timing and hook competition adjustments not yet applied
- Preliminary modelling of O32 WPUE data from IPHC Regulatory Areas 2A, 4A and 4B has been undertaken:
    - No new data in these areas in 2020
    - Estimates for 2020 depend on past observations via temporal correlation and on covariate relationships estimated from 1993-2019 data within the space-time models.

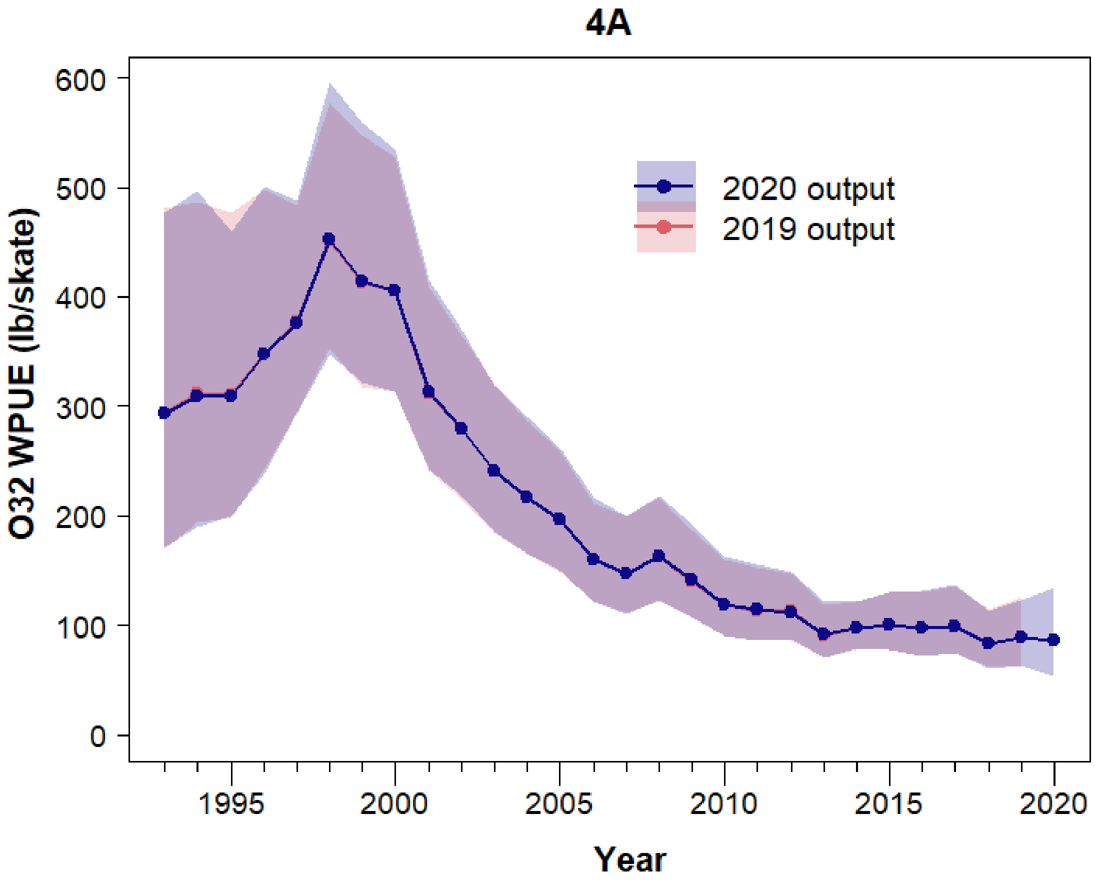
Preliminary 2020 Regulatory Area 2A modelling results



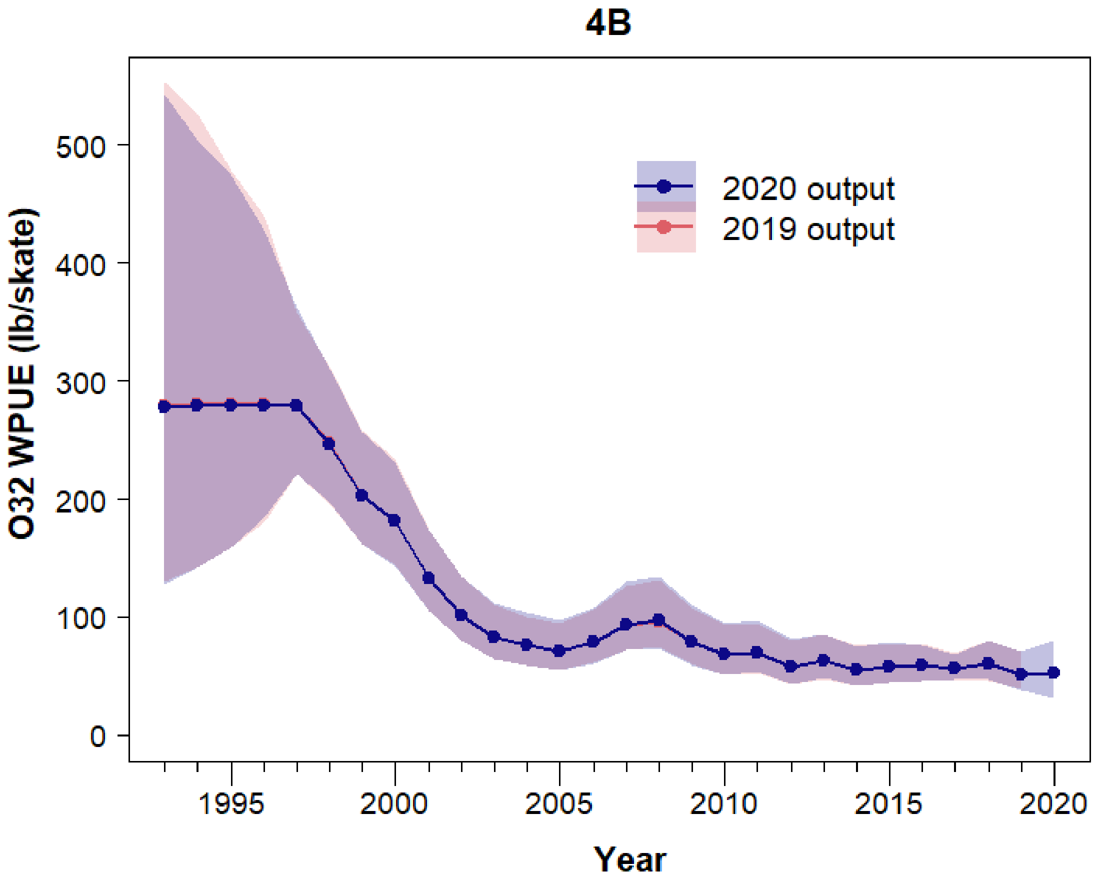
Compared with 2019:

- Similar mean
- Greater uncertainty

Preliminary 2020 Regulatory Area 4A modelling results



Preliminary 2020 Regulatory Area 4B modelling results



Recommendations

That the SRB:

NOTE paper IPHC-2020-SRB017-05 which provides an update on space-time modelling data inputs for 2020 and preliminary results of 2020 FISS modelling.

INTERNATIONAL PACIFIC

HALIBUT COMMISSION

IPHC-2020-SRB017-06

Review: Rationalisation of the FISS following the 2014-19 expansion series

PREPARED BY: IPHC SECRETARIAT (R. WEBSTER; 20 AUGUST 2020)

PURPOSE

To provide background on and review the methods for the IPHC's Fishery-Independent Setline Survey (FISS) rationalisation following the 2014-19 expansion series, along with discussion of the resulting FISS design proposals for the 2020-22 period and presentation of the proposed designs for 2021-23.

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 caught 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 1993-2010

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 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) trawl survey (Webster et al. 2020).

FISS expansions 2011-19

Examination of commercial logbook data and information from other sources, it became clear by 2010 that the 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 regions within the 20-275 fathom depth range within each IPHC Regulatory Area. The latter included the following notable gaps in coverage:

- Regulatory Area 2A: Salish Sea and northern California
- Regulatory Area 2B: Salish Sea, coastal inlets and fjords, shallow waters east of Haida Gwaii

- Regulatory Area 3A: Cook Inlet, gaps inside and outside Prince William Sound
- Regulatory Area 3B: the waters around the Sanak and Shumagin Islands
- Regulatory Area 4A: western Aleutian region, waters shallower than 75 fathoms on Bering Sea shelf edge
- Regulatory Area 4B: eastern Aleutian region, Bowers Ridge and other waters in central region
- Regulatory Area 4CDE: northern Bering Sea shelf edge

This led the IPHC Secretariat to propose expanding the FISS to provide coverage within 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 fishing 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, with the goal of sampling the entire FISS design of 1890 stations in the shortest time logistically possible. Each year included FISS expansions in one or two IPHC Regulatory Areas:

- 2014: IPHC Regulatory Areas 2A and 4A
- 2015: IPHC Regulatory Area 4CDE eastern Bering Sea flats
- 2016: IPHC Regulatory Area 4CDE shelf edge
- 2017: IPHC Regulatory Areas 2A and 4B
- 2018: IPHC Regulatory Areas 2B and 2C
- 2019: IPHC Regulatory Areas 3A and 3B

The FISS expansion program has 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. This has also allowed the Commission to, for the first time, fully quantify the uncertainty associated with estimates based on partial 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. 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).

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. 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 were recently published in a peer-review journal (Webster et al. 2020).

FISS design objectives

The primary purpose of the annual FISS is to sample Pacific halibut to provide data for the stock assessment and estimates of stock distribution for use in the IPHC's management procedure. The priority of a 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

Review process

At the 96th Session of the IPHC Annual Meeting (AM096) in February 2020, alternative designs were presented to IPHC Commissioners that had been evaluated based on scientific criteria (IPHC-2020-AM096-07), in particular, meeting specific precision targets (coefficients of variation, CVs, below 15%) for WPUE and NPUE indices, and ensuring low probability of large bias in estimators of those indices. These evaluation methods had been previously reviewed by the SRB at SRB014 (IPHC-2019-SRB014-05 Rev_1) with application to IPHC Regulatory Areas 4B and (in presentation) 2A, and introduced to Commissioners at IM095 (IPHC-2019-IM095-07 Rev_1). While development of the proposed designs focused on the Primary Objective of the FISS (Table 1), logistics and cost (Secondary Objective) were also considered in developing proposals based on annual sampling of subareas of each IPHC Regulatory Area on a rotating basis. The final design adopted by the IPHC at AM096 (IPHC-2020-AM096-R) combined the proposed subarea design in IPHC Regulatory Areas 2A, 4A and 4B, an enhanced randomized design in the core of the stock (IPHC Regulatory Areas 2B, 2C, 3A and 3B, with sample sizes in excess of those required to meet precision targets), and sampling all standard FISS stations in IPHC Regulatory Area 4CDE (Figure 1).

Following the completion of the coastwide FISS expansion efforts, 2019/2020 was the first year fully rationalised designs could be proposed. It is expected that the design proposal and review process going forward will be as follows:

- Secretariat staff present design proposals to SRB for three subsequent years at the June meeting
- First review of design proposals by Commissioners will occur at the September work meeting, revised if necessary based on June SRB input
- Presentation of proposed designs at the November Interim Meeting
- Designs presented and potentially modified at the January/February Annual Meeting given Commissioner direction
- Adopted AM design for current year modified for cost and logistical reasons prior to summer implementation in FISS (February-April)

PROPOSED DESIGNS FOR 2021-23

Due to budgetary constraints and the impact of COVID-19, neither the proposed nor adopted AM096 designs described below were implemented in 2020. Instead, a design with sampling only within the core areas was undertaken for the 2020 FISS (IPHC-2020-CR-013; Figure 2). Because of this, our proposal for 2021-23 is to shift the 2020-22 Secretariat-preferred compromise proposal presented at AM096 (see below) to instead be implemented in 2021-23 (Figures 3-5). This design uses efficient subarea sampling in IPHC Regulatory Areas 2A, 4A and 4B, but incorporates a randomized design 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 1,000 stations in an average year. Outside the core areas, the subarea design allows for logistically efficient sampling, and therefore accounts for the Secondary Objective discussed above (Table 1). It is likely that this design represents the maximum effort that can be deployed outside the core areas in coming years, while still meeting the Secondary Objective. These designs were reviewed by the SRB at SRB016 (IPHC-2020-SRB016-R), which stated the following in its report:

> “The SRB **AGREED** with the proposed Compromise FISS design for 2021-2023. However, the SRB **NOTED** that the analyses presented in IPHC-2020-SRB016-INF02 were based on a pre-COVID-19 FISS sampling plan for 2020 that differs substantially from current 2020 sampling plans. Thus, the Compromise FISS design for 2021-2023 is likely no longer optimal from a purely scientific perspective. However, it does still appear to be reasonably justified given previous scientific work and within the context of the 3-tiered FISS objectives framework.”

Preliminary cost estimates for the proposed 2021 design are being generated at the time of writing, and will be available for discussion at WM2020.

FISS DESIGN EVALUATION

Precision targets

Prior to 2019, the IPHC Secretariat had an informal goal of maintaining a coefficient of variation (CV) of no more than 15% for mean WPUE for each IPHC Regulatory Area. Including all expansion data to date, this goal was achieved in all areas beginning in 2011, the year of the first pilot expansion (Table 2), except Regulatory Area 4B in 2011-14 and 2019 for O32 WPUE and 2011-12 and 2019 for all sizes WPUE, and Regulatory Area 4A in 2016-19 (O32 and all sizes WPUE).

In order to maintain the quality of the estimates used for the assessment, and for estimating stock distribution, we proposed that FISS designs should meet target CVs below 15% for 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.

Table 2. Range of coefficients of variation for O32 and all sizes WPUE from 2011-19 by Regulatory Area.

Reg Area	O32 WPUE (2011-19)				All sizes WPUE (2011-19)			
	Lowest CV (%)	Year	Highest CV (%)	Year	Lowest CV (%)	Year	Highest CV (%)	Year
2A	10	2014*	13	2019	10	2014*	13	2019
2B	5	2018*	7	2019	5	2018*	7	2012
2C	5	2018*	6	2012	5	2018*	6	2011
3A	4	2017	5	2011	5	2019	5	2011
3B	7	2019*	8	2015	9	2018	10	2015
4A	12	2014*	18	2019	10	2014*	19	2019
4B	10	2017*	16	2012	10	2017*	16	2012
4CDE	10	2017#	11	2013	5	2015*	6	2019

* Year of FISS expansion in Reg. Area. # Year of NMFS trawl expansion in Reg. Area 4CDE.

Reducing the potential for bias

With these targets set, we can proceed to using the space-time modelling to evaluate different FISS designs by IPHC Regulatory Area and Biological Region. However, if stations are not selected randomly, sampling a subset of the full data frame in any area or region brings with it the potential for bias, due to trends in the unsurveyed portion of a management unit (Regulatory Area or Region) potentially differing from those in the surveyed portion. To reduce the potential for bias, we also looked at how frequently part of an area or region (called a “subarea” here; see Appendix A) should be surveyed in order to reduce the likelihood of appreciable bias. For this, we proposed a threshold of a 10% absolute change in biomass percentage: how quickly can a subarea’s percent of the biomass of a Regulatory Area or Region’s change by at least 10%? 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 or Region’s indices as a whole.

To illustrate the process applied to each IPHC Regulatory Area, an example of IPHC Regulatory Area 4B, first presented at SRB014, is detailed in Appendix B.

Analytical methods

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

- Where a randomized design is not used, identify logistically feasible 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

Extending the modelling beyond three years was not considered worthwhile, as we expect further evaluation undertaken following collection of data during the one to three-year time period to substantially influence design choices for subsequent years. In this manner, projected designs can be evaluated and then efficiently updated to reflect observed data as they become available.

Ideally, a full simulation study with many replicate data sets would be used, but this is impractical for the computationally time-consuming spatio-temporal modelling. Instead, "simulated" sample data sets for the future years will be taken from the 2000 posterior samples from the most recent year's modelling. Each year's simulated data will have to be added and modelled sequentially, as subsequent data can improve the precision of prior years' estimates, meaning the terminal year is often the least precise (given a consistent design). If time allows, the process can be repeated with several simulated data sets to ensure consistency in results, although with large enough sample sizes (number of stations) in each year, we would expect even a single fit to be sufficiently informative for design development.

SAMPLING DESIGN OPTIONS

The historical sampling, combined with FISS expansions from 2014-2019, established a full sampling design of 1890 stations from California to the Bering Sea shelf edge on a 10 nmi grid from depths of 10 – 400 ftm (Figure 1). Future annual FISS designs will comprise a selection of stations from this frame. Sample design options include the following:

- Full sampling of the 1890 station design (Figure 1).
- Completely randomized sampling of stations within each IPHC Regulatory Area (example in Figure 6).
- Randomized cluster sampling (example in Figure 7), in which clusters of stations are selected that comprise (where possible) 3-4 stations to make an operationally efficient fishing day.
- Subarea sampling, in which IPHC Regulatory Areas are divided into non-overlapping subareas (see Appendix A), and all stations within a selection of these are sampled to allow for more efficient vessel activity on each sampling trip.

The latter two options above are examples that meet primary (statistical) sampling objectives, but also include a consideration of logistics and cost. For designs such as those in Figures 6 and 7, the randomization ensures that resulting estimates (eg, WPUE, NPUE indices) are unbiased. Designs based on sampling subareas require an evaluation of the potential for bias, as discussed above.

From a scientific perspective, more information is always better; however, sampling the full grid (Figure 1) is unnecessary as the precision target for the index can be maintained with substantial subsampling. While a fully randomized subsampling design (or a randomized cluster subsampling design) with sufficient sample size will still meet scientific needs, in several IPHC Regulatory Areas where Pacific halibut are concentrated in a subset of the available habitat, such a design can be inefficient. For this reason, we considered the subarea design, in which effort is focused in most years on habitat with highest density (which generally contributes most to the overall variance), while sampling other habitat with sufficient frequency to maintain low bias.

'Core' areas vs ends of the stock distribution

In considering potential FISS designs, it is helpful to make a distinction between the 'core' IPHC Regulatory Areas 2B, 2B, 3A and 3B, and the areas at the southern and northern ends of the stock's North America range, IPHC Regulatory Areas 2A, 4A, 4B and 4CDE. The former has generally high density throughout, while the latter have relatively high density limited to distinct subareas within each IPHC Regulatory Area. In other words, Pacific halibut distribution tends to become more heterogeneous ('patchy') toward the ends of the species range in the IPHC Convention Area. These areas are also much more logistically challenging to sample and generally produce lower catch rates. For these end areas, a fully randomised design would be inefficient, both logistically and statistically, as it would require effort where little is needed for estimation with low variance, while the frequently narrow bathymetric habitat area would result in a sparse randomised design with high vessel running time between selected stations. Provided the sampling rate is sufficient, a randomised design is generally more practical in the core areas, and it also avoids concerns about bias that could arise from a subarea design that omits subareas with relatively high density.

2020-22 DESIGN PROPOSALS AND EVALUATION

For AM096, the IPHC Secretariat put forward two alternative design proposals, one based on a subarea design in all IPHC Regulatory Areas, and the other on a randomised design in the four core areas, and a subarea design elsewhere (IPHC-2020-AM096-07). The full design and randomised cluster design were also presented, but received little discussion during the meeting.

IPHC Regulatory Area 4CDE was given special attention by staff, with each proposal including sampling of the full 10 nmi grid along the Regulatory Area 4CDE shelf edge in 2020-22 (last fished in 2016). While it may be possible to reduce FISS sampling and still meet precision/bias targets, we noted that ecosystem conditions have been anomalous in the Bering Sea for several years, making the Pacific halibut distribution more difficult to predict in unsurveyed habitat. Indeed, recent NMFS trawl surveys in the northern Bering Sea have shown a generally increasing trend in that region, but over the last three years, deeper waters in the north covered by the FISS grid have been unsampled. The IPHC is interested in better understanding density trends and possible links with Pacific halibut in Russian waters in the Bering Sea, and the data obtained from sampling the full FISS grid would help greatly in achieving these goals. The need to sample these stations in 2021-22 was to have been re-evaluated following the results of the 2020 FISS.

Subarea design

Each of the IPHC Regulatory Areas at the ends of the stock was divided into 3-4 subareas for future sampling, based on a combination of recent Pacific halibut density and geography (Appendix A). Prior to developing a final proposal, several options for each of these IPHC Regulatory Areas were evaluated to help plan which subareas could be sampled in each year while maintaining CVs within targets (Appendix A). For the core areas, rotating sampling of IPHC

FISS charter regions was considered to allow for less than 100% sampling effort while still maintaining a logistically efficient design.

The proposed subarea designs for 2020-22 are shown in Figures 8-10.

Compromise design

The proposed compromise design featured random sampling of stations within each of the core areas, and the subarea design elsewhere. The sampling rate in the core areas was chosen to produce an annual sampling design with approximately 1000 stations, representing a modest reduction of recent years' sample sizes and while still meeting precision targets.

The proposed compromise designs for 2020-22 are shown in Figures 11-13.

All designs were evaluated to ensure that they were projected to meet precision targets for 2020-22, using simulated data to augment the observed time series as described above. Subarea designs in IPHC Regulatory Areas 2A, and 4B were evaluated prior to IM094 based on space-time modelling output from 2018, while evaluation of designs in other IPHC Regulatory Areas was completed prior to AM096. Table 3 shows projected CVs for the proposed compromise design based on fitting models to the FISS data augmented with simulated data for 2020-22. No evaluation was undertaken for IPHC Regulatory Area 4CDE as the full design was proposed in all years.

Table 3. Projected CVs for 2020-22 for the compromise design. Target CV is 15% in all IPHC Regulatory Areas.

	Projected CV (%)		
Regulatory Area	**2020**	**2021**	**2022**
2A	13.0	13.0	14.2
2B	6.2	6.0	6.4
2C	6.4	6.3	6.7
3A	4.8	4.9	5.1
3B	8.2	8.2	8.5
4A	9.6	9.3	9.7
4B	8.7	8.7	14.2

CONSIDERATION OF COST

Both the subarea and compromise design incorporate some consideration of cost by using a logistically efficient design in at least some IPHC Regulatory Areas. 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. 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 (see below), particularly if such reductions in effort relative to proposed designs continue over multiple years.

IMPLICATIONS OF 2020 FISS ON ESTIMATION IN SUBSEQUENT YEARS

The reduced FISS in 2020 has some implications for data quality, not only in the current year, but in subsequent years. IPHC Regulatory Areas 2A, 4A, 4B and 4CDE will have no FISS sampling in 2020, and WPUE and NPUE indices estimated from the space-time modelling will almost certainly not meet precision targets. Information for 2020 for these areas comes only from covariate relationships in the space-time model and from prior years' data through the modelled temporal correlation. Not only will the estimates for 2020 be imprecise relative to prior years, but the lack of data on stock trends from 2019 to 2020 means that there is the potential for bias in the estimates. The impact of the reduced FISS design will propagate into subsequent years' estimates. For example, the 2021 estimates will be less precise than they would have been if data had been collected in 2020. However, if the proposed 2021 design is implemented, we expect this to bring the FISS back on track to meet data quality targets in coming years. The high sampling effort in 2020 in IPHC Regulatory Areas 2B, 2C and 3A means that estimates from these areas should meet data quality targets this year. The reduced sampling in IPHC Regulatory Area 3B should be sufficient for precision targets to be met, given that CVs have been well within the 15% target in recent years in this area. There is a chance for some modest bias with the more variable western portion of IPHC Regulatory Area 3B being unsampled, but with some information on stock trend from the eastern region, this is of less concern than the bias potential in areas with no 2020 sampling.

RECOMMENDATION

That the SRB:

1) **NOTE** paper IPHC-2020-SRB017-06 that provides background on and review the methods for the IPHC's Fishery-Independent Setline Survey (FISS) rationalisation following the 2014-19 expansions series of the FISS, along with discussion of the resulting FISS design proposals for the 2020-22 period and presentation of the proposed designs for 2021-23;
2) **ENDORSE** the final 2021-23 FISS design.

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Webster RA, Soderlund E, Dykstra CL, and Stewart IJ (in press). Monitoring change in a dynamic environment: spatio-temporal modelling of calibrated data from different types of fisheries surveys of Pacific halibut. Can. J. Fish. Aquat. Sci

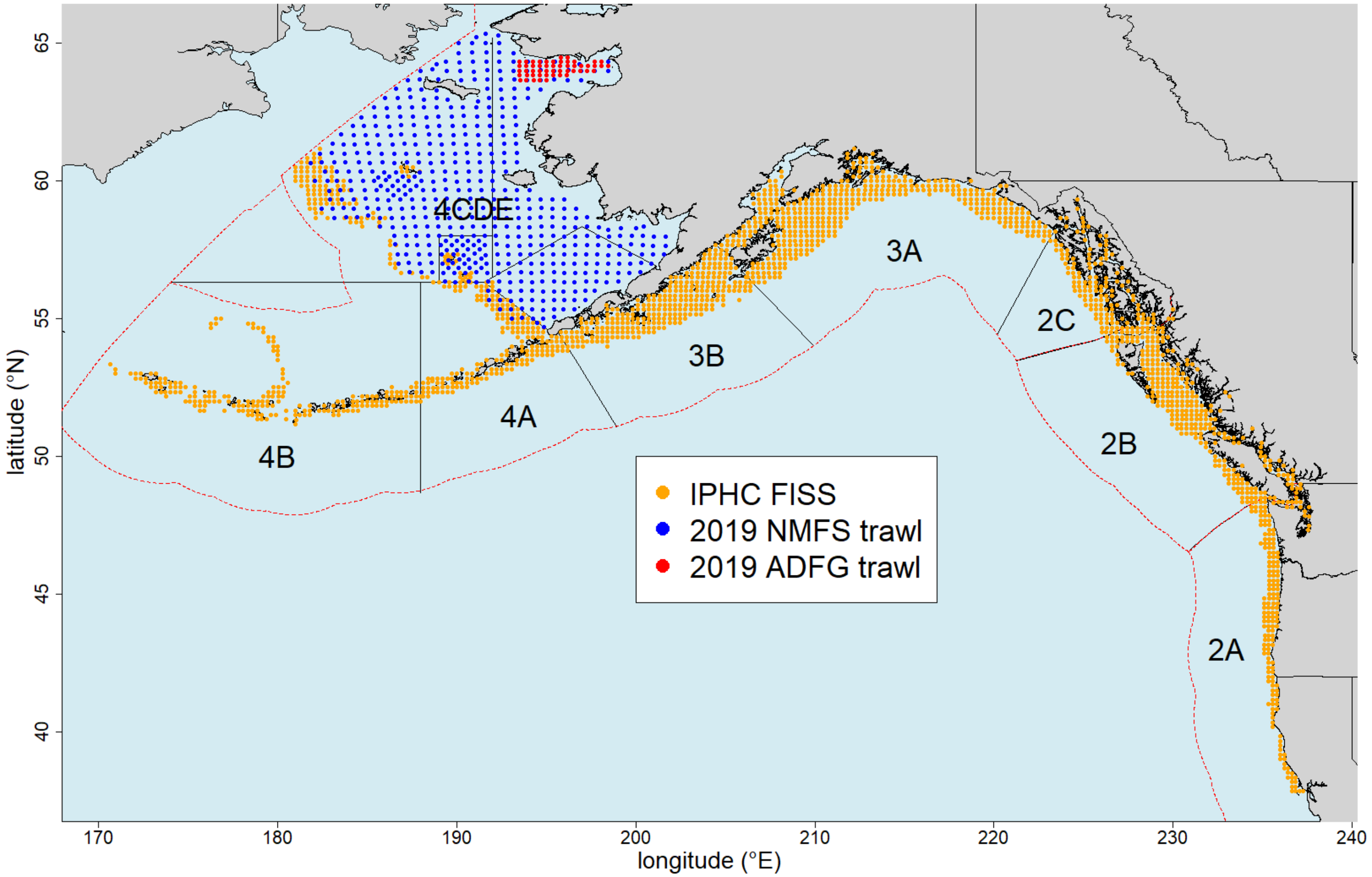


Figure 1. Map of the full 1890 station FISS design, with orange circles representing stations available for inclusion in annual sampling designs, and other colours representing trawl stations from 2019 NMFS and ADFG surveys used to provide complementary data for Bering Sea modelling.

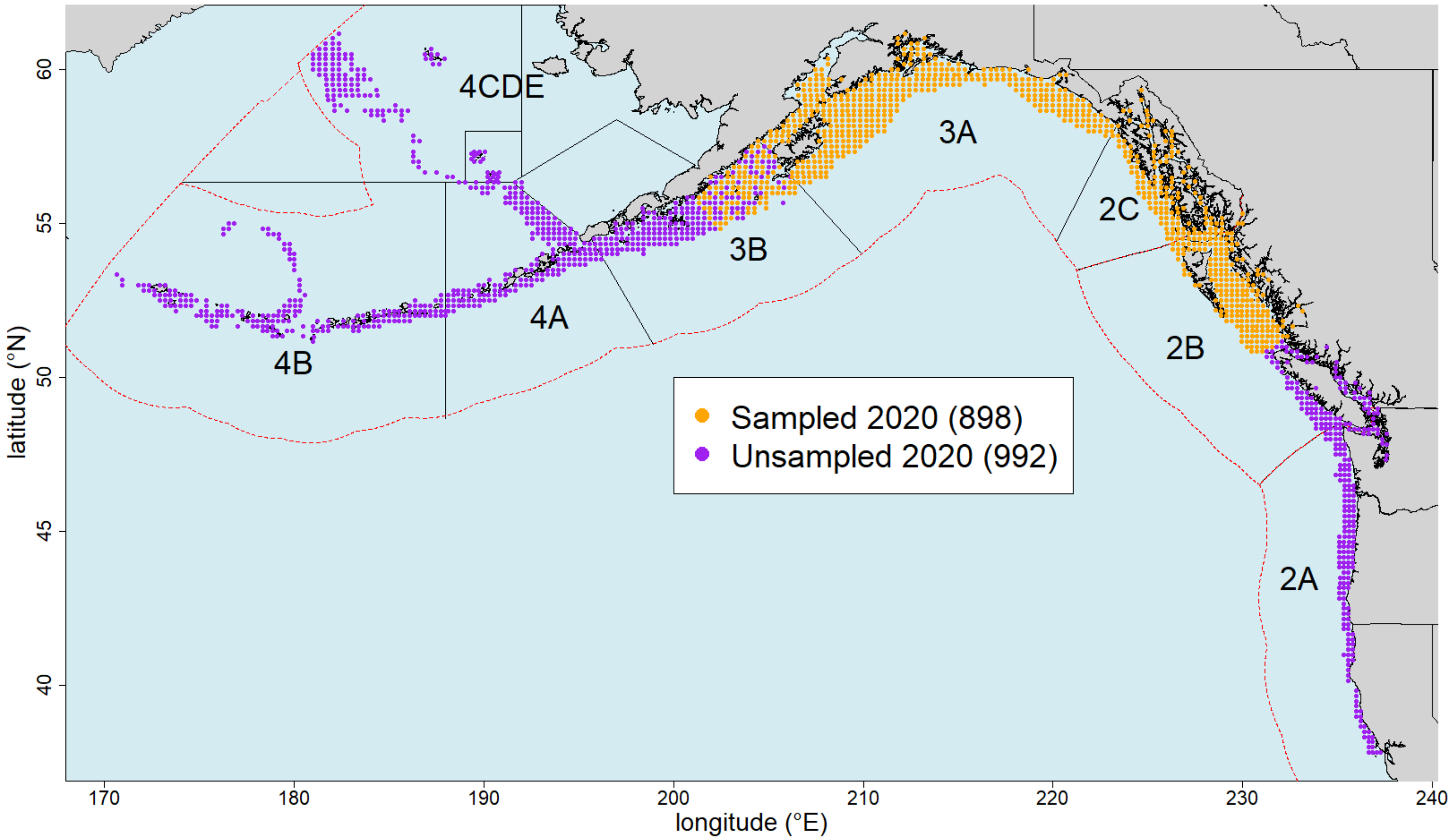


Figure 2. Map of the implemented 2020 FISS design, with orange circles representing those stations to be fished in 2020, and purple circles representing stations to be next fished in subsequent years.

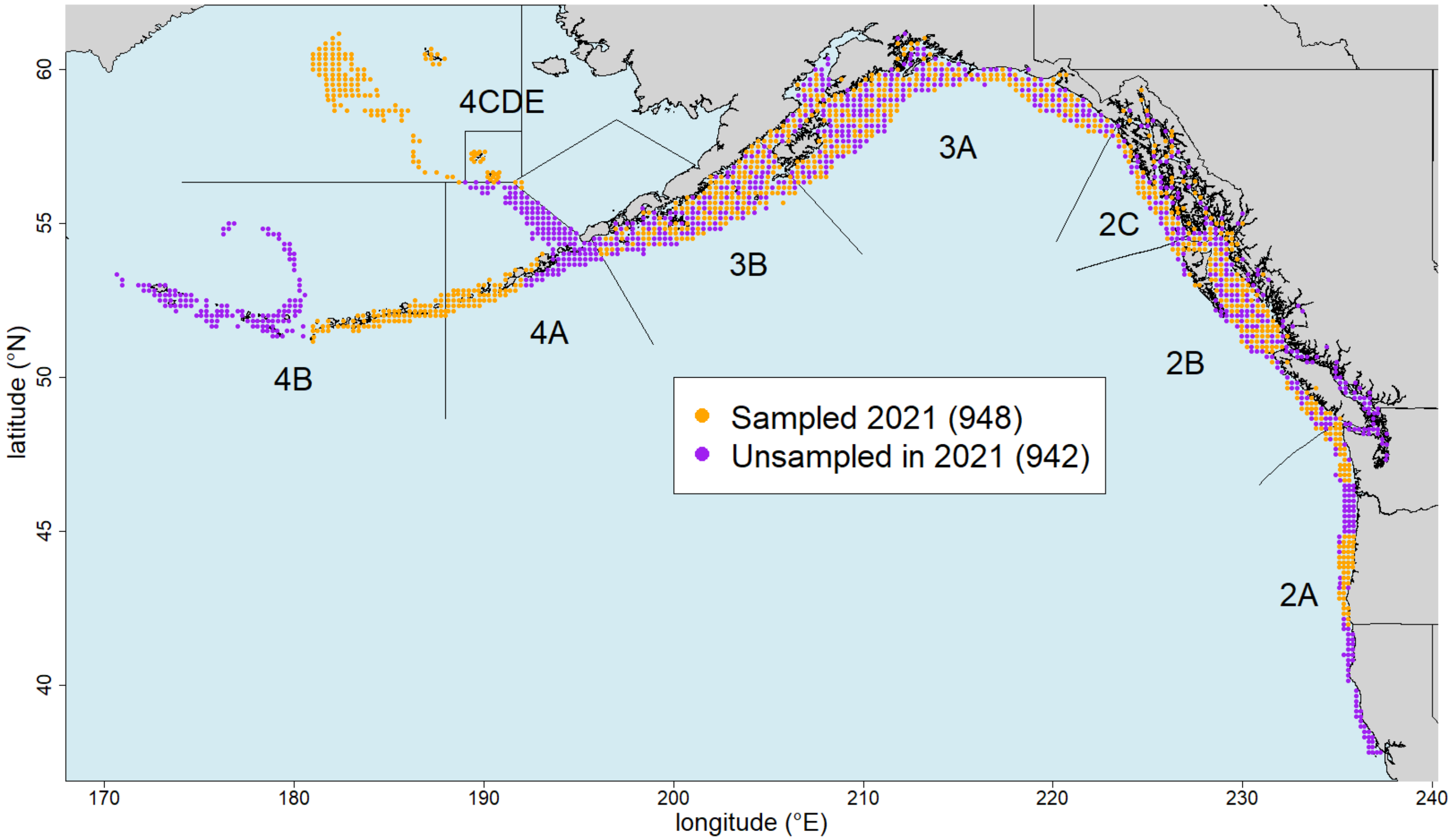


Figure 3. Proposed minimum FISS design in 2021 (orange circles) based on randomized sampling in 2B-3B, and a subarea design elsewhere. Purple circles are optional for meeting data quality criteria.

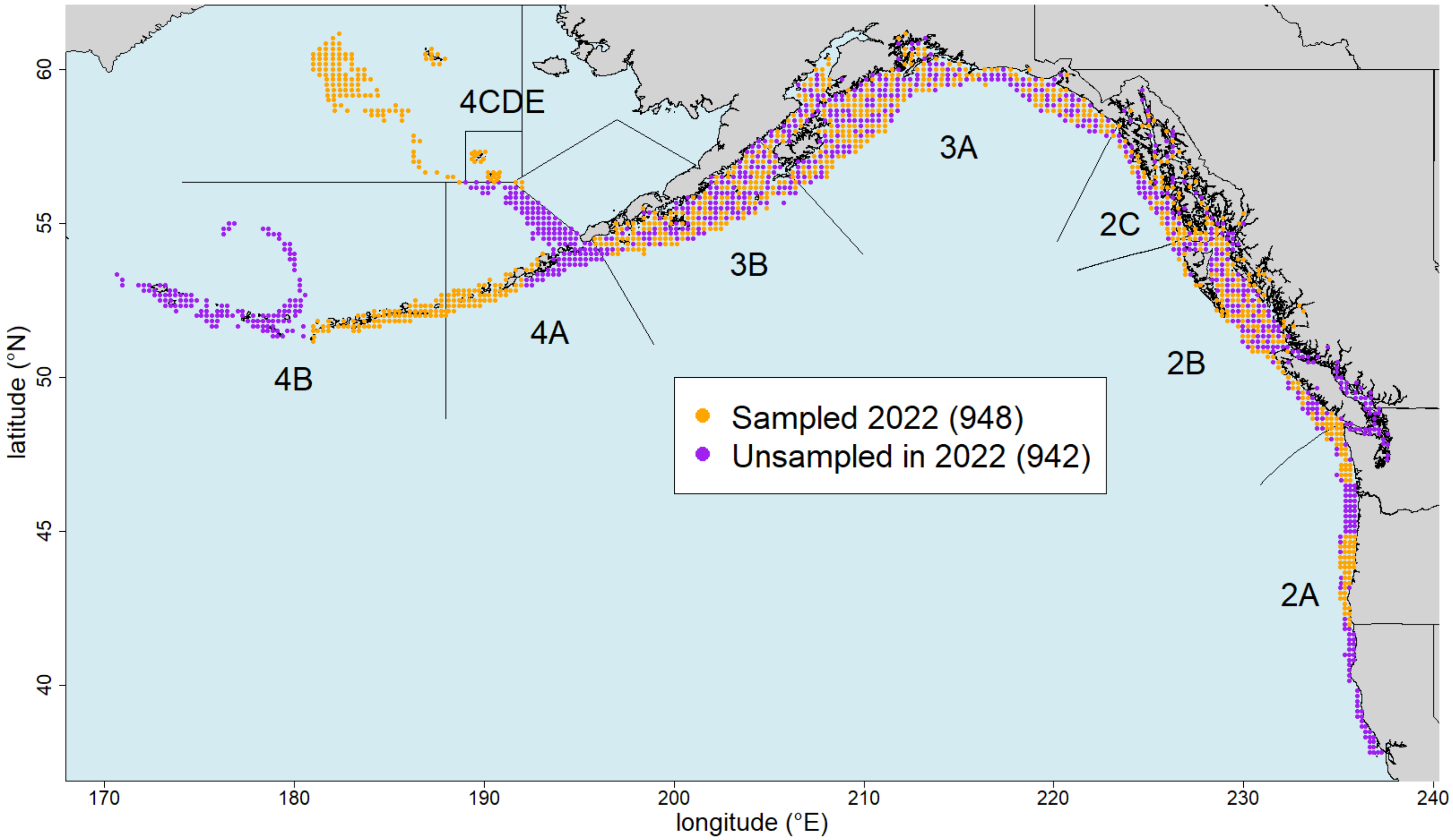


Figure 4. Proposed minimum FISS design in 2022 (orange circles) based on randomized sampling in 2B-3B, and a subarea design elsewhere. Purple circles are optional for meeting data quality criteria.

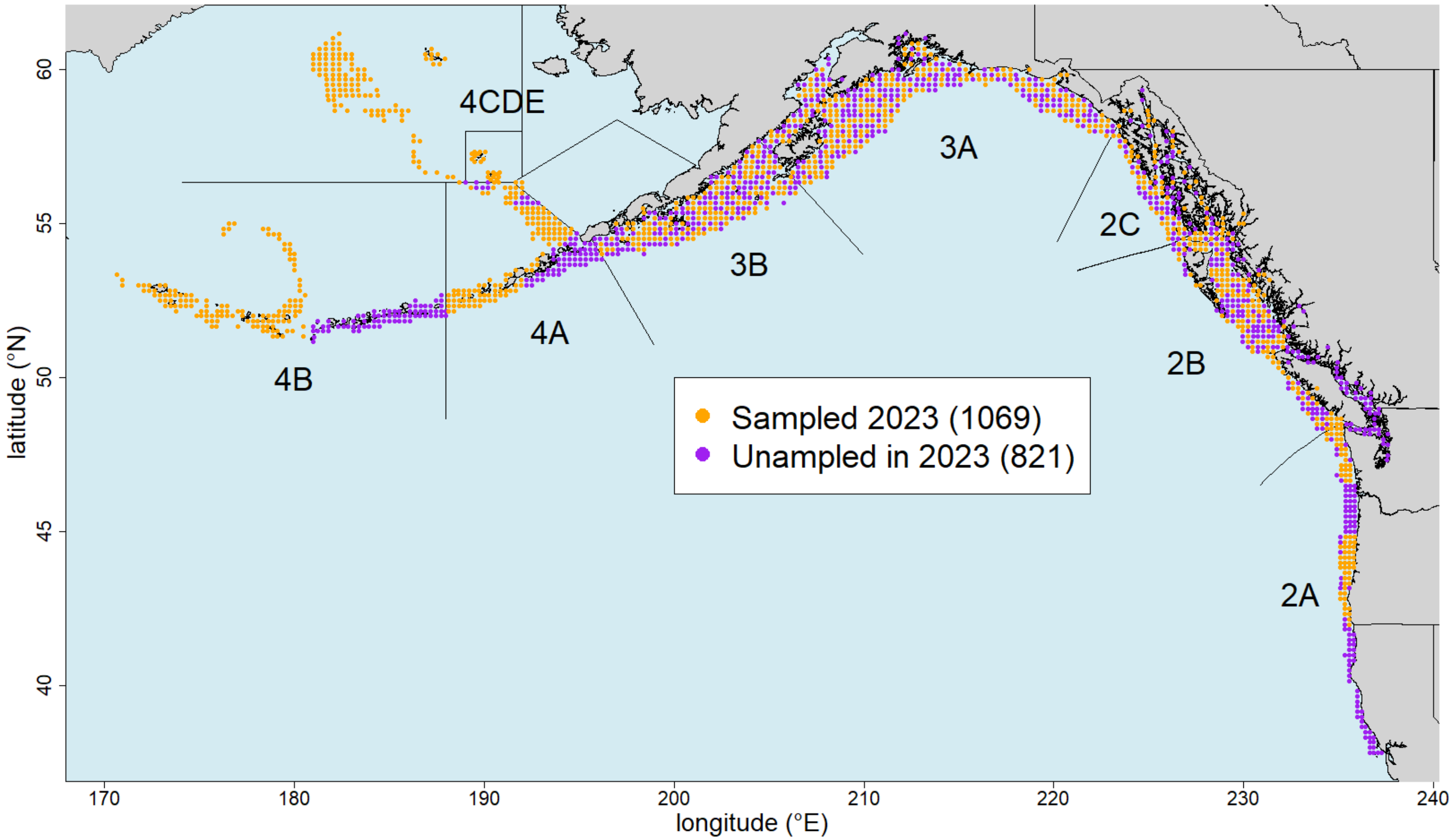


Figure 5. Proposed minimum FISS design in 2023 (orange circles) based on randomized sampling in 2B-3B, and a subarea design elsewhere. Purple circles are optional for meeting data quality criteria.

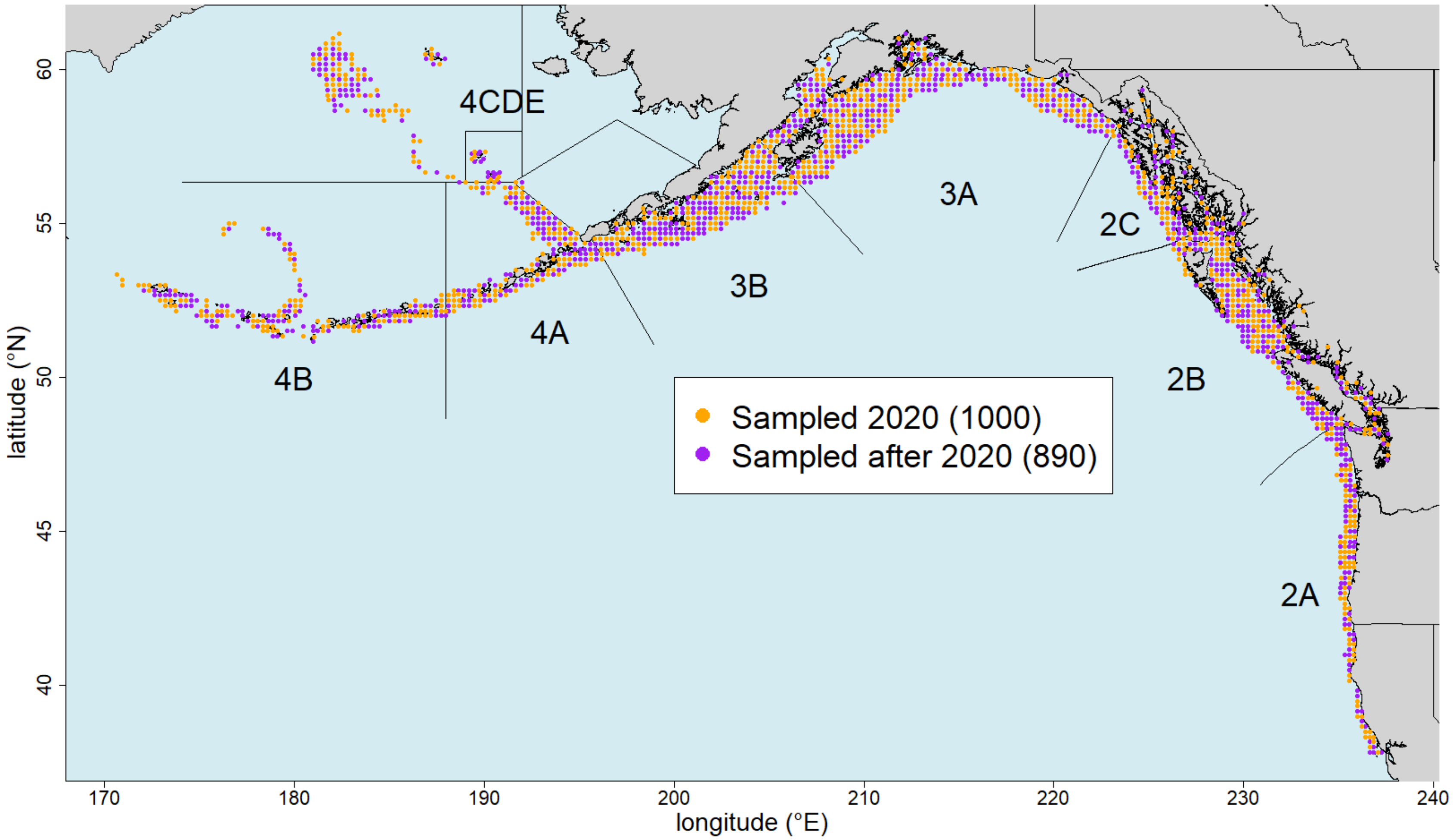


Figure 6. Map of a potential 1000 station FISS design, with completely randomized station selection within each IPHC Regulatory Area. Orange circles represent stations selected for sampling, while purple circles represent stations to be sampled in subsequent years.

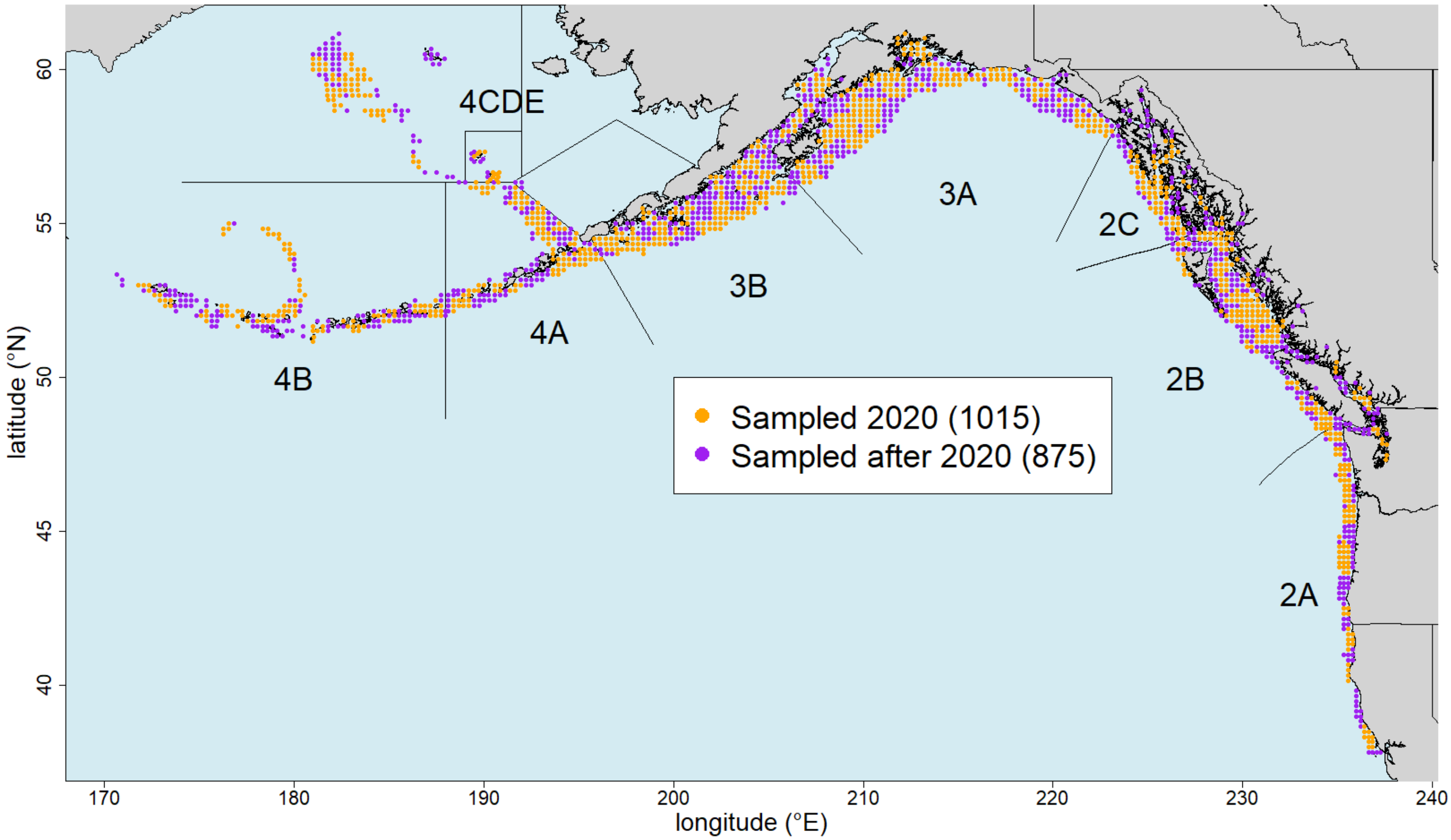


Figure 7. Map of a potential approximately 1000 station FISS design, with randomized selection of clusters of 3-4 stations within each IPHC Regulatory Area. Orange circles represent stations selected for sampling, while purple circles represent stations to be sampled in subsequent years.

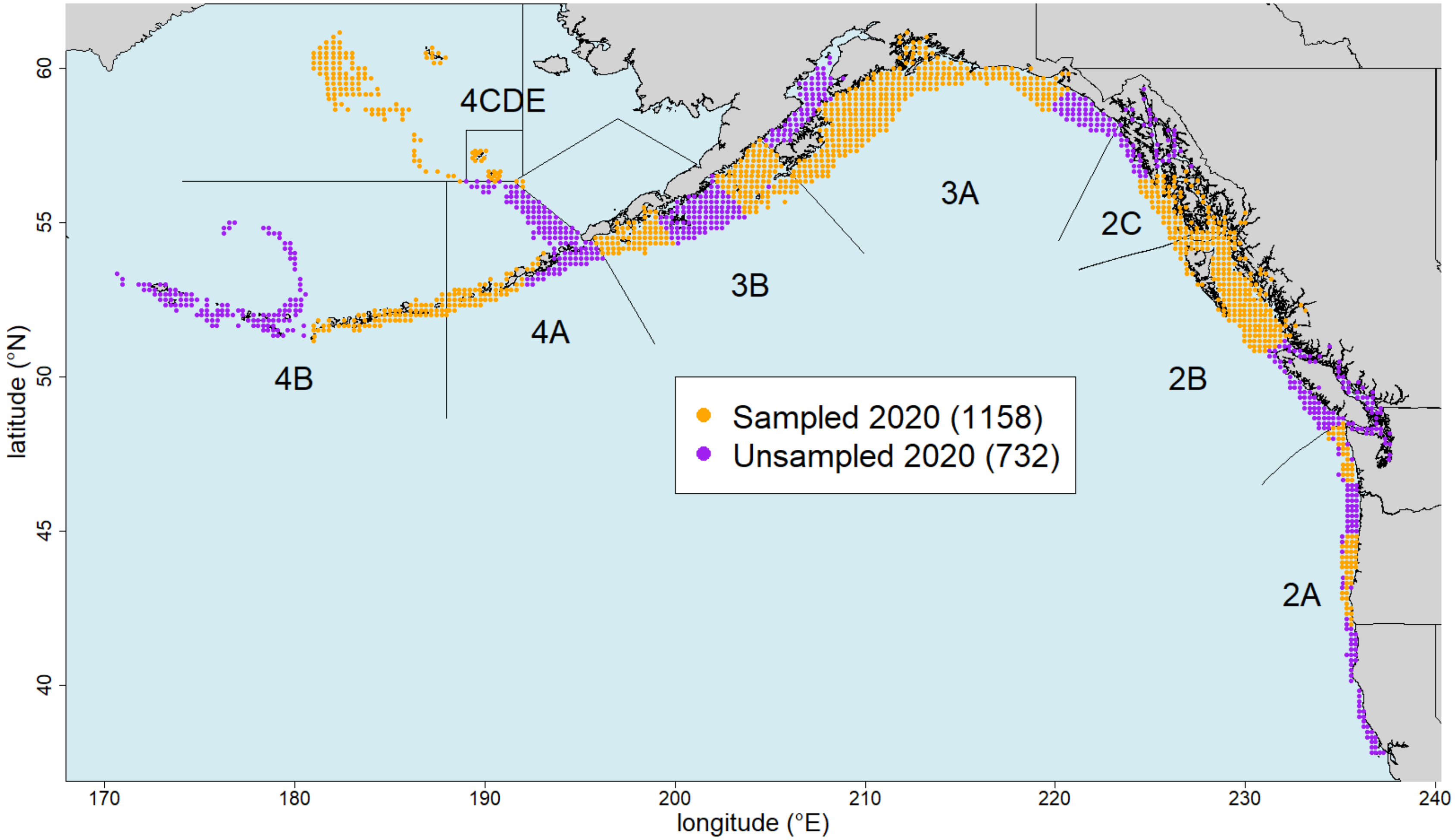


Figure 8. Minimum FISS design for 2020 (orange circles) proposed at AM096 based on subareas. Purple circles are optional for meeting data quality criteria.

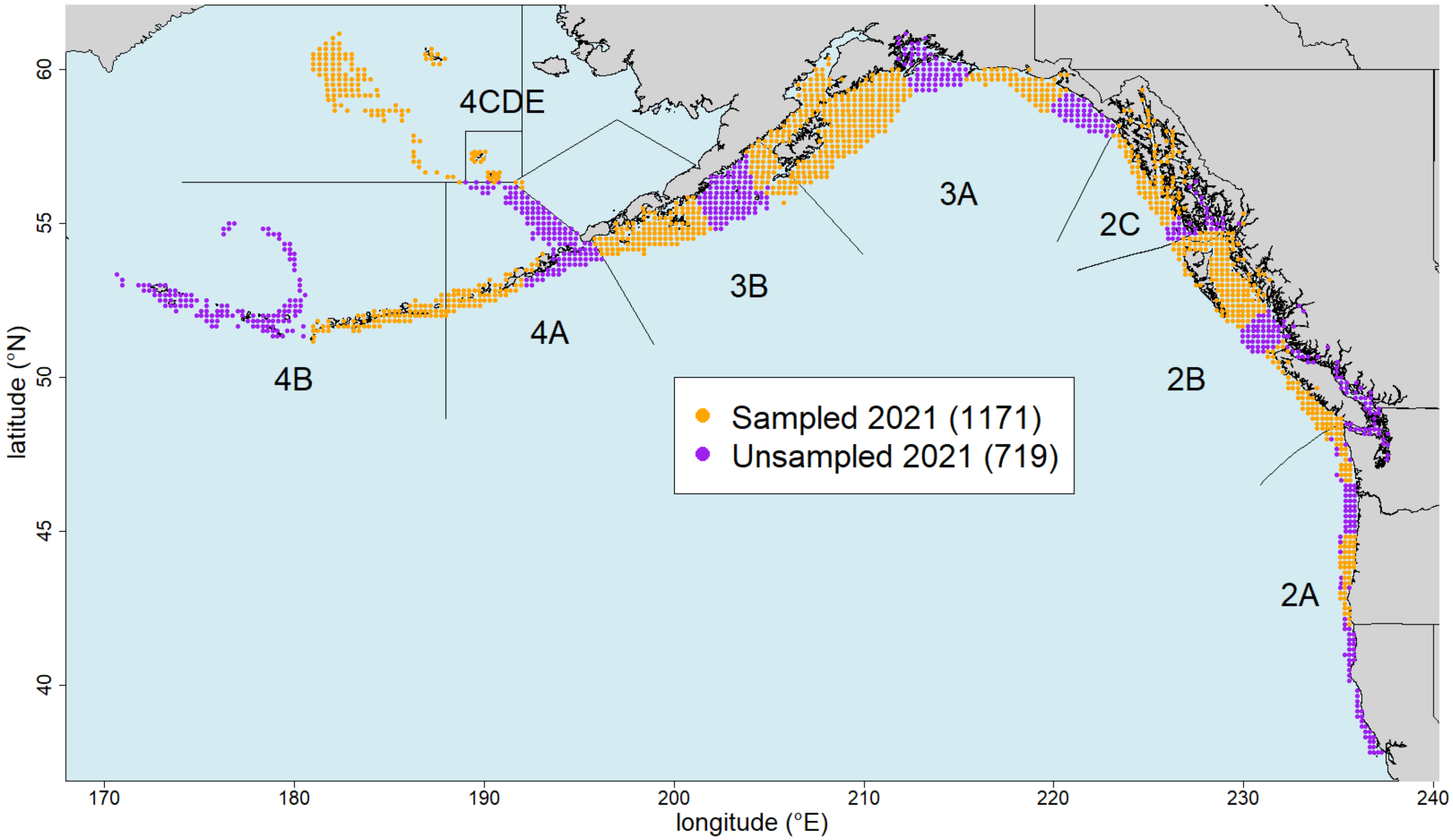


Figure 9. Minimum FISS design for 2021 (orange circles) proposed at AM096 based on subareas. Purple circles are optional for meeting data quality criteria.

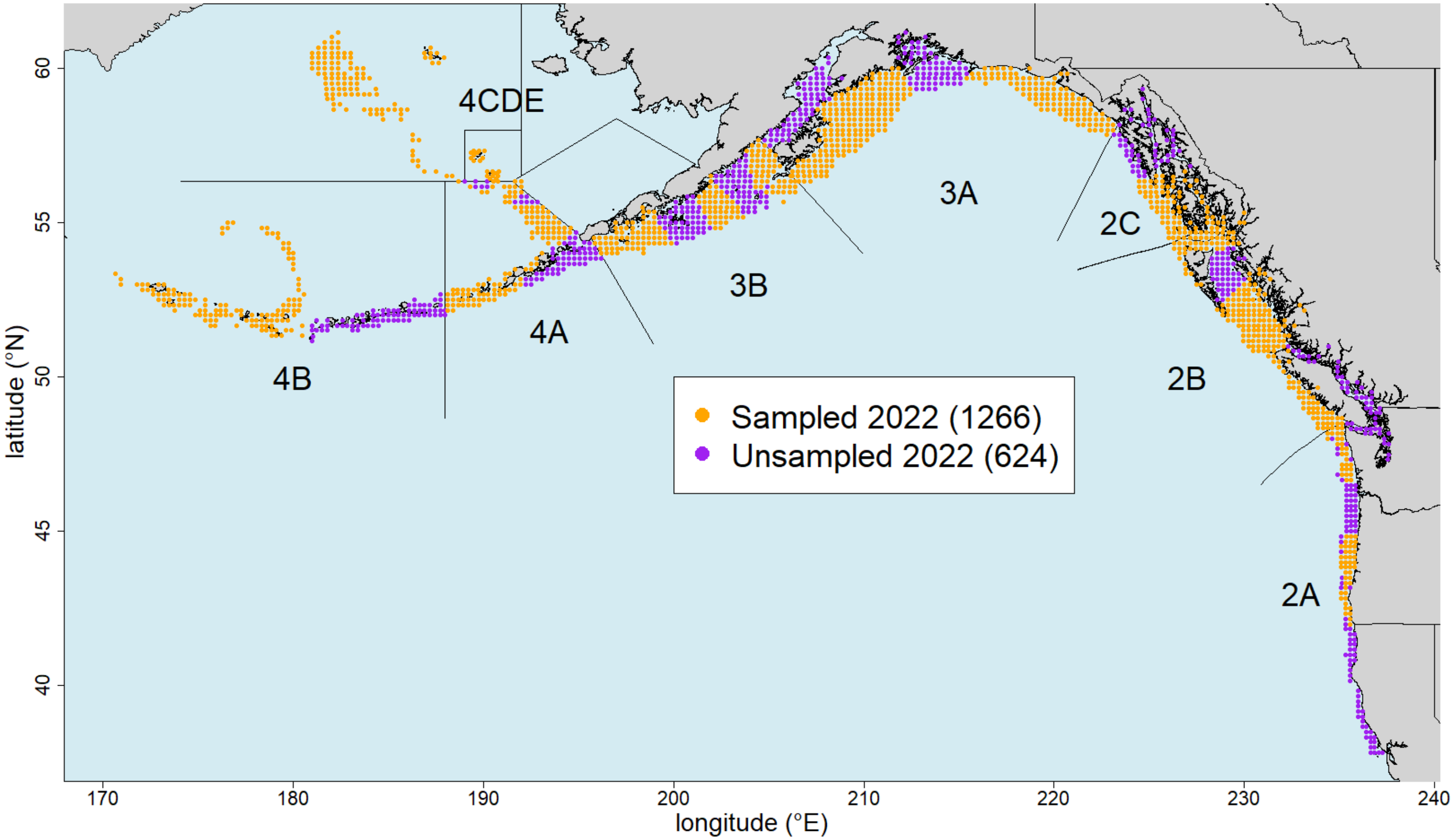


Figure 10. Minimum FISS design for 2022 (orange circles) proposed at AM096 based on subareas. Purple circles are optional for meeting data quality criteria.

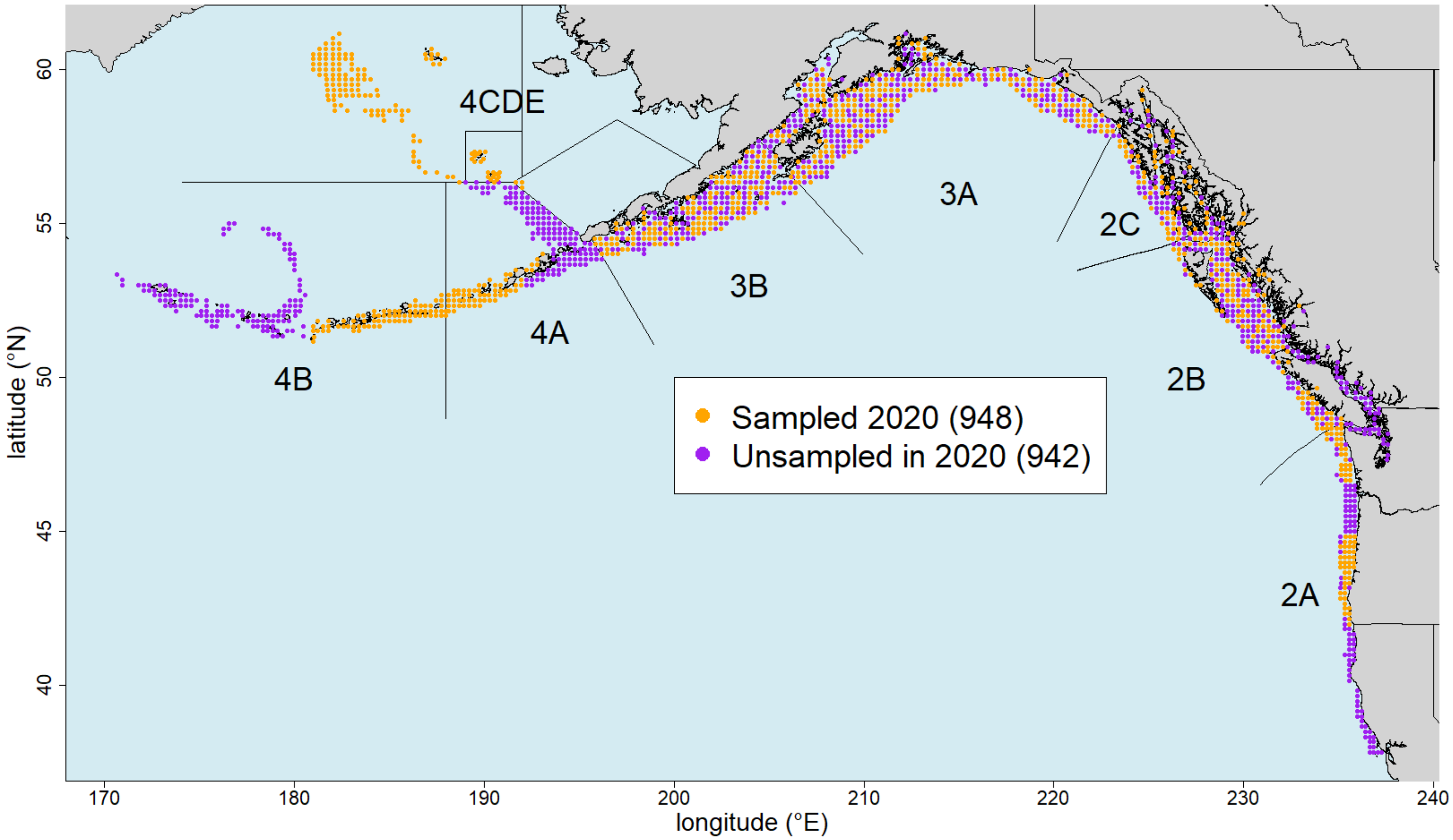


Figure 11. Minimum FISS design for 2020 (orange circles) proposed at AM096 based on randomized sampling in 2B-3B, and a subarea design elsewhere. Purple circles are optional for meeting data quality criteria.

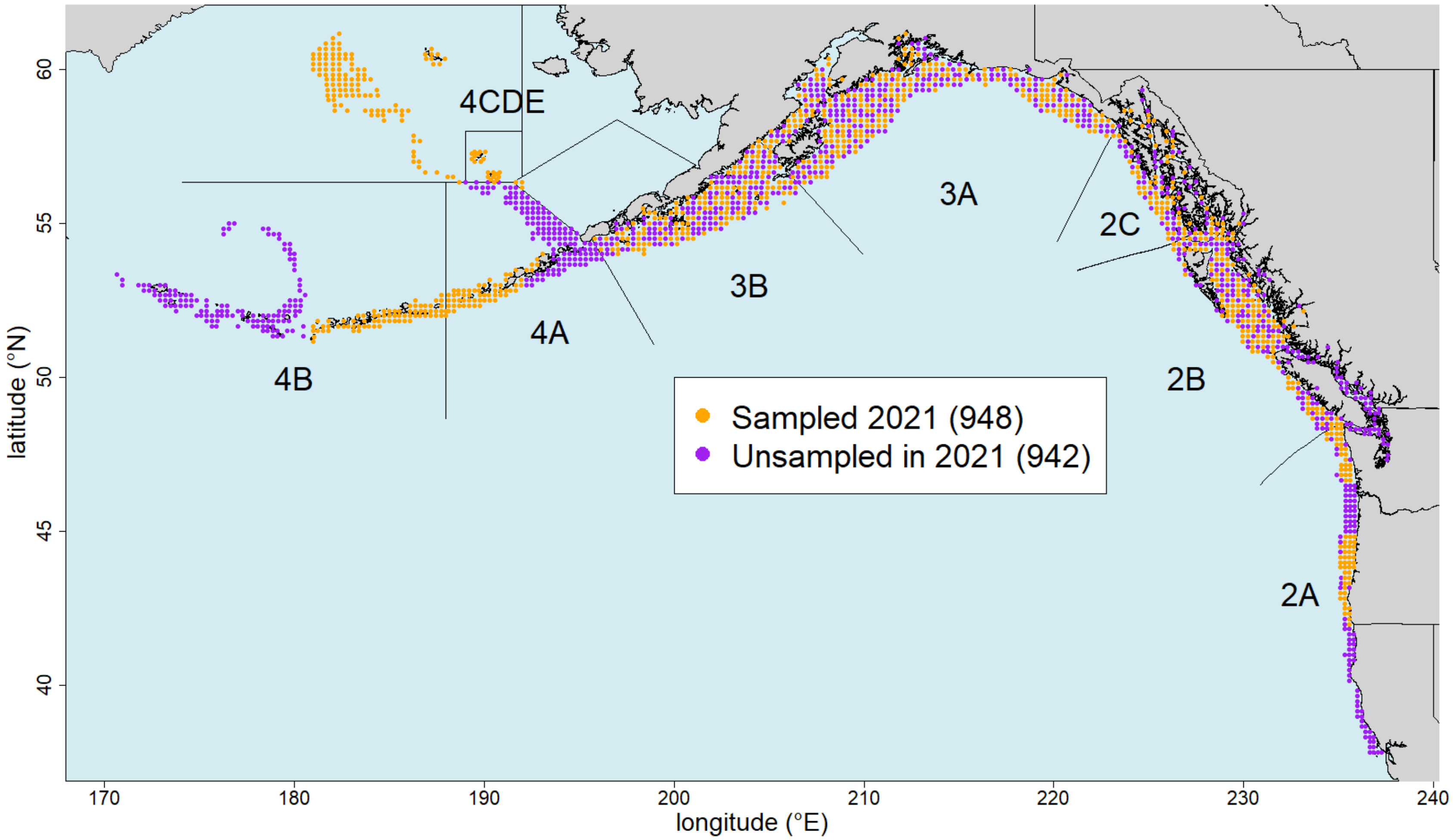


Figure 12. Minimum FISS design for 2021 (orange circles) proposed at AM096 based on randomized sampling in 2B-3B, and a subarea design elsewhere. Purple circles are optional for meeting data quality criteria.

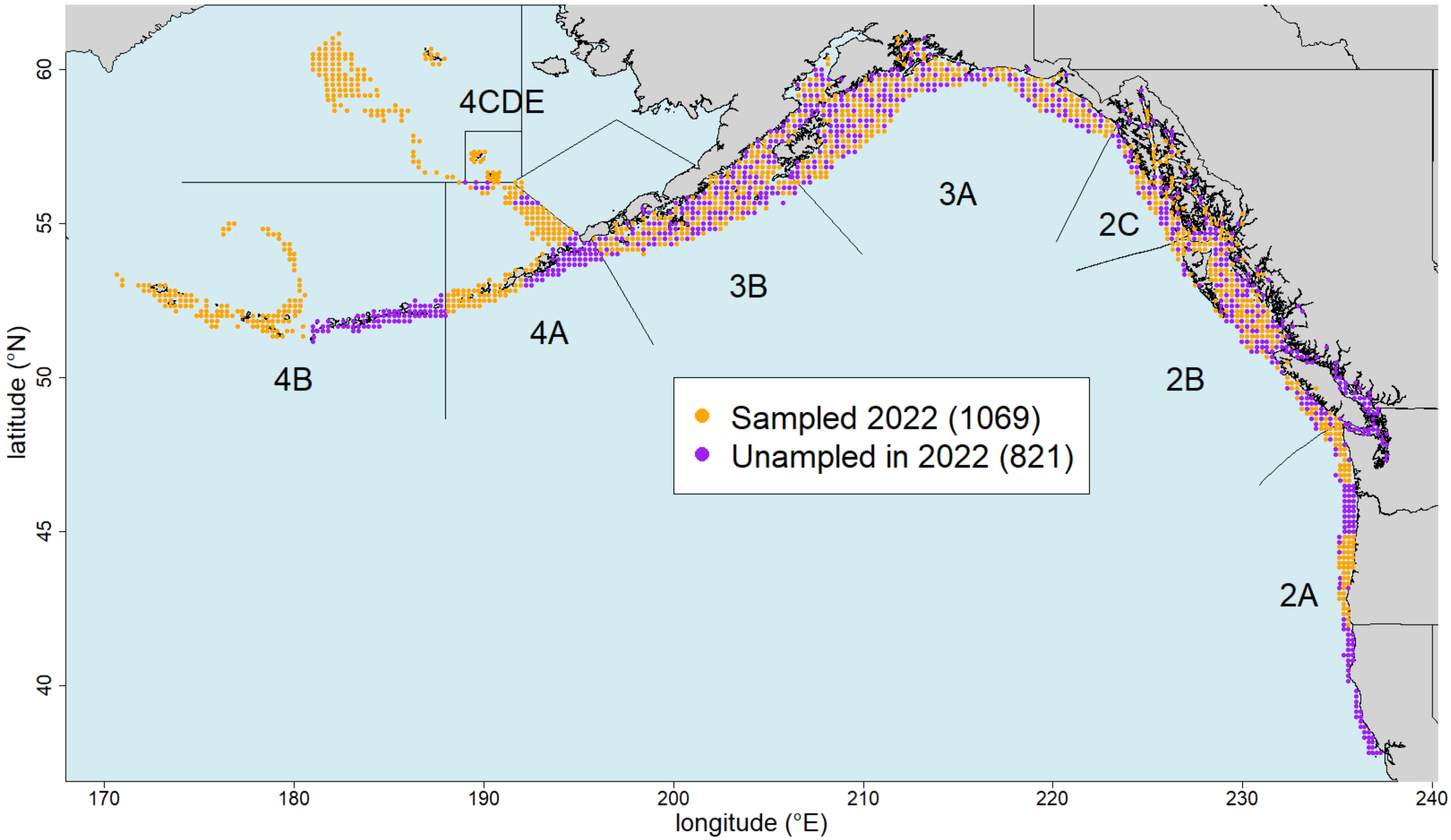


Figure 13. Minimum FISS design for 2022 (orange circles) proposed at AM096 based on randomized sampling in 2B-3B, and a subarea design elsewhere. Purple circles are optional for meeting data quality criteria.

Appendix A

Subareas within IPHC Regulatory Areas

IPHC Regulatory Area 4B

Regulatory Area 4B is a relatively small area, can be divided into fairly distinct subareas based on the 2017 FISS expansion results (Figure A.1):

1. West of Kiska Is. At present, a relatively low density subarea, but one that previously had much higher densities of Pacific halibut. (57 stations)
2. East of Kiska Is, and west of Amchitka Pass, including Bowers Ridge. Also at present a low density subarea, but one largely unsurveyed before 2017. (73 stations)
3. East of Amchitka Pass. Currently, a subarea of relatively high density and stability, although with higher density in the past. (73 stations)

In recent years, the bulk of the 4B stock (70-80%, Figure A.2) is estimated to have been in Subarea 3. With standard deviations typically increasing with the mean for this type of data, focusing FISS effort on this subarea in future surveys should succeed in maintaining target CVs, while reducing net cost. However, additional analysis of the historical WPUE time series shows Subarea 1's percentage of the biomass can also change by relatively large amounts over short time frames, with absolute changes of over 10% over as little as 3-4 years (see Appendix B). This also should be accounted for in a three-year design plan.

We augmented the 1993-2018 data with simulated data sets for 2019-22. For 2019, the planned FISS design was used, while the following designs were considered for subsequent years:

- 2020: Only Subarea 3 fished (73 stations)
- 2021: Only Subarea 3 fished (73 stations)
- 2022a: Only Subarea 3 fished (73 stations)
- 2022b: Only Subarea 1 fished (57 stations)
- 2022c: Subareas 1 and 2 fished (130 stations)

The three options for 2022 allow either a continuation of Subarea 3 only (2022a), Subarea 1 only to reduce the chance of bias due to changes in density in Subarea 1 over the three years since 2019 (2022b), and a third option (2022c) in case 2022b leads to CVs above the 15% target. The third option is also precautionary in that while there is apparent stability in Subarea 2's biomass percentage (Figure 3 and Table 5), most of Subarea 2 has been surveyed just once, in the 2017 expansion.

Fitting space-time models to the augmented data sets showed that fishing only Subarea 3 from 2020-22 is expected to be sufficient to reduce and then maintain CVs to below 15%. Fishing Subarea 1 and 2 in 2022 should also meet the precision target, and would be the preferred minimum design in that year in order to ensure that bias remained low.

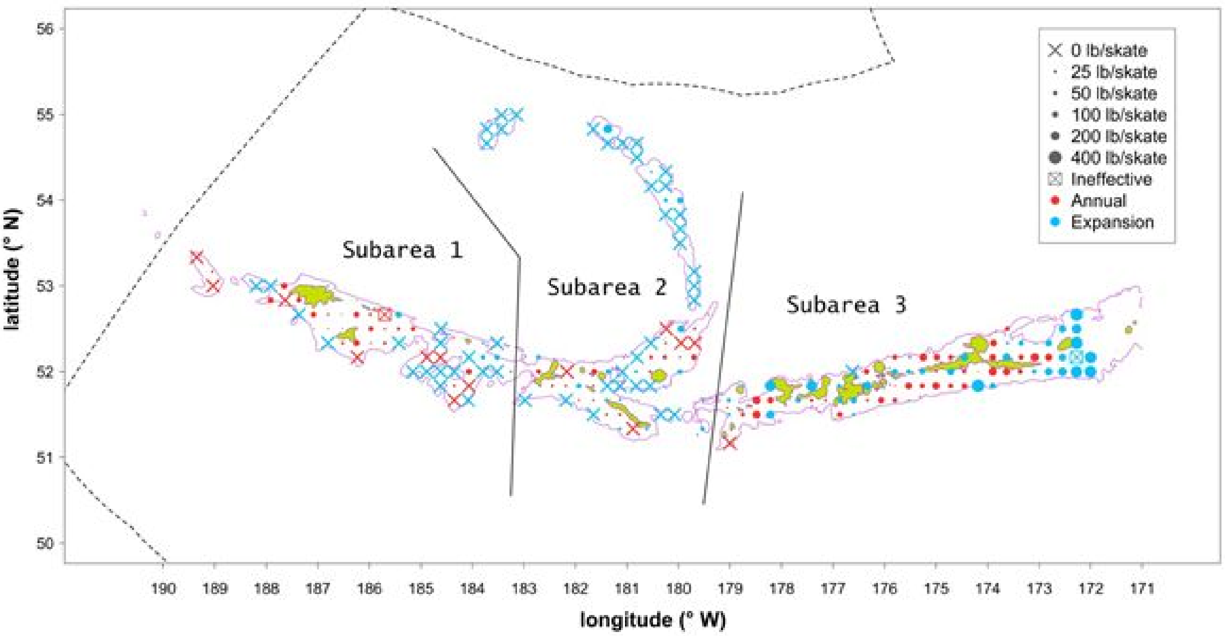


Figure A.1. Map of the 2017 FISS expansion design in IPHC Regulatory Area 4B showing the subareas used in the analysis.

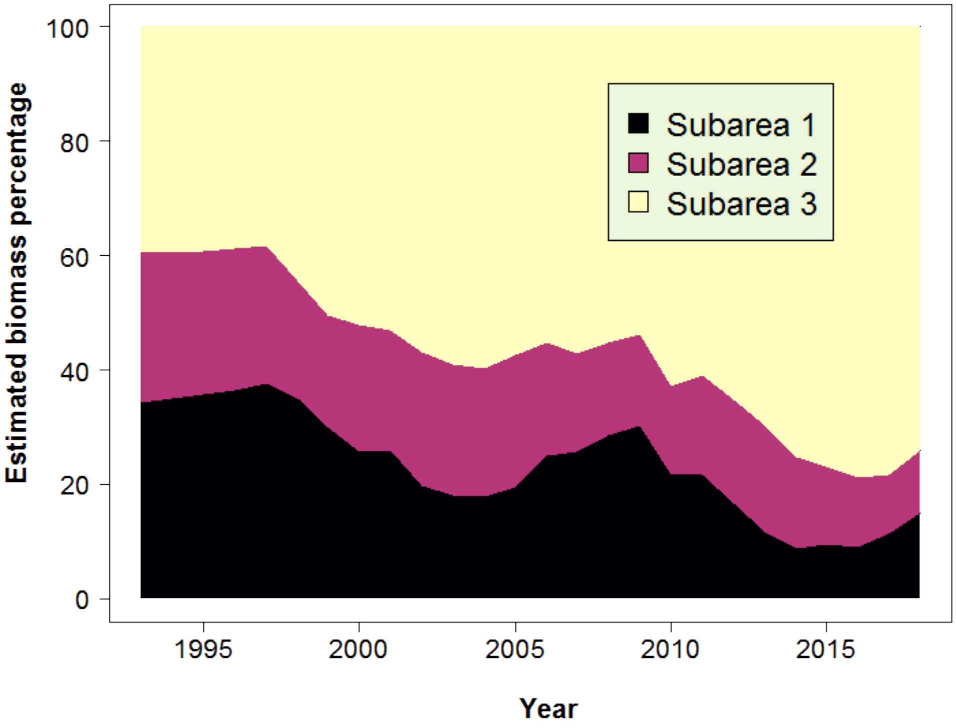


Figure A.2. Estimated IPHC Regulatory Area 4B biomass % by subarea and year.

IPHC Regulatory Area 4A

Like Regulatory Area 4B, we have divided Regulatory Area 4A into geographic subareas (Figure A.3) for use in devising an efficient FISS design. Subarea 1 is a high density subarea, which in recent years has had 65-85% of the biomass, and has been historically variable in terms of its proportion of the biomass (Figure A.4). Subarea 2 is a low-density area with a very stable proportion of the Regulatory Area 4A biomass, while Subarea 3 has had more variable biomass. (The smallest subarea, Subarea 4, is covered by the annual NMFS trawl survey, and we are not proposing to sample it as part of the annual survey.)

Based on this information, the following designs were evaluated for 2020-22:

- 2020: Only Subarea 1 fished (59 stations)
- 2021: Only Subarea 1 fished (59 stations)
- 2022a: Only Subarea 3 fished (63 stations)
- 2022b: Subareas 2 and 3 fished (114 stations)
- 2022c: Subareas 1 and 3 fished (122 stations)

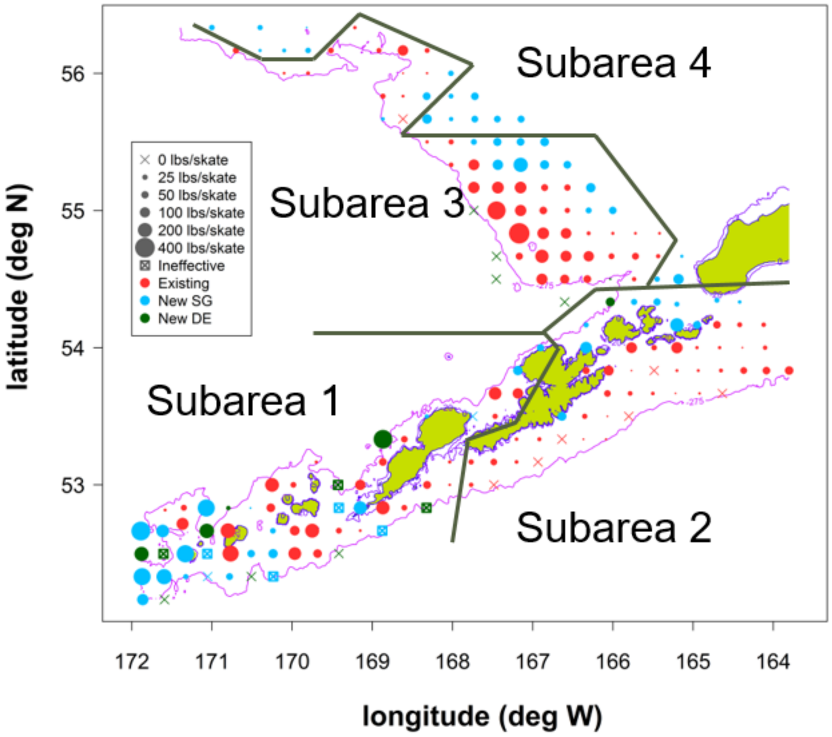


Figure A.3. Map of the 2014 FISS expansion design in IPHC Regulatory Area 4A showing the subareas used in the analysis.

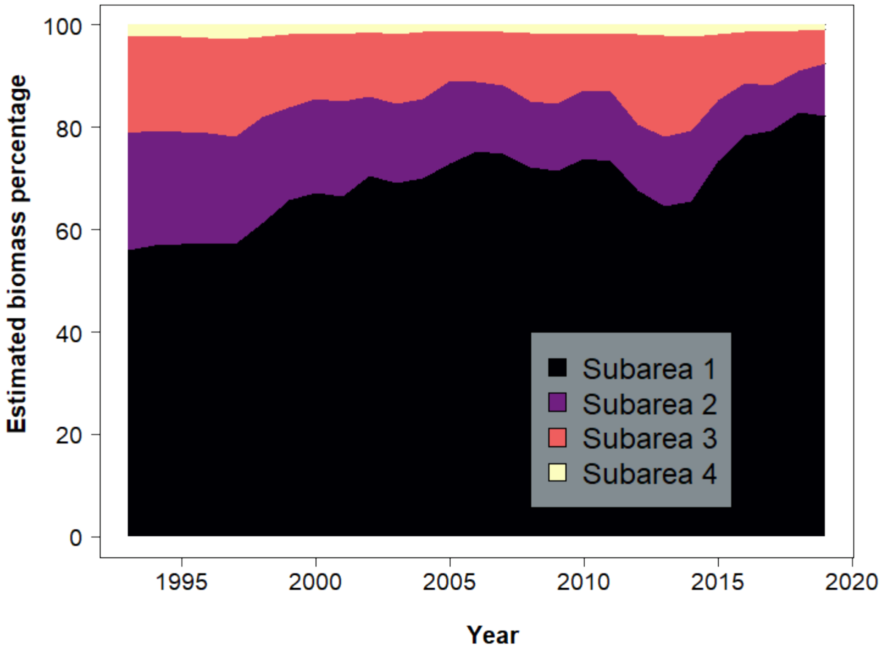


Figure A.4. Estimated Regulatory Area 4A biomass % by subarea and year.

Sampling only Subarea 1 in Regulatory Area 4A was sufficient to meet precision targets in 2020-21. For 2022, designs that omitted Subarea 1 were not expected to meet precision targets, and the minimum proposed design for 2022 is to fish Subareas 1 and 3.

IPHC Regulatory Area 2A

In IPHC Regulatory Area 2A, we again proposed subareas based on density and geography, but these subareas were not contiguous due to the existence of two distinct higher density regions, one off the north Washington coast, and the other of the central Oregon coast (Figure A.5). Thus, we created Subarea 1 to include both of these higher density regions, while Subarea 2 includes the moderate density zone between them, as well as the northern part of California. Subarea 3 includes the remaining low density regions in the Salish Sea, California, and the stations in deep and shallow waters throughout the Regulatory Area. The proportion of biomass in each subarea does not change greatly over periods less than five years (Figure A.6), and this relative stability should allow us to reduce sampling frequency in lower density subareas while maintaining precision targets.

For the 2020-22 period, we evaluated a sampling design in which only Subarea 1 was sampled. This 72-station design was sufficient to maintain CVs for mean WPUE below the 15% target in all years, while having low expected bias due to the stability of the biomass distribution among subareas.

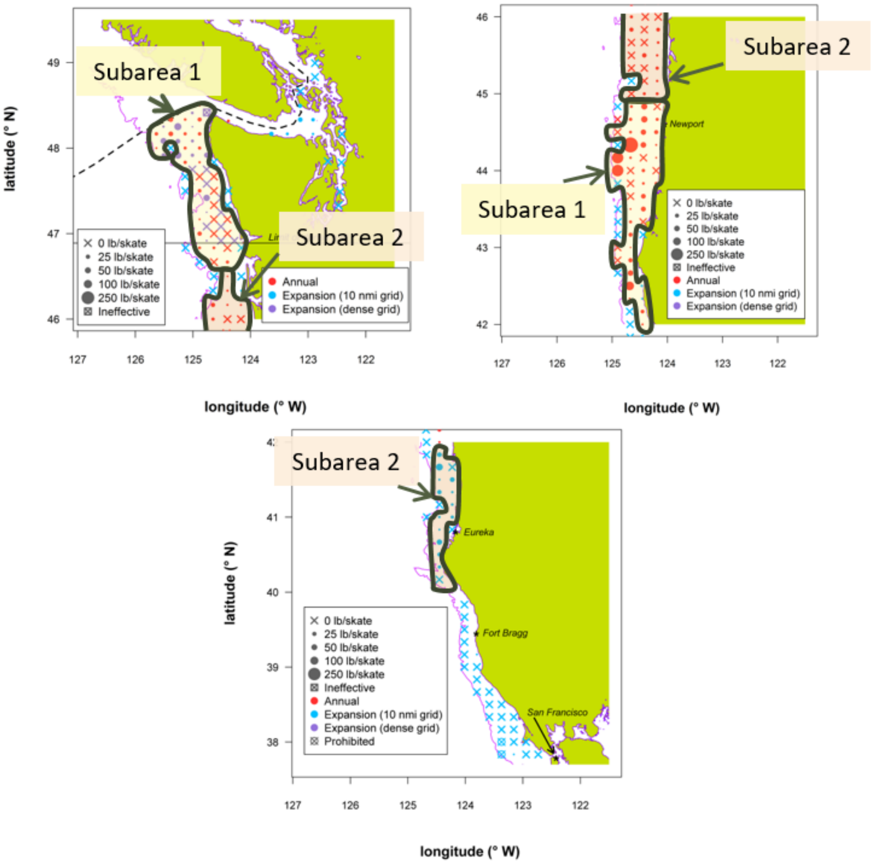


Figure A.5. Map of the 2017 FISS expansion design in IPHC Regulatory Area 2A showing the subareas used in the analysis. Subarea 3 is unlabeled but is comprised of the stations outside of Subareas 1 and 2.

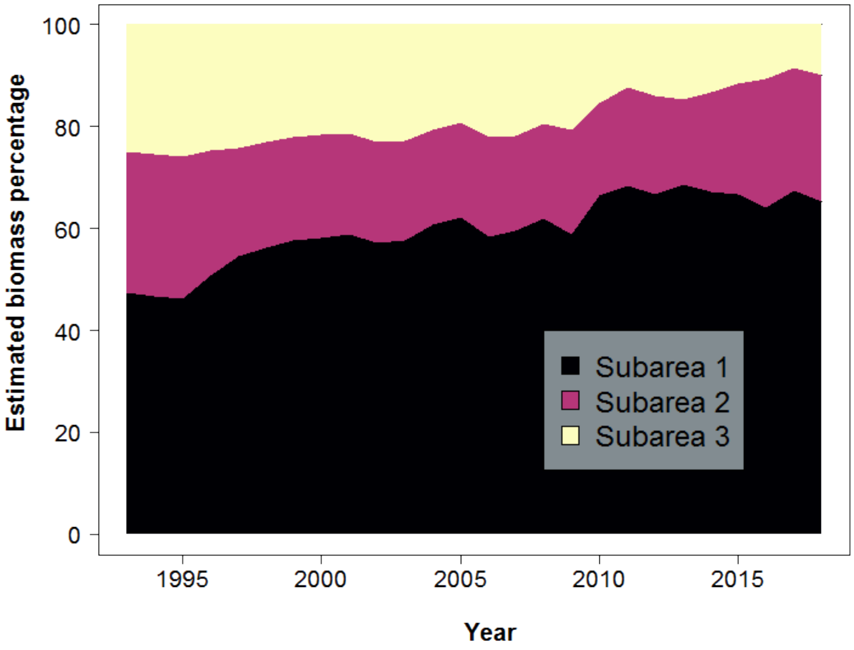


Figure A.6. Estimated IPHC Regulatory Area 2A biomass % by subarea and year.

Appendix B

Example of managing bias when subareas are employed: IPHC Regulatory Area 4B

The division of IPHC Regulatory 4B into subareas was described in Appendix A. Along with Figure A.1, showing trends in biomass proportions within IPHC Regulatory Area 4B, we also considered Table B.1 when determining the frequency with which each subarea should be sampled in order to maintain low bias. This table, derived from the data in Figure A.1, shows how many years until at least a 10% absolute change in estimated biomass proportion is recorded by year and subarea.

Subarea 1 often sees changes of at least 10% over a 3-4 year period. For example, the value “4” in 1996 in Table B.1 for Subarea 1 means that a 10% absolute change in this subarea’s biomass proportion from the 1996 estimate was first observed four years later, in 2000. Likewise, a change of at least 10% from the 1997 estimate also first observed in 2000, and so on. Table cells with dashes (from 2012 onwards for Subarea 1) mean that a change of at least 10% has yet to be observed.

We interpret the data in Table B.1 to mean that Subareas 1 and 3 should be sampled every 3-4 years to maintain low bias, while Subarea 2 can be sampled less frequently (with the caveat discussed in Appendix A).

Similar tables were referenced when determining sampling priorities for subareas within other IPHC Regulatory Areas for subarea-based designs.

Table B.1 For each year, the number of years until at least a 10% absolute change in estimated biomass share is observed.

Subarea	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
1	9	8	7	4	3	4	3	13	12	7	5	4	4
2	17	21	20	19	18	19	−	16	16	14	13	12	11
3	6	5	4	3	2	4	11	10	11	11	10	9	8
Subarea	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
1	7	6	4	3	4	3	−	−	−	−	−	−	−
2	−	−	−	−	−	−	−	−	−	−	−	−	−
3	6	6	4	3	4	3	3	−	−	−	−	−	−

INTERNATIONAL PACIFIC HALIBUT COMMISSION

Rationalisation of the FISS following the 2014-19 expansion series

Agenda item: 4.2

IPHC-2020-SRB017-06

Summary

- Background
  - IPHC history of FISS, 1993-2010
  - FISS expansions 2011-19
  - Space-time modelling
  - FISS design objectives
  - Review process
- Proposed FISS designs for 2021-23
  - Evaluation and revision of designs
- Consideration of cost

IPHC FISS

- Our most important source of data on Pacific halibut
- Provides data for estimating weight and numbers per unit effort (WPUE and NPUE) indices of density and abundance of Pacific halibut
  - Used to estimate stock trends
  - Used to estimate stock distribution
  - Important input in the IPHC stock assessment
- Provides biological data for use in the stock assessment

FISS history 1993-2010

- A standardised FISS has been conducted by the IPHC each year since 1993
  - Standardised for bait and fishing gear
- From 1993-97 coverage was limited and generally restricted to IPHC Regulatory Areas 2B, 2C, 3A and 3B
- The modern FISS design on a 10 nmi grid began in 1998
- By 2001, annual coverage occurred in all IPHC Regulatory Areas
  - Depth range 20-275 fathoms in Gulf of Alaska and Aleutian Islands
  - Depth range 75-275 fathoms along Bering Sea shelf edge

FISS history 2011-2019

- By 2010, data from other sources showed that not all Pacific halibut habitat was covered by the FISS
  - Pacific halibut were present outside the FISS depth range, in both deep and shallow waters
  - All IPHC Regulatory Areas had coverage gaps, even within the standard depth range
- Such unsampled habitat meant there was the potential for bias in estimates derived from FISS data
- This led IPHC staff to propose expanding FISS coverage to include the unsurveyed habitat

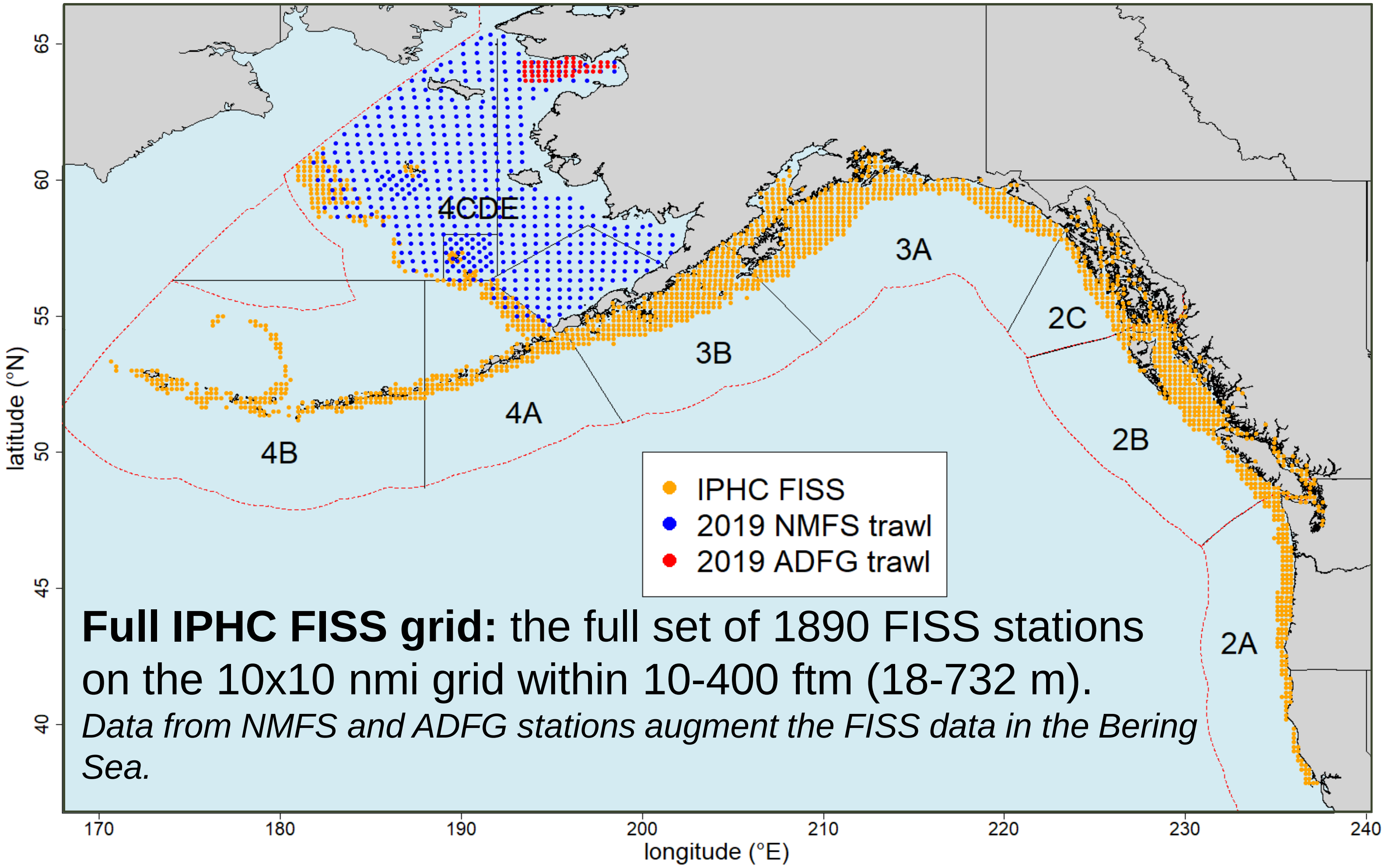
FISS history 2011-2019

- Pilot FISS expansions were undertaken in IPHC Regulatory Area 2A in 2011 (deep, shallow waters, other “missing” stations) and 2013 (northern California)
- From 2014-19, a planned program of FISS expansions took place in all IPHC Regulatory Areas as follows (with previously unsampled % of stations):
  - 2014: Regulatory Areas 2A and 4A (42%)
  - 2015: Regulatory Area 4CDE eastern Bering Sea flats
  - 2016: Regulatory Area 4CDE shelf edge (62%)
  - 2017: Regulatory Areas 2A (46%) and 4B (55%)
  - 2018: Regulatory Areas 2B (42%) and 2C (25%)
  - 2019: Regulatory Areas 3A (18%) and 3B (19%)

FISS history 2011-2019

- During the expansions, the FISS occupied for the first time 34% of the stations on the full 10 nmi FISS grid that had been previously unsampled
- The result was an improved understanding of Pacific halibut density and distribution
  - Bias was reduced, with indices for several Regulatory Areas being revised upwards or downwards
  - Uncertainty in estimates of WPUE and NPUE was reduced in most Regulatory Areas
  - These improvements were apparent throughout the time series, not only in the year of the expansion
- The resulting expanded grid of 1890 stations has provided a full FISS design from which stations can be selected for sampling in each annual FISS

Full FISS grid



Full IPHC FISS grid: the full set of 1890 FISS stations on the 10x10 nmi grid within 10-400 ftm (18-732 m).

Data from NMFS and ADFG stations augment the FISS data in the Bering Sea.

Space-time modelling

- Space-time modelling of survey data has been used since 2016 to produce WPUE and NPUE estimates
- The modelling has two key purposes:
  - It smooths the data in time and space
    - Makes use of information on spatial and temporal relationships among survey stations to “sort the signal from the noise”
  - It fills in gaps in survey coverage using model predictions, while accounting for uncertainty
    - Gaps previously filled using ad hoc scaling factors based on ratio of averages in surveyed and unsurveyed habitat

Reviews of space-time modelling methods

- The IPHC's Scientific Review Board (SRB) has repeatedly endorsed the space-time modelling approach, e.g. in 2018:

  IPHC-2018-SRB013-R, Para. 10. *"NOTING that this is the sixth review of the space-time modelling approach, the SRB reiterated its ENDORSEMENT of the approach as cutting-edge and could be widely used.*

- The space-time modelling methods have been published in a peer-reviewed journal:
  - **Webster et al.** (2020) Monitoring change in a dynamic environment: spatio-temporal modelling of calibrated data from different types of fisheries surveys of Pacific halibut. Can. J. Fish. Aquat. Sci 77(8): 1421-1432

FISS objectives and 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

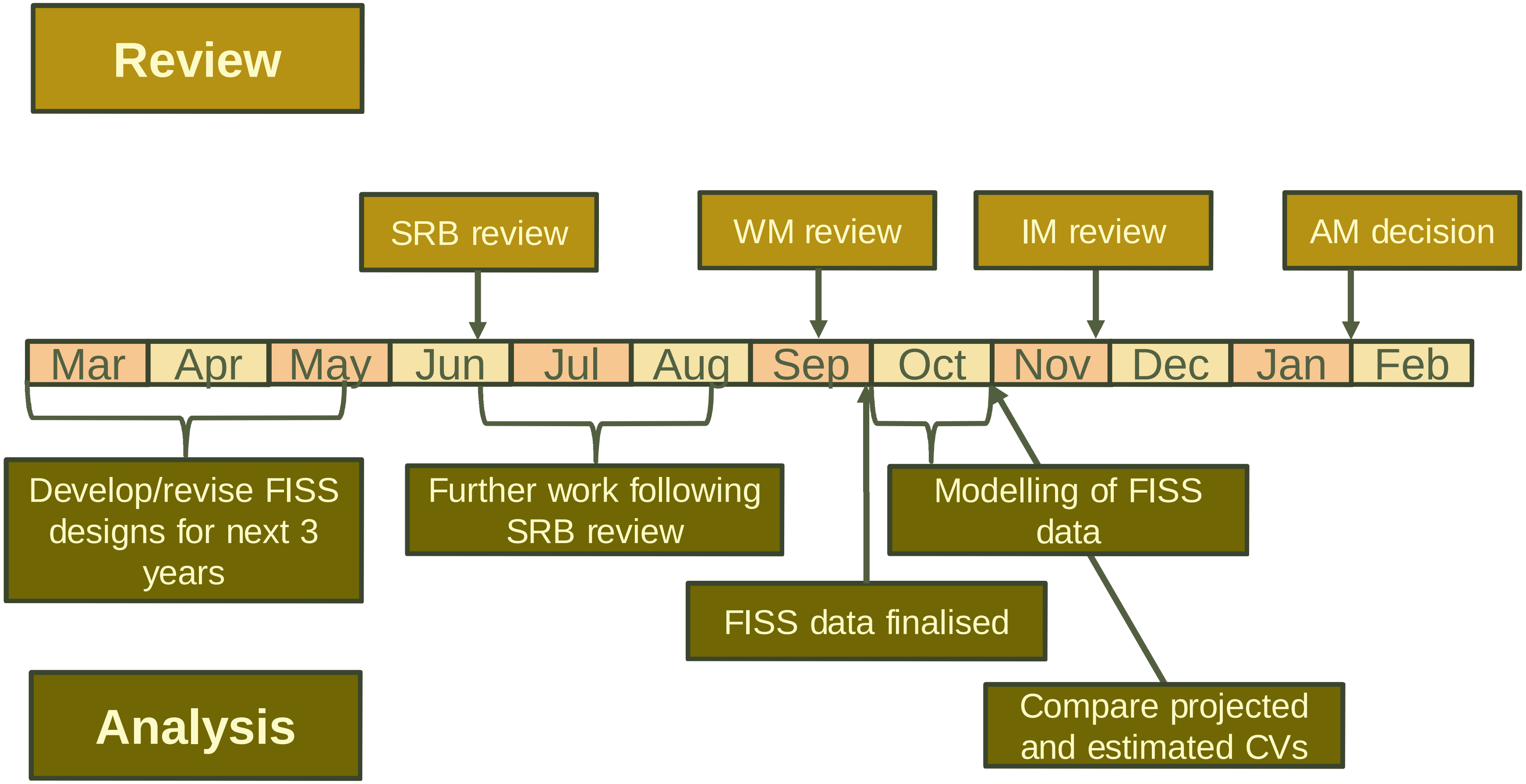
Review process

- Based on these objectives, the IPHC Secretariat staff developed methods for evaluating potential future FISS designs, and presented proposed designs for review:
  - Evaluation methods were reviewed at SRB014 and SRB016
  - Design proposals for 2020-22 were presented at IM095 and AM096
  - At AM096, Commissioners adopted an enhanced version of one of the proposed designs

Review process

- Following the completion of the coastwide FISS expansion efforts, 2019/20 was the first year fully rationalised designs could be proposed
- Beginning in 2020, it is expected that the design proposal and review process going forward will be as follows:
  - IPHC Secretariat present design proposals to the SRB for three subsequent years at the June meeting (✓ completed for 2021-23 designs)
  - First review of design proposals by Commissioners at September work meeting, revised if necessary based on SRB input (✓ completed for 2021-23 designs)
  - Presentation of proposed designs at the November Interim Meeting
  - Designs presented and potentially modified at January/February Annual Meeting given Commissioner direction
  - Adopted AM design for current year modified for cost and logistical reasons prior to summer implementation in FISS (February-April)

Annual FISS design review/analysis timeline



Review

SRB review

WM review

IM review

AM decision

Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb

Develop/revise FISS designs for next 3 years

Further work following SRB review

Modelling of FISS data

FISS data finalised

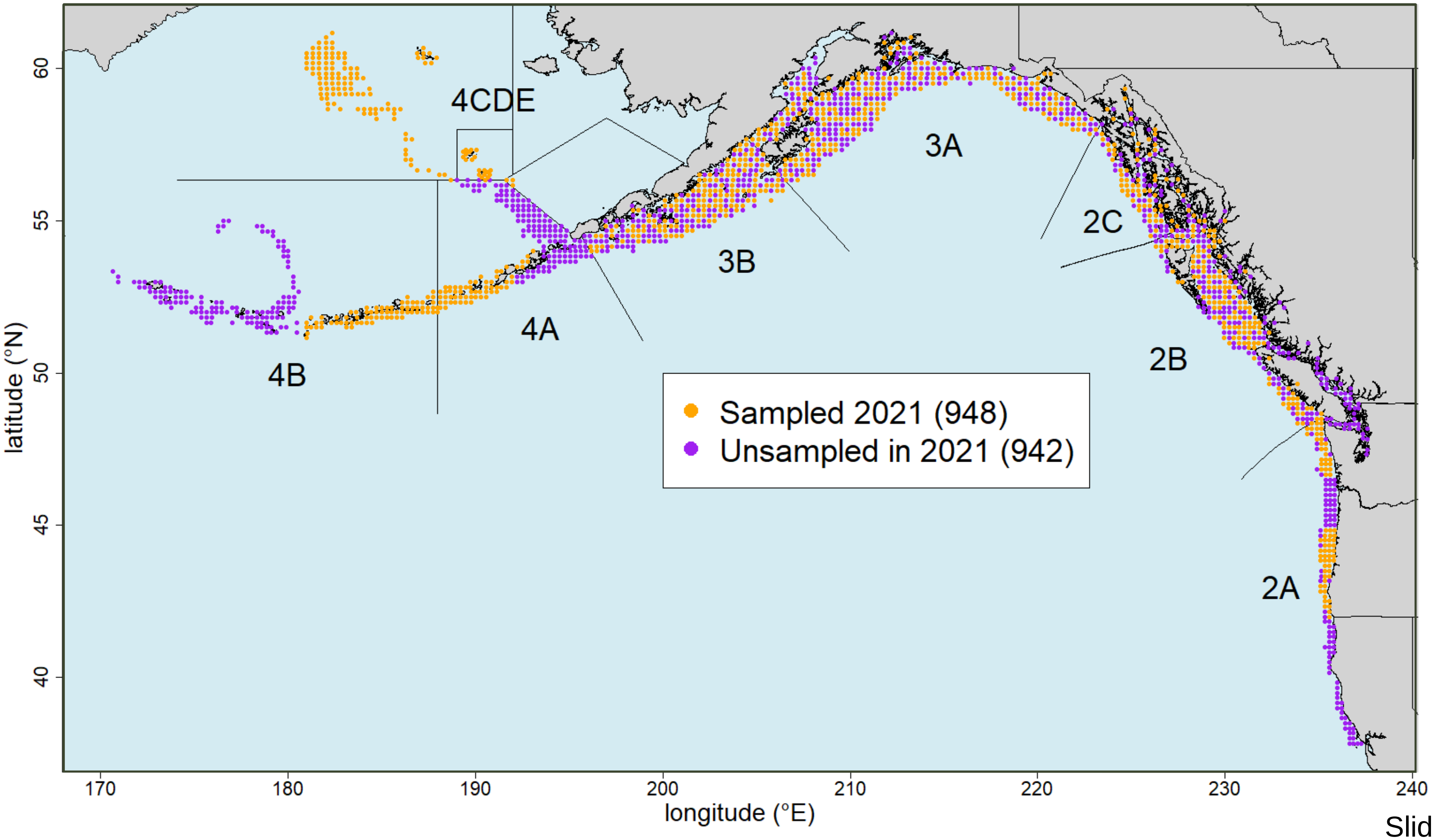
Compare projected and estimated CVs

Analysis

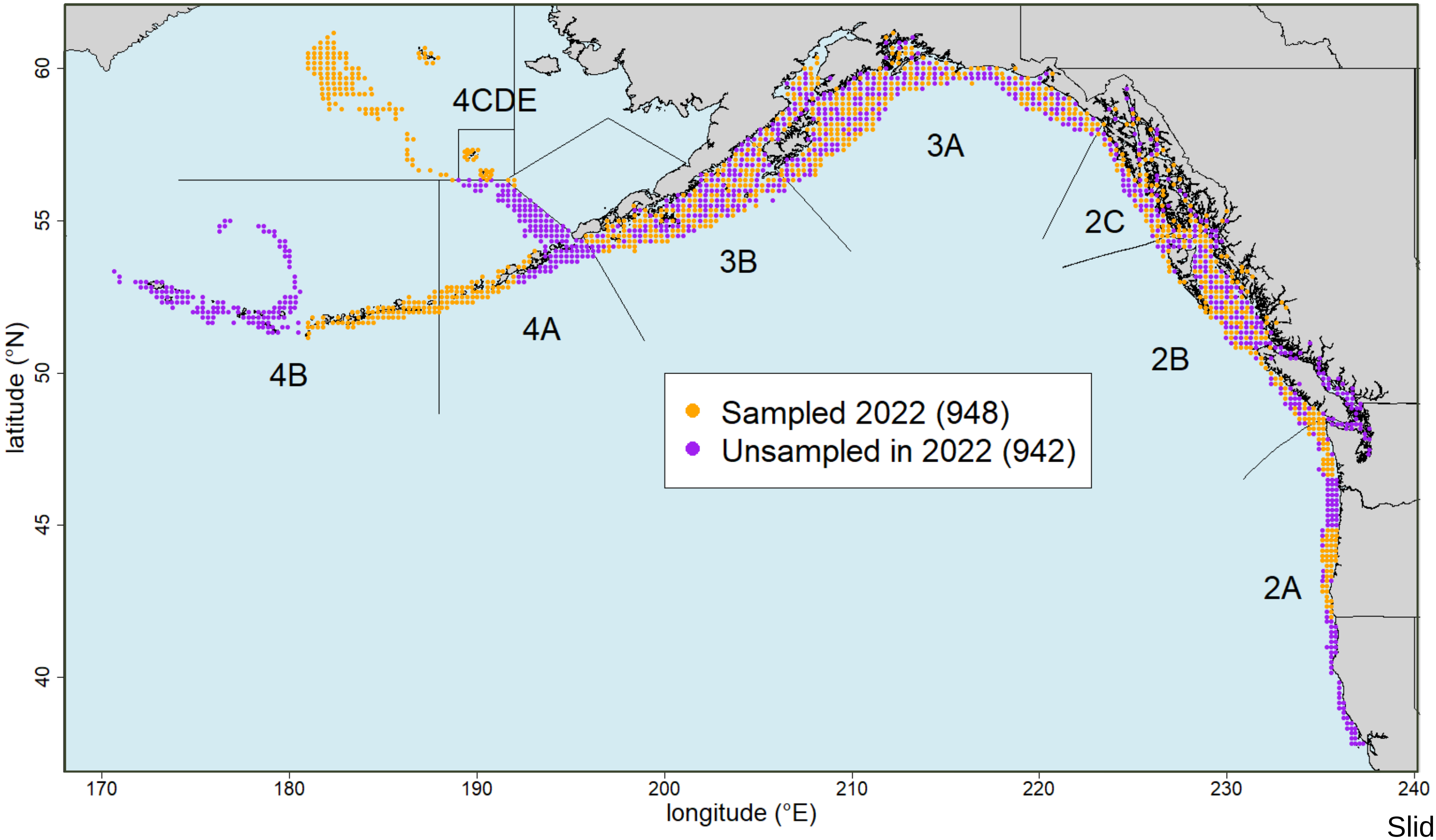
Proposed FISS designs for 2021-23

- Due to budgetary constraints and the impact of COVID-19, neither the proposed nor adopted AM096 designs were implemented in 2020
- Instead, sampling was only conducted within the core areas (2B, 2C, 3A and 3B) for the 2020 FISS
- Because of this, our proposal for 2021-23 is to shift the 2020-22 Secretariat-preferred compromise proposal presented at AM096 to instead be implemented in 2021-23
- This design uses efficient subarea sampling in IPHC Regulatory Areas 2A, 4A and 4B, but incorporates a randomized design in IPHC Regulatory Areas 2B, 2C, 3A; and
- It is likely that this design represents the maximum effort that can be deployed outside the core areas in coming years, while still meeting the Secondary Objective.

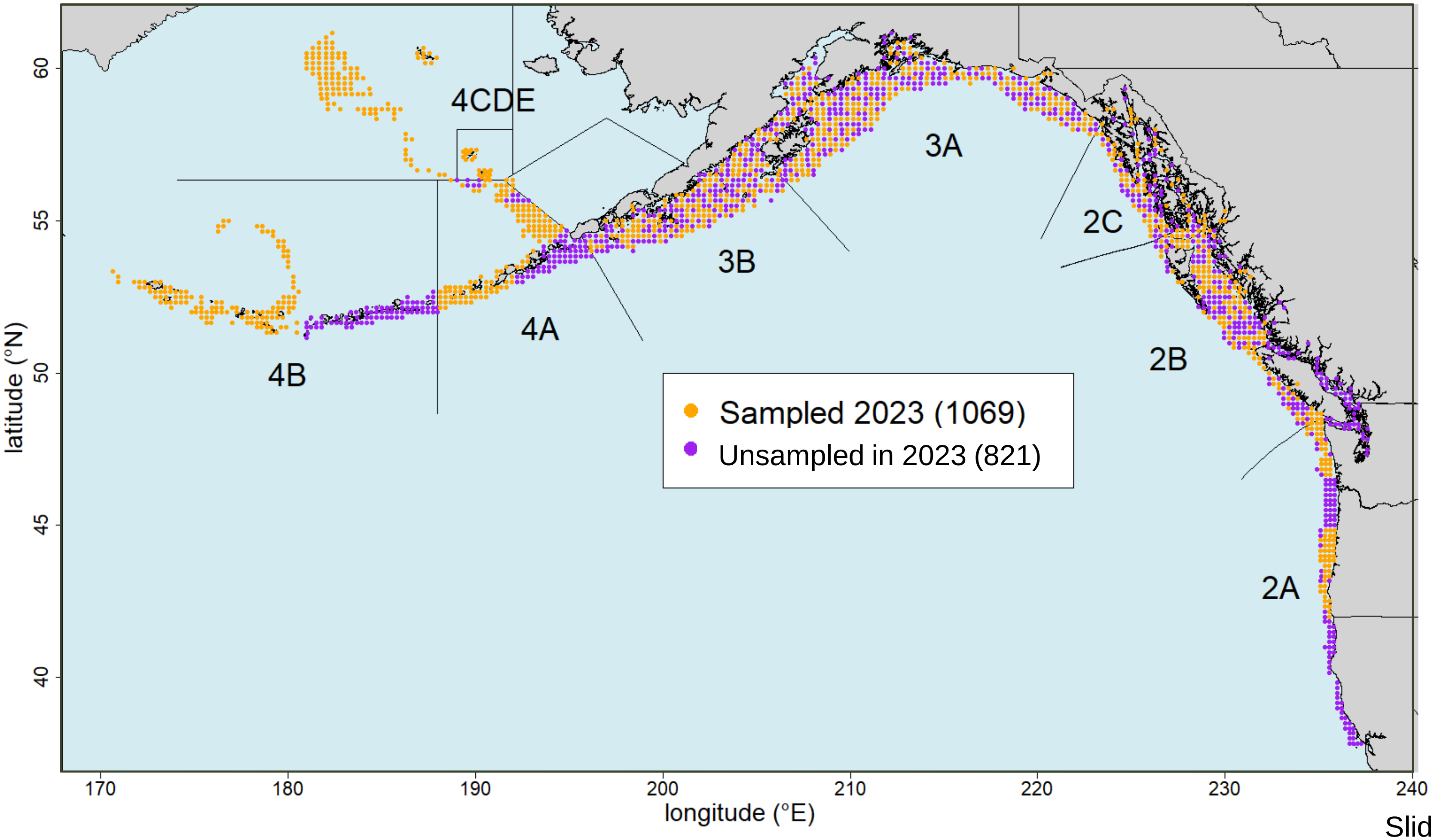
Proposed 2021 FISS design



Proposed 2022 FISS design



Proposed 2023 FISS design



Projected CVs

- The proposed designs have high sampling rates in Regulatory Areas 2B, 2C, 3A, 3B and 4CDE
  - CVs will remain well within targets (15% per Reg. Area)
- Randomised or full sampling designs in these areas will result in unbiased estimation
- In other Reg. Areas we project the following CVs (%) following completion of the 2023 FISS:

Reg. Area	2020	2021	2022	2023
2A	22	13	13	15
4A	16	9	9	10
4B	16	11	10	13

Minimizing bias

- To minimize bias due to not sampling one or more subareas each year, we selected a sampling frequency that aims to keep the change in biomass proportion of each subarea within 10% between successive sampling years.
  - This is based on estimated changes in WPUE over the 1993-2019 period
- For example, if a subarea's % of its Reg. Area's biomass changed by no more than 8% over 1 or 2 years but by up to 12% over 3 years, we should sample it at least every three years.

Maximum expected change in biomass % across all subareas since previous sampling based on proposed 2021-23 designs and no sampling in 2020

Reg. Area	2020	2021	2022	2023
2A	8%	8%	8%	10%
4A	8%	8%	10%	8%
4B	9%	10%	**14%**	9%

Annual revision of FISS design proposals

- As new FISS data come in each year, we revise our understanding of the spatial distribution of Pacific halibut.
- Local contraction or expansion of the distribution, or changes in inter-annual variability in subareas, can lead to revisions in the future frequency of FISS sampling in each subarea that will be incorporated into subsequent design proposals.

Projected CVs

- As part of our evaluation of the FISS design process, each year we will compare projected CVs for all sampled IPHC Regulatory Areas with those estimated from the models including the most recent data.

Reg. Area	2020 projected CV	2020 estimated CV
2A	-	21%
2B	6%	TBD
2C	6%	TBD
3A	4%	TBD
3B	10%	TBD
4A	-	24%
4B	-	25%
4CDE	-	TBD

Consideration of cost

- The proposed FISS designs for 2021-23 incorporate some consideration of cost
  - Logistically efficient subarea designs are proposed in lower-density IPHC Regulatory Areas.
- The goal here was to provide statistically efficient and logistically feasible designs for consideration by the Commission
- 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 costs

Consideration of cost

- Balancing these factors may result in modifications to the design proposals:
  - e.g. may need to increase sampling effort in high-density regions and decrease effort in low density regions
- At present, with stocks near historic lows and 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.

Recommendations

That the Scientific Review Board:

1) **NOTE** paper IPHC-2020-SRB017-06 that provides background on and review the methods for the IPHC's Fishery-Independent Setline Survey (FISS) rationalisation following the 2014-19 expansions series of the FISS, along with discussion of the resulting FISS design proposals for the 2020-22 period and presentation of the proposed designs for 2021-23;

2) **ENDORSE** the final 2021 FISS design;

3) Provisionally **ENDORSE** the 2022 and 2023 FISS design proposals, recognizing that these will be reviewed again at subsequent SRB meetings.

INTERNATIONAL PACIFIC

HALIBUT COMMISSION

Update on the development of the 2020 stock assessment

PREPARED BY: IPHC SECRETARIAT (I. STEWART & A. HICKS; 20 AUGUST 2020)

PURPOSE

To provide the IPHC's Scientific Review Board (SRB) with a response to requests made during SRB016 (IPHC-2020-SRB016-R) and to provide the Commission with an update on the development of the 2020 stock assessment.

INTRODUCTION

The 2019 stock assessment included a complete re-evaluation of all data sources and modelling choices as part of a full stock assessment analysis. A summary of results (IPHC-2020-AM096-09_Rev_2) was presented to the Commission during AM095 (Stewart et al. 2020b). Full assessment (Stewart and Hicks 2020) and data overview (Stewart and Webster 2020) documents were posted directly to the stock assessment page of the IPHC's website. The 2019 scientific review comprised both the standard SRB reviews in June (SRB014) and September (SRB015), as well an external peer review (Stokes 2019).

This document builds upon the preliminary stock assessment development reported for SRB016 (IPHC-2020-SRB016-07). It includes updates on requests made during SRB016, and on additional development toward the final 2020 stock assessment. The 2020 assessment represents an update of the 2019 assessment, and will include two new sources of information: recreational fishery sex-ratio data and 2019 commercial fishery sex-ratio data, as well as newly available information from existing data series collected during 2020. The assessment model structure was updated for SRB016 in order to accommodate sex-specific selectivity for the recreational mortality; there are no additional structural changes to the individual models or the ensemble.

SRB REQUESTS AND RESULTS

The SRB made the following four requests during SRB016:

1. SRB016–Req.04 (para. 21): *"The SRB AGREED that data weighting approaches, including alternative error distributions (e.g. self-weighting), should be evaluated further in the context of the next full stock assessment, and should strive to make use of the best methods available, noting that there are a range of approaches in use for similar stock assessments. In particular, the SRB REQUESTED that the IPHC Secretariat investigate the feasibility of a logistic-normal distribution to incorporate correlated errors in age composition data (see Francis, R.I.C.C. 2014. Replacing the multinomial in stock assessment models: A first step. Fisheries Research 151: 70–84). This change may be technically challenging given the current assessment software, as well as having sexed age composition data, and could non-trivially affect the stock assessment estimates of biomass and recruitment. Therefore, the SRB does not expect new results until at least SRB018 in June 2021."*
2. SRB016 (para. 20): *"The SRB REQUESTED that the IPHC Secretariat continue to update data weighting on an annual basis, even for updated stock assessments, in order to maintain internal model consistency and to best reflect changes in existing and new data as they arise."*
3. SRB016 (para. 22): *"The SRB REQUESTED that the Secretariat staff continue to evaluate whether the Stock Synthesis modelling framework is the most efficient for*

Commission needs, and to coordinate future development with the MSE framework as features and technical needs evolve together for the two efforts."

4. SRB016 (para. 23): *"The SRB REQUESTED an update at SRB017 on all data available at that time and any additional changes anticipated for the final 2020 stock assessment."*

These four requests are addressed below. As for SRB016, all results are based on individual models extended to include 2020 (preliminarily including projected 2020 mortality from all sources based on the mortality limits set during AM096). Software was updated to use stock synthesis version 3.30.15.09, from the version used for the 2019 stock assessment (3.30.13) and for SRB016 (3.30.14). Most of the changes to the software were unimportant for the assessment of Pacific halibut; however, on request from the Secretariat staff NOAA Fisheries developers added the calculation and reporting of variance estimates for the dynamic unfished spawning biomass. This quantity is used to calculate the relative biomass in each year for use in the IPHC's interim management procedure, and the variance (and covariance) calculations replace a proxy variance and covariance used for the 2019 stock assessment (Stewart and Hicks 2019). Effects of this change are described as part of the fourth request below.

Request 1 – logistic-normal for composition data

After investigating the Dirichlet-multinomial for SRB016, the Secretariat staff identified four issues that made its use non-optimal for the Pacific halibut stock assessment (and likely many other assessments). These issues were:

1) Increased weighting of small samples as the estimated variance in the composition data gets large.

2) The parameterization is not self-weighting near the nominal sample size as the estimated parameter goes to a bound and requires fixing at a static value to avoid potential estimation problems.

3) The approach produced standardized residuals that were inconsistent with the likelihood assumption (far more than 2.5% > 1.96).

4) The Dirichlet-multinomial does not allow for the correlation structure known to exist among proportions-at-age (or length).

On request from SRB016, the Secretariat staff reviewed the recent literature on error distributions for compositional data, with a particular focus on the logistic-normal. Francis (2014) introduces several likelihood function options for compositional data and provides discussion of each with relative shortcomings and advantages. He found clear theoretical support for the logistic-normal because: 1) it is self-weighting (not requiring an iterative approach), 2) his suggested parameterization can maintain the relative annual input sample sizes in the likelihood, and 3) it allows for estimated correlations among bins. He noted that the logistic-normal does not allow for zero proportions, and so requires compressing the tails of the distribution to positive values and/or a method for either combining bins with internal zeros or adding a small constant to observed (and expected) proportions. His analysis did not include fitting assessment models to data, but instead relied on comparing the likelihood of previous assessment model fits to compositional data. He found the LM performed well in most cases, but was quite sensitive to the choice of the small robustifying constant added to zero observations.

To address the variance and correlation structure among bins, he described three cases: 'LN1' with just a single variance parameter (σ), 'LN2' using an AR(1) process and including one additional correlation parameter, and 'LN3' using an AR(2) process and also adding a second correlation parameter. Francis suggested that the estimated variance parameter (σ) may be multiplied by some function of the input sample size (*n*) in each year (*y*) to retain the inter-annual variability created by the sampling intensity, as well as the variability inherent in the compositional data for each data set. This seemingly reasonable approach increases the weight as the sample size increases, but less so at very large sample sizes relative to the mean ($\bar{n}$):

$$\sigma_y = \sigma \left({}^{\bar{n}}/_{n_y} \right)^{0.5}$$

Francis suggested that allowing for a realistic correlation structure was one of the primary benefits of the logisitic-normal. He found that this correlation structure included both positive and negative correlations among age bins, and clearly did not following the structure implied by the simple multinomial. Miller and Skalski (2006) also found a complex correlation structures in fisheries length data that did not resemble that of a multinomial or Dirichlet-multinomial, with correlations among bins that were both positive and negative. The largest remaining impediment to application of the logistic-normal identified by Francis was the need to allow for a two-dimensional correlation structure that included both males and females for data that were sex-specific. Francis specifically notes that any simple AR(1) or AR(2) process would be incomplete, as the order of the bins among the two sexes would matter because the correlation structure operates on the bin index.

Other authors have both investigated and implemented versions of the logistic-normal. Cadigan (2016) used the multiplicative logistic-normal in a state-space model for Atlantic cod. His example was relatively simple compared to Pacific halibut: he had sexes-aggregated data, did not retain the annual sample sizes, and did not include correlations among the proportions, instead estimating a single variance parameter for all proportions that was then adjusted using *ad hoc* scaling of the youngest (age-2) and oldest (age-8+) bins. Schnute and Richards (1995) used what they called the 'multivariate logistic', which appears to be equivalent to the logistic-normal later described by Schnute and Haigh (2007). These authors also did not include sex-specific compositional data or include a provision to weight the variance by the observed sample size in each year. Finally, Albertsen et al. (2017) compared a range of compositional models (among other structuring choices, including comparing numbers-at-age with proportions-at-age), including the Dirichlet and logistic-normal, and finding that the latter performed better on their data sets. They considered both the additive and multiplicative versions of the logistic-normal. They used an AR(1) approach to correlation among age bins but again did not have sex-specific information.

Specifically for the halibut stock assessment there should be little problem with the robustifying constant for internal zeros (there are none in our current data sets) and the assessment already compresses the tails to the first positive observation. Due to the importance of sex-specific age composition data to the estimation of historical and current population dynamics, any proposed likelihood must be able to accommodate sex-specific data in a meaningful way. This means that we would need to explore methods for allowing a two-dimensional correlation among age- and sex-specific bins, where (for example) males and females of the same (or similar) age might be more correlated than those of differing ages, and within a sex similar ages are more correlated than those that are very different (Figure 1).

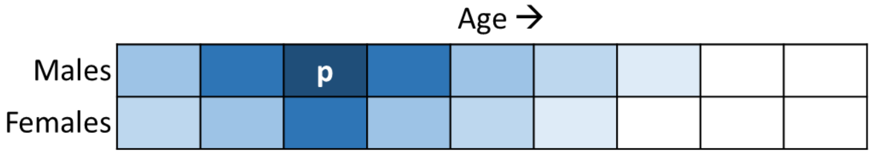


Figure 1. One type of hypothetical correlation (colors denote a negative or positive relationship with intensity equal to the correlation) between a specific male proportion-at-age (p) and surrounding ages for males and females. Note that evidence for this type of correlation was not found in all data sets by Francis (2014).

The Secretariat will continue to investigate published work for approaches to model two-dimensional correlation structure, and may initiate a graduate student project or other collaboration in order to potentially derive and test a candidate logistic-normal implementation that meets all of the needs of the current Pacific halibut stock assessment. A further update will be provided at SRB018.

Request 2 – update data weighting

The weighting of compositional data will be updated as one of the last steps in developing the final 2020 stock assessment, along with checking parameters on bounds and other convergence criteria, after all available data sources have been included.

Request 3 – modelling framework considerations

The only new information to report on this topic is the addition of the direct estimation of the variance of the unfished stock size in each year (‘dynamic SB_0’) of the modelled time-series to the optional outputs from stock synthesis. The IPHC Secretariat staff had contacted the SS development team with this need in 2019, and it was subsequently included in recent mid-version releases of 3.30.15 (in time for use in the 2020 stock assessment development). Although this process of requesting a new feature represented a delay in the implementation of the full calculation, the SS development team remains responsive and helpful to IPHC requests and the level of trouble-shooting required by IPHC Secretariat staff was modest.

Request 4 – data and model updates for 2020

Bridging and final steps for 2020 modelling

For SRB016 the 2019 stock assessment models were extended to 2021, and the newly available recreational sex-ratios-at-age included in the model fitting. To create a ‘bridge’ from the 2019 results to 2020, three steps were taken for SRB017:

1) Go back to the extended time-series and update to the newest version of stock synthesis available (3.30.15.09).
2) Add the recreational data again (and allow for separate selectivity asymptotes for males and females as done earlier).

3) Include the newly available sex-ratios-at-age for the 2019 commercial fishery (building on the 2017 and 2018 sex-ratios used in the 2019 stock assessment).

The first bridging step allowed for the directed estimation of the variance of the unfished spawning biomass in each year as well as the covariance of this quantity and the estimated spawning biomass in each year; the two quantities used to describe the relative stock status. In the 2019 stock assessment, the variance of the unfished spawning biomass in each year and the covariance with the estimated spawning biomass were both unavailable, so proxy values were used (Stewart et al. 2020a). These proxies proved to be quite close to the actual estimates, resulting in only a very small change to the estimated relative spawning biomass at the beginning of 2021 in the context of the approximate 95% asymptotic confidence intervals (Table 1). There was no change in the estimated spawning biomass or recruitment time-series for the short coastwide model (Figure 2), the long coastwide model (Figure 3), the short areas-as-fleets model (Figure 4) or the long areas-as-fleets model (Figure 5) as a function of the software version change.

Table 1. Comparison of relative biomass at the beginning of 2021 (prior to the addition of any new data other than the projected mortality for 2020) using the approximation from the 2019 stock assessment, and the improved calculation of variance available for the 2020 stock assessment. Low and high values correspond to an approximate 95% confidence interval.

	Low	$SB_{2021,fished}/SB_{2021,unfished}$	High	$P(SB_{2021}<SB_{30\%})$	$P(SB_{2021}<SB_{20\%})$
Approx. in 2019	20.1%	31.5%	46.2%	49	2
Calc. for 2020	19.8%	30.3%	47.4%	49	3

As observed previously, the recreational sex-ratio information had only a small effect on the time-series estimates. Similarly, the addition of the 2019 commercial sex-ratio estimates also had a very small effect on the stock assessment results. This is likely due to the aggregate fishery proportions observed for 2019 being very similar to those from 2017 and 2018 (Figure 6). Although the sample sizes (particularly for Biological Region 4B) are somewhat smaller when disaggregated to age-specific sex-ratios, the general pattern remained similar over the three years: a very high ratio of females at the younger ages (where males have a low probability of exceeding the minimum size limit) trending toward a more equal ratio at the oldest ages (Figure 7). There was a trend toward a lower percent female across the three years in all Biological Regions (Table 2). This may be due to the weak cohorts from 2006-2010 leading to an increase in the average age in the landings. Additional years of data will be needed to better delineate between real trends and inter-annual variability as they affect projection of fishing intensity when setting mortality limits for the upcoming year.

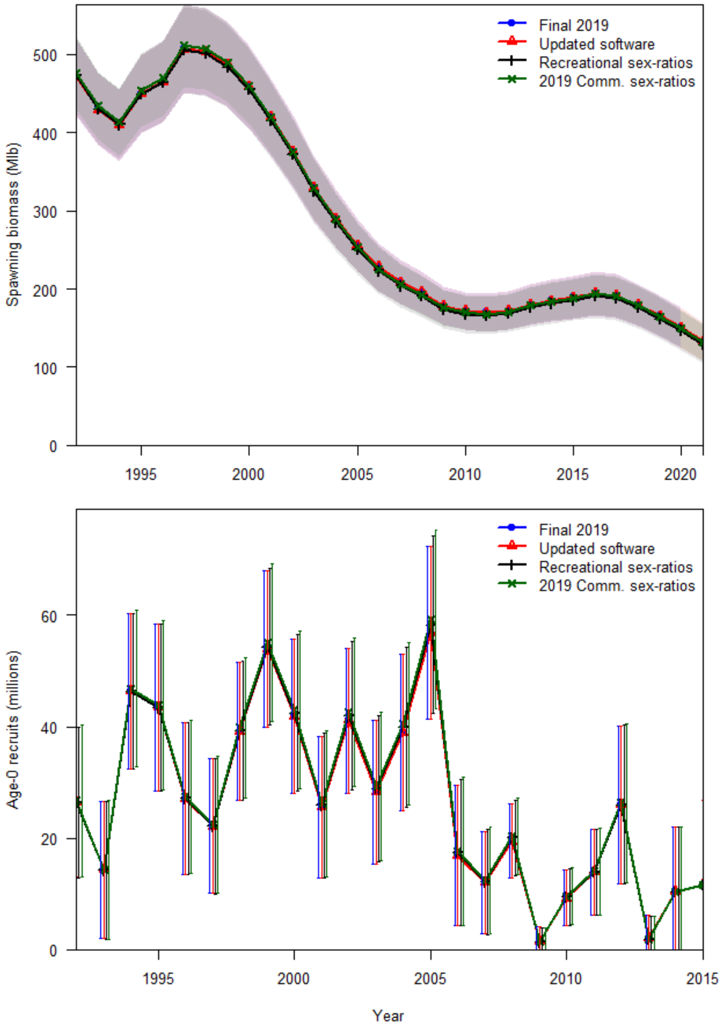


Figure 2. Bridging analysis for spawning biomass (upper panel) and recruitment (lower panel) for the short coastwide assessment model.

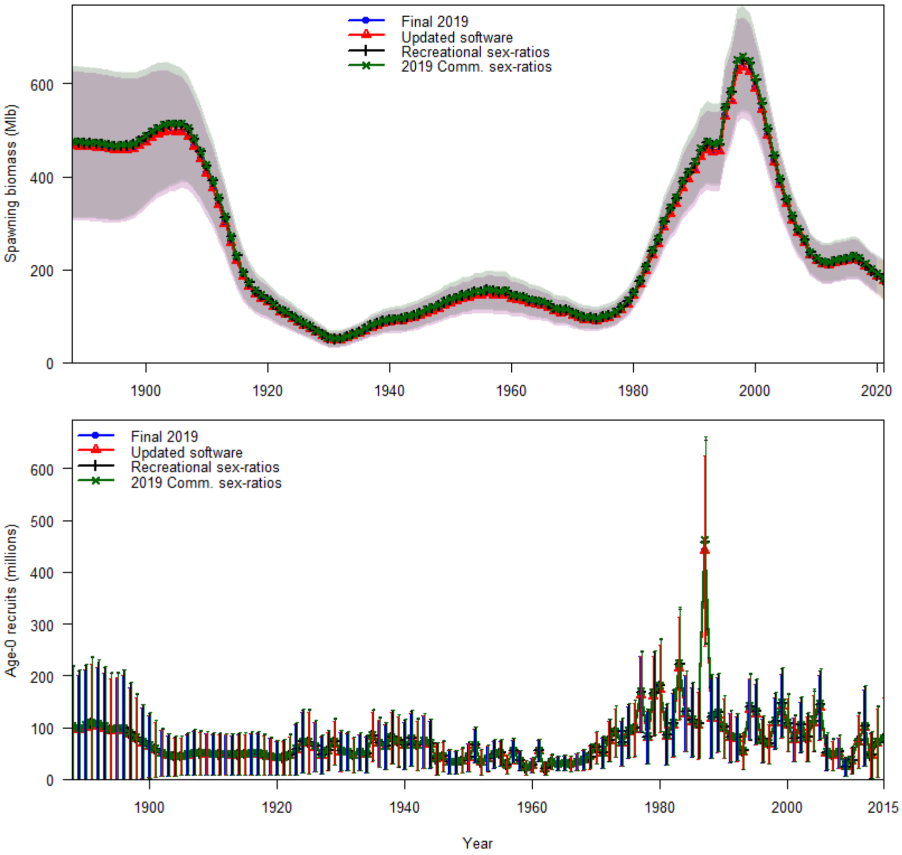


Figure 3. Bridging analysis for spawning biomass (upper panel) and recruitment (lower panel) for the long coastwide assessment model.

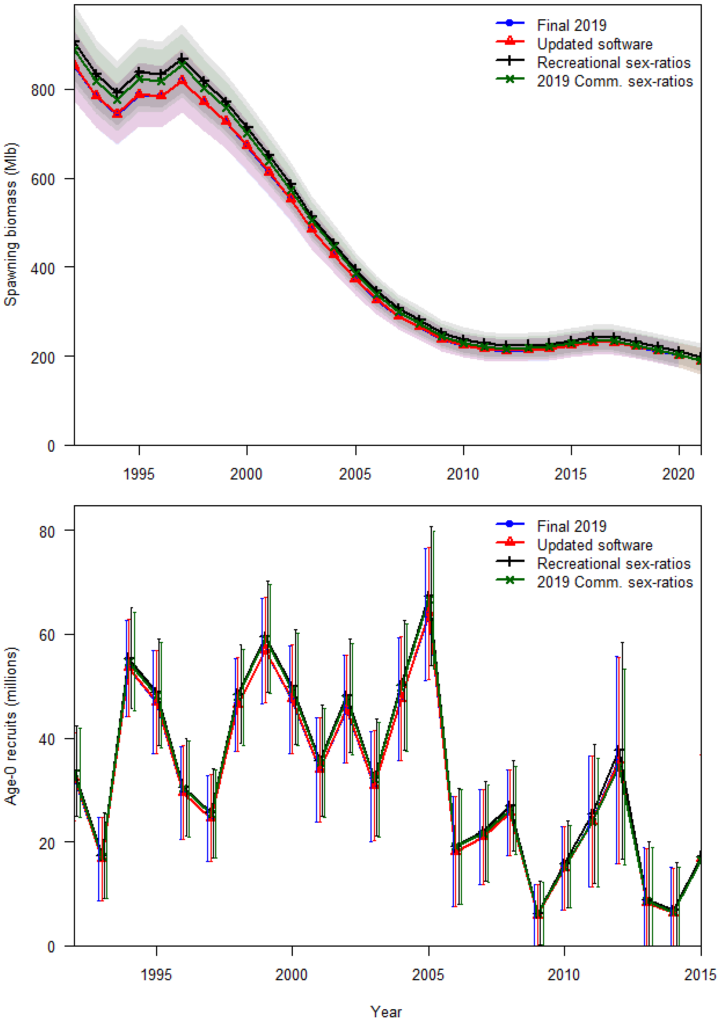


Figure 4. Bridging analysis for spawning biomass (upper panel) and recruitment (lower panel) for the short areas-as-fleets assessment model.

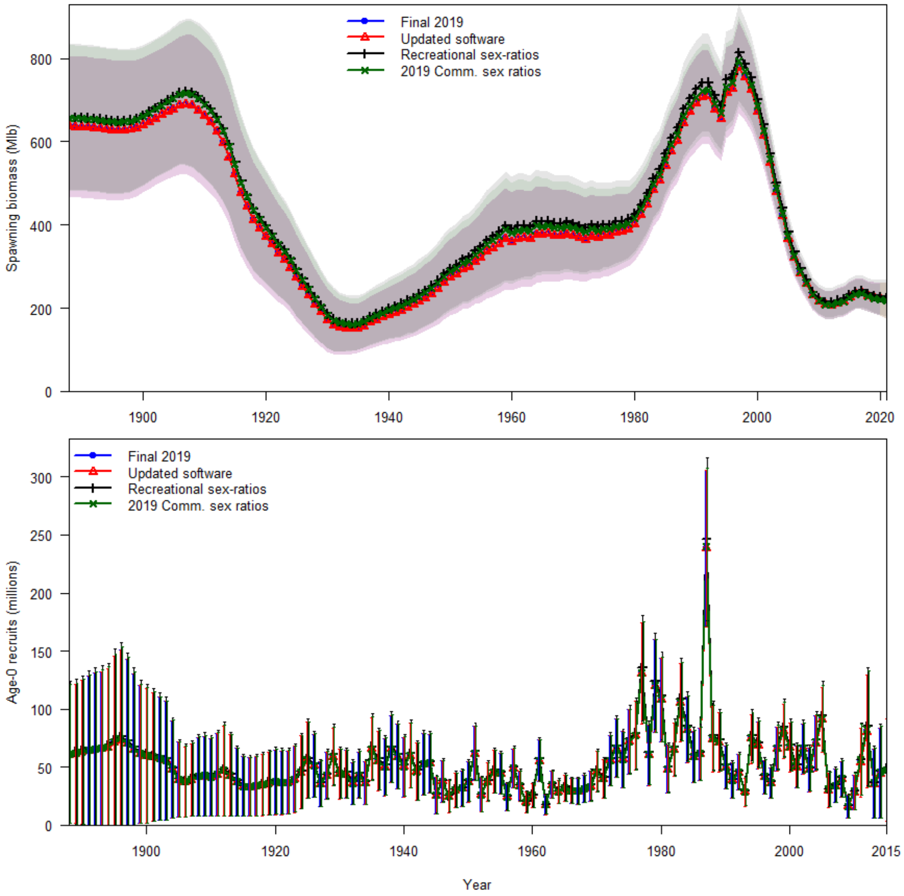


Figure 5. Bridging analysis for spawning biomass (upper panel) and recruitment (lower panel) for the long areas-as-fleets assessment model.

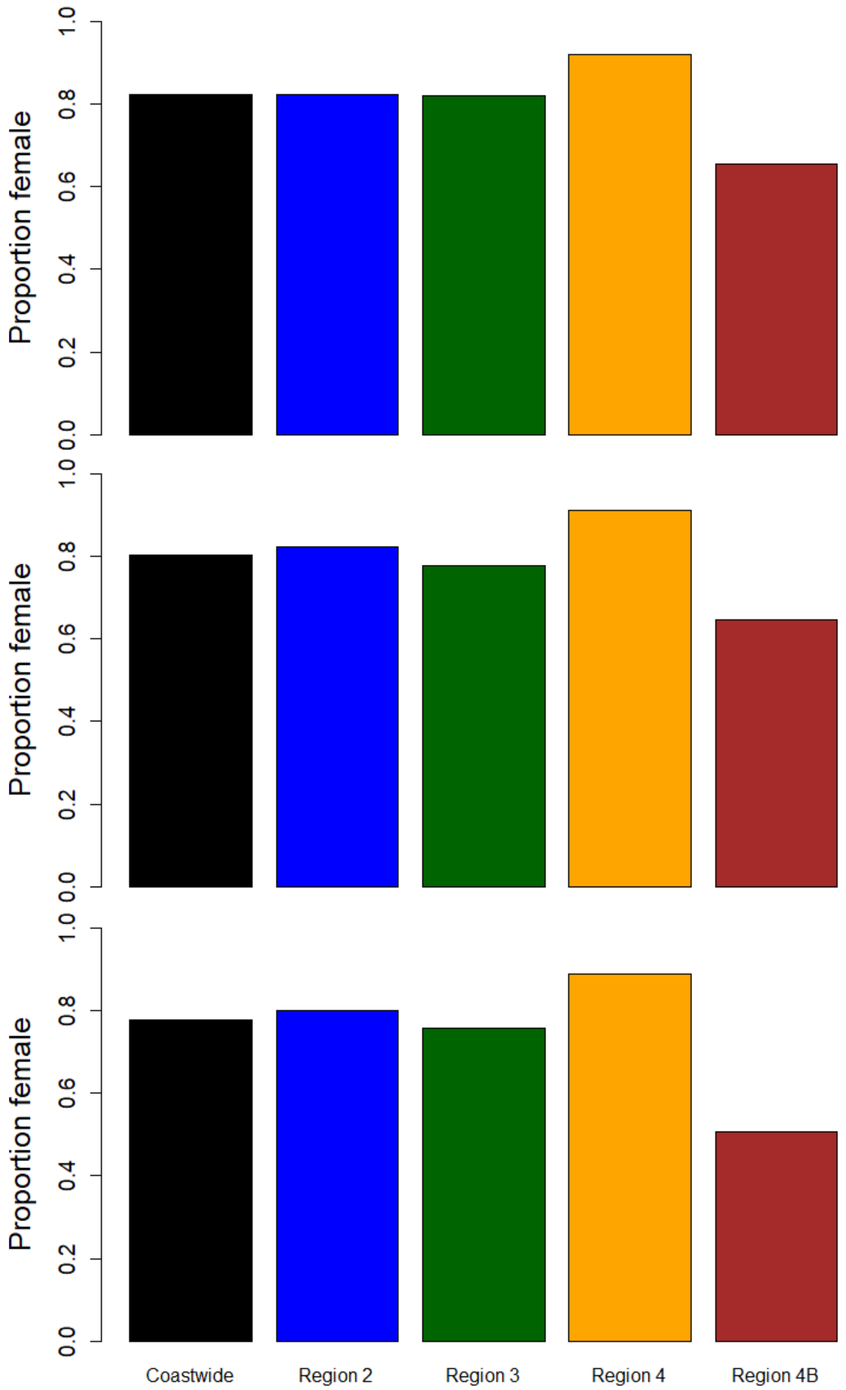


Figure 6. Commercial sex-ratios for 2017 (upper panel), 2018 (middle panel) and 2019 (lower panel) by Biological Region.

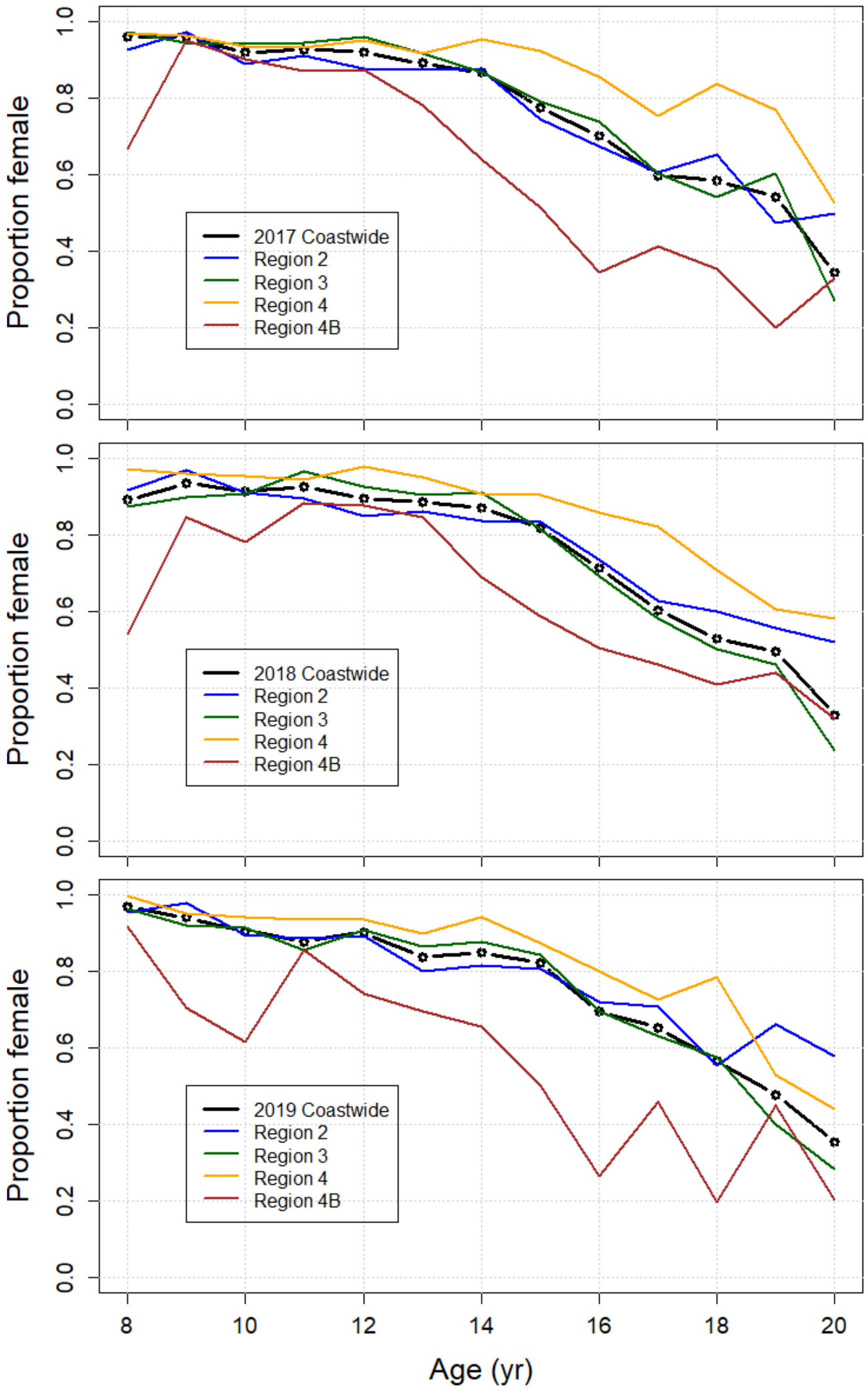


Figure 7. Commercial sex-ratios-at-age for 2017 (upper panel), 2018 (middle panel) and 2019 (lower panel) by Biological Region.

Table 2. Aggregate commercial fishery sex-ratios by Biological Region, 2017-2019.

	Coastwide	Biological Region 2	Biological Region 3	Biological Region 4	Biological Region 4B
2017	82%	82%	82%	92%	65%
2018	80%	82%	78%	91%	65%
2019	78%	80%	76%	89%	51%

Preliminary data updating existing sources

No additional preliminary data was available beyond the projected mortality for 2020. Additional data anticipated for the final 2020 stock assessment include:

1) New modelled trend information from the 2020 FISS including predictions covering both sampled and unsampled (but informed by covariates and the temporal correlation parameters) IPHC Regulatory Areas.
2) Age, length, individual weight, and average weight-at-age estimates from the 2020 FISS for all sampled IPHC Regulatory Areas.
3) 2020 (and a small amount of 2019) Commercial fishery logbook trend information from all IPHC Regulatory Areas.
4) 2020 Commercial fishery biological sampling (age, length, individual weight, and average weight-at-age) from all IPHC Regulatory Areas.
5) Biological information (lengths and/or ages) from non-directed discards (all IPHC Regulatory Areas) and the recreational fishery (IPHC Regulatory Area 3A only) from 2019.
6) Updated mortality estimates from all sources for 2019 (where preliminary values were used) and estimates for all sources in 2020.

RECOMMENDATION/S

That the SRB:

a) **NOTE** paper IPHC-2020-SRB017-07 which provides a response to requests from SRB016 and a final update on model development for 2020.
b) **RECOMMEND** any further changes to be made for the final 2020 stock assessment.
c) **REQUEST** any additional analyses to be provided at SRB018, June 2021.

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Stewart, I., Hicks, A., Webster, R., and Wilson, D. 2020b. Summary of the data, stock assessment, and harvest decision table for Pacific halibut (*Hippoglossus stenolepis*) at the end of 2019. IPHC-2020-AM096-09 Rev_2. 26 p.

Stokes, K. 2019. Independent peer review for the 2019 IPHC stock assessment. August 2019. 31 p. https://www.iphc.int/uploads/pdf/sa/2019/stokes_2019-independent_peer_review_for_the_2019_iphc_stock_assessment.pdf.


L. Boitor

INTERNATIONAL PACIFIC

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Update on the development of the 2020 stock assessment

Agenda item 5

IPHC-2020-SRB017-07

Topics covered

- SRB requests
- New data
- Bridging results
- Remaining data for 2020

SRB requests

1) Explore the logistic-normal
2) Update data weighting
    - *Will be completed after the rest of the 2020 data are included*
3) Modelling framework considerations
4) Data and model updates for 2020

1) The logistic-normal

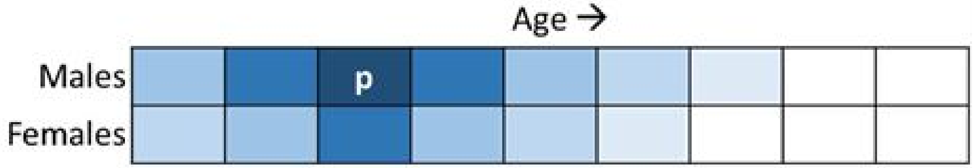
- Self-weighting (no iteration)
- Can include annual sample sizes
- Allows for (potentially complex) correlations among bins
- Requires non-zero proportions
  - compression of distribution tails
  - internal binning and/or addition of a small constant

1) The logistic-normal

- Francis (2014) – primary discussion reference
- Several other applications:
  - Generally don't include more than AR(1) correlations among bins
  - Often ignore inter-annual sample size variation
  - None fit to non sex-specific data (one vector per year)

1) The logistic-normal

- Development for Pacific halibut:
  - Already includes tail compression and a small constant added to observed and expected proportions
  - Implement Francis' annual sample size adjustment
  - Will require a new correlation approach that can accommodate 2-dimensional structure of sex-specific data



1) The logistic-normal

- Next steps:
  - Further investigation for SRB018
  - Potential student project/collaboration
    - Derivation
    - Simulation testing
    - Programming/implementation
    - Application testing

3) Modelling framework

- Stock synthesis development continues
  - Development team remains receptive to requests from and collaboration with the IPHC
- Variance of unfished spawning biomass added in 2020 (we requested this addition during the 2019 assessment)
- MSE operating model development may help guide future assessment development avenues

4) Data and model updates

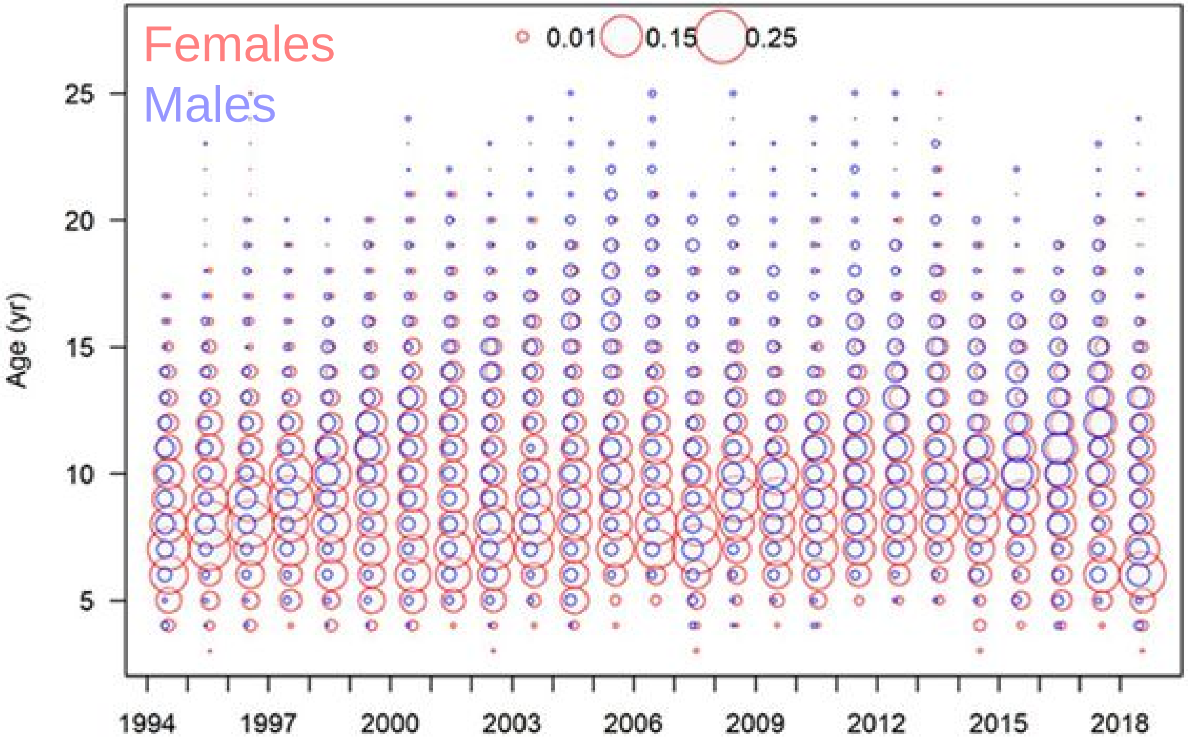
- New data
- Bridging
- Remaining data for 2020

New data

- Sex-specific age composition information from the recreational fishery in 3A
- Sex-specific age composition information from the 2019 directed commercial fishery

Recreational age data (included for June)

Average: 72% female, higher than expected, but little effect on model results



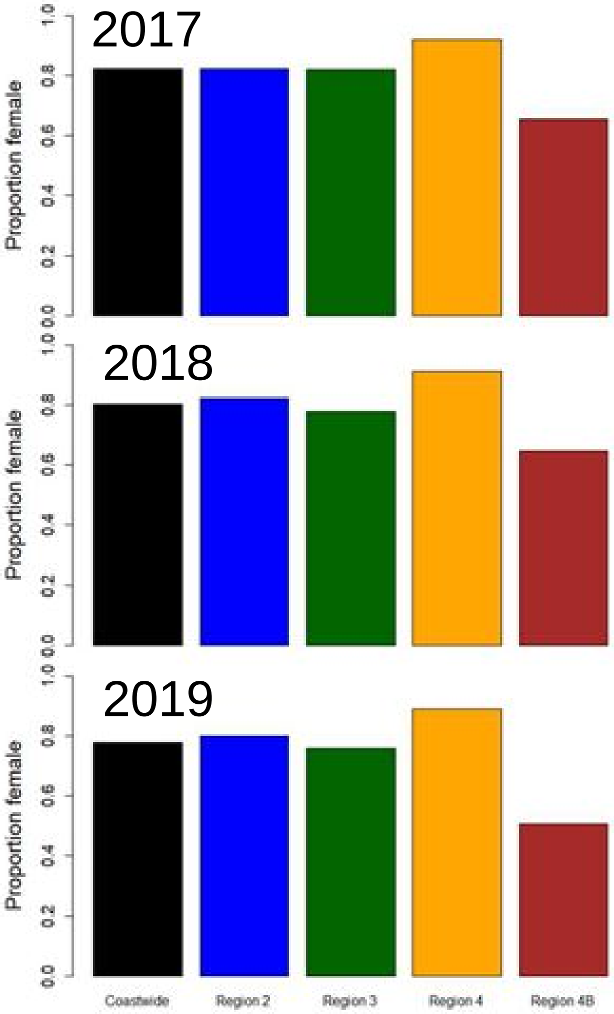
Thanks to Sarah Webster (ADFG)

Directed commercial fishery sex-ratios

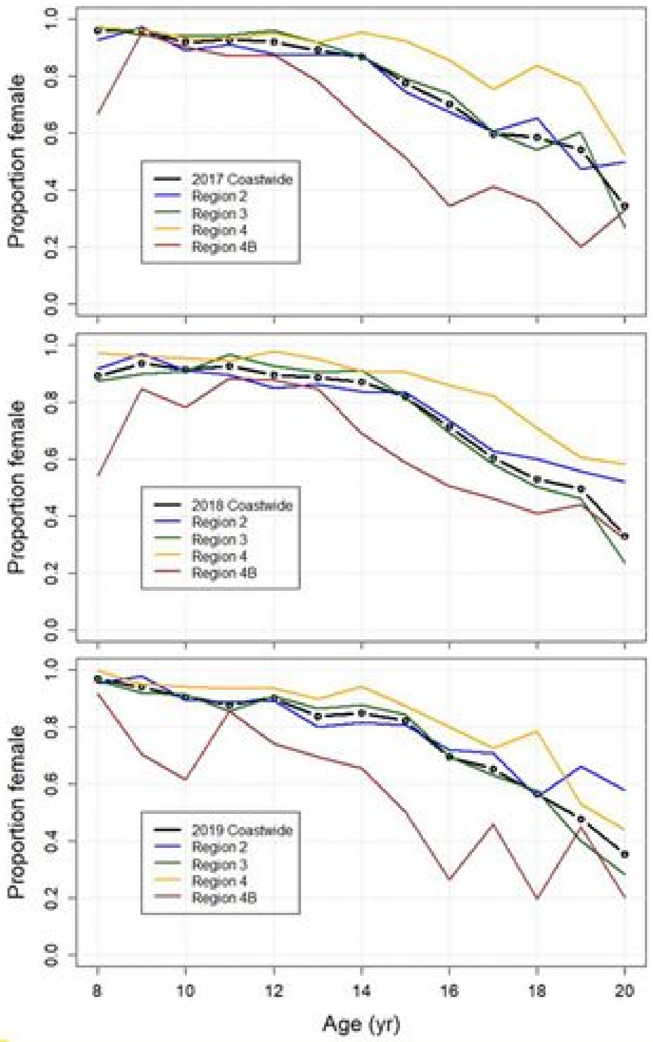
Percent female

	Coastwide	Region 2	Region 3	Region 4	Region 4B
2017	82%	82%	82%	92%	65%
2018	80%	82%	78%	91%	65%
2019	78%	80%	76%	89%	51%

(Note small sample sizes in 4B: ~ 10-17 trips per year)



Directed commercial fishery sex-ratios (by age)



Bridging analysis

- Restarted (relative to June) to add software update prior to any new data
- Three steps:
  - SS version update
  - Recreational sex-ratios at age
  - Directed commercial fishery sex-ratios at age

Routine software update

- Variance (and covariance) now available for unfished spawning biomass in each year

Beginning of 2021 relative biomass (projected)

	Low	Relative SB	High	$P(SB_{2021}<SB_{30\%})$	$P(SB_{2021}<SB_{20\%})$
Approx. in 2019	20.1%	**31.5%**	46.2%	49	2
Calc. for 2020	19.8%	**30.3%**	47.4%	49	3

Bridging

- Figures 2-5 in document
- No meaningful changes in SB or recruitment time-series
- Will be extended to include remaining data and final data reweighting

Data to finalize the 2020 assessment

- 2020 FISS results: modelled trends and biological data
- 2020 Commercial fishery logbook and biological sampling
- Biological information from other sources (non-directed commercial and recreational)
- Mortality estimates for 2020 and updates to 2019 where necessary

Recommendation/s

That the SRB:

a) **NOTE** paper IPHC-2020-SRB017-07 which provides a response to requests from SRB016 and a final update on model development for 2020.

b) **RECOMMEND** any further changes to be made for the final 2020 stock assessment.

c) **REQUEST** any additional analyses to be provided at SRB018, June 2021.

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Biological and Ecosystem Science Research Updates

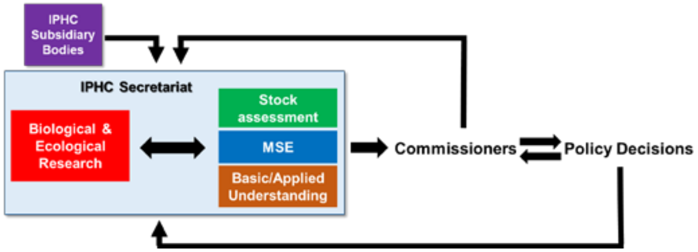
Agenda Item 6

IPHC-2020-SRB017-08

Five-year research program and management implications (2017-2021)

SRB016–Req.17 (para. 44)	***Research integration*** The SRB **REQUESTED** an updated presentation on the plan and timelines for integrating research and results from biological and ecosystem science research plan into specific functions and parameters of the assessment and MSE.	**In Progress**: The IPHC Secretariat is updating the plan and timelines of the integration between research activities and stock assessment and MSE needs. This information will be presented at the SRB017

Integration of biological research, stock assessment, and policy


IPHC Subsidiary Bodies
IPHC Secretariat
Biological & Ecological Research
Stock assessment
MSE
Basic/Applied Understanding
Commissioners
Policy Decisions

Biological research		**Stock assessment**	**Stock assessment MSE**
Research areas	***Research outcomes***	***Relevance for stock assessment***	***Inputs to stock assessment and MSE development***
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
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
Genetics and Genomics	Genetic structure of the population Sequencing of the Pacific halibut genome	Spatial dynamics Management units	Information for structural choices

Integration of research, SA and MSE

Research areas	Research activities	Research outcomes	Relevance for stock assessment	Relevance for MSE	Specific analysis input
Migration	Larval and juvenile connectivity studies	Improved understanding of larval and juvenile distribution	Improve estimates of productivity	Improve parametization of the Operating Model	Will be used to generate potential recruitment covariates and to inform minimum spawning biomass targets by Biological Region.
Reproduction	Histological maturity assessment	Updated maturity schedule	Scale biomass and reference point estimates	Improve simulation of spawning biomass in the Operating Model	Will be included in the stock assessment, replacing the current schedule last updated in 2006.
	Examination of potential skip spawning	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.
	Fecundity assessment	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.
	Examination of accuracy of current field macroscopic maturity classification	Revised field maturity classification			Revised time-series of historical (and future) maturity for input to the stock assessment.
	Sex ratio of current commercial landings	Sex ratio-at-age	Scale biomass and fishing intensity		Annual sex-ratio at age for the commercial fishery fit by the stock assessment.
	Historical sex ratios based on archived otolith DNA analyses	Historical sex ratio-at-age			Annual sex-ratio at age for the commercial fishery fit by the stock assessment
	Recruitment strength and variability	Establishment of temporal and spatial maturity and spawning patterns	Improve stock-recruitment curve for more precise assessment	Improve simulation of recruitment variability and parametization of recruitment distribution in the Operating Model	May be used to provide a weighted spawning biomass calculation and or inform targets for minimum spawning biomass by Biological Region
Growth	Evaluation of somatic growth variation as a driver for changes in size-at-age	Identification and application of markers for growth pattern evaluation	Scale stock productivity and reference point estimates	Improve simulation of variability and allow for scenarios investigating climate change	May inform yield-per-recruit and other spatial evaluations of productivity that support mortality limit-setting.
		Environmental influences on growth patterns			May provide covariates for projecting short-term size-at-age. May help to delineate between effects due to fishing and those due to environment, thereby informing appropriate management response.
		Dietary influences on growth patterns and physiological condition			May provide covariates for projecting short-term size-at-age. May help to deleineate between effects due to fishing and those due to environment, thereby informing appropriate management response.

Integration of research, SA and MSE

Research areas	Research activities	Research outcomes	Relevance for stock assessment	Relevance for MSE	Specific analysis input
Mortality and survival assessment	Discard mortality rate estimate: longline fishery	Experimentally-derived DMR	Improve trends in unobserved mortality	Improve estimates of stock productivity	Will improve estimates of discard mortality, reducing potential bias in stock assessment results and management of mortality limits.
	Discard mortality rate estimate: recreational fishery	Experimentally-derived DMR			Will improve estimates of discard mortality, reducing potential bias in stock assessment results and management of mortality limits.
	Best handling practices: longline fishery	Guidelines for reducing discard mortality			May reduce discard mortality, thereby increasing available yield for directed fisheries.
	Best handling practices: recreational fishery	Guidelines for reducing discard mortality			May reduce discard mortality, thereby increasing available yield for directed fisheries.
	Whale depredation accounting and tools for avoidance	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.
Genetics and genomics	Population structure	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.
	Distribution	Assignment of individuals to source populations and assessment of distribution changes	Improve estimates of productivity	Improve parametization of the Operating Model	Will be used to define management targets for minimum spawning biomass by Biological Region.
	Close-kin mark-recapture studies	Genomic analysis of population size and connectivity			Population size estimates to fit in the stock assessment.
	Landscape genomics	Identification of adaptive loci, decipher genomic basis of adaptation and detect genomic responses to climate change			Will be used to define management targets for minimum spawning biomass by Biological Region.
	Genome-wide association analyses	Understand the genetic basis of phenotypic variation, including size-at-age, age-at-maturity, spawning timing, etc.			May help to delineate between effects due to fishing and those due to environment, thereby informing appropriate management response.

Integration of research, SA and MSE: temporal chart

Research areas	Research activities	Research outcomes	2020				2021				2022				2023				2024			
Migration	Larval and juvenile connectivity studies	Improved understanding of larval and juvenile distribution																				
Reproduction	Histological maturity assessment	Updated maturity schedule	▨	▨	▨	▨	▨	▨	▨	X												
	Examination of potential skip spawning	Incidence of skip spawning			▨	▨	▨	▨	▨	X												
	Fecundity assessment	Fecundity-at-age and -size information						▨	▨	▨	▨	▨	▨	▨	▨	X						
	Examination of accuracy of current field macroscopic maturity classification	Revised field maturity classification	▨	▨	▨	▨	▨	▨	▨	X												
	Sex ratio of current commercial landings	Sex ratio-at-age	▨	▨	X		▨	▨	X		▨	▨	X		▨	▨	X		▨	▨	X	
	Historical sex ratios based on archived otolith DNA analyses	Historical sex ratio-at-age			▨	▨	▨	▨	▨	▨	▨	▨	▨	X								
	Recruitment strength and variability	Establishment of temporal and spatial maturity and spawning patterns					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	X				
Growth	Evaluation of somatic growth variation as a driver for changes in size-at-age	Identification and application of markers for growth pattern evaluation	▨	▨	▨	▨	▨	▨	▨	X												
		Environmental influences on growth patterns							▨	▨	▨	▨	▨	▨	▨	▨	X					
		Dietary influences on growth patterns and physiological condition							▨	▨	▨	▨	▨	▨	▨	▨	X					

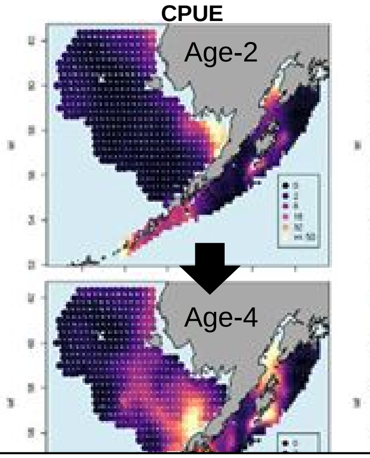
Integration of research, SA and MSE: temporal chart

Research areas	Research activities	Research outcomes	2020				2021				2022				2023				2024			
Discard mortality and survival assessment	Discard mortality rate estimate: longline fishery	Experimentally-derived DMR	▨	▨	▨	X																
	Discard mortality rate estimate: recreational fishery	Experimentally-derived DMR						▨	▨	▨	▨	X										
	Best handling practices: longline fishery	Guidelines for reducing discard mortality			▨	▨	▨	X														
	Best handling practices: recreational fishery	Guidelines for reducing discard mortality								▨	▨	▨	▨	X								
	Whale depredation accounting and tools for avoidance	New tools for fishery avoidance/deterence; improved estimation of depredation mortality					▨	▨	▨	▨	▨	▨	▨	X								
Genetics and genomics	Population structure	Stock structure of IPHC Regulatory Area 4B relative to the rest of the Convention Area				▨	▨	▨	▨	X												
	Distribution	Assignment of individuals to source populations and assessment of distribution changes							▨	▨	▨	▨	▨	▨	▨	X						
	Close-kin mark-recapture studies	Genomic analysis of population size and connectivity								▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	X
	Landscape genomics	Identification of adaptive loci, decipher genomic basis of adaptation and detect genomic responses to climate change									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	X
	Genome-wide association analyses	Understand the genetic basis of phenotypic variation, including size-at-age, age-at-maturity, spawning timing, etc.						▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	X				

1. Migration and Distribution

1. Larval and early juvenile dispersal

- **Key findings:**
  - Aleutian Islands constrain connectivity, but large island passes act as conduits between the GOA and Bering Sea
  - Degree of inter-basin larval connectivity is influenced by spawning location.
  - Large degree of within-basin connectivity
  - Demersal stage fish in the Bering Sea migrate outward from Bristol Bay and reach Unimak Pass



Manuscript currently in (2nd) revision in *Fisheries Oceanography*

Multiple life-stage connectivity of Pacific halibut (*Hippoglossus stenolepis*) across the Bering Sea and Gulf of Alaska

Sadorus, L. L.[1], Goldstein, E.[2], Webster, R. A.[1], Stockhausen, W. T.[2], Planas, J. V.[1], and Duffy-Anderson, J.[2]

[1] International Pacific Halibut Commission, Seattle, Washington, U.S.A.
[2] National Oceanic and Atmospheric Administration, Alaska Fisheries Science Center, Seattle, Washington, U.S.A.

1. Migration and Distribution

1. Larval and early juvenile dispersal

RB016–Req.11 (para. 36)	***Migration and distribution*** **NOTING** that the genetic data may be complimentary to data collected using other methods, for example, stock structure at the genetic level could be reflected in individual differences in otolith chemistry (if primary otolith annuli are interrogated), the SRB **REQUESTED** that a portion of individuals that are selected for otolith chemistry also be used for whole genome sequencing.	**Pending**: Future planning of studies involving otolith chemistry will incorporate the collection of tissue (fin clip) samples for whole genome sequencing

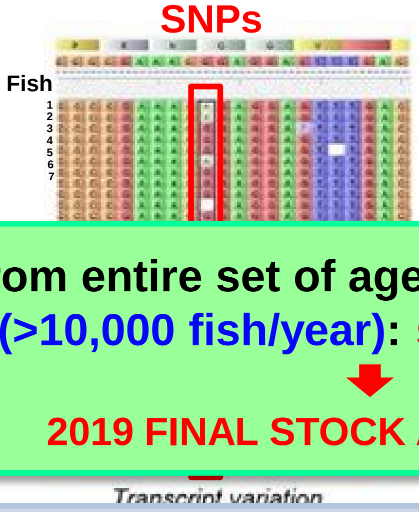
Research projects to investigate larval and early life stage source locations and pelagic duration through otolith geochemical analyses combined with genomic analyses are under consideration

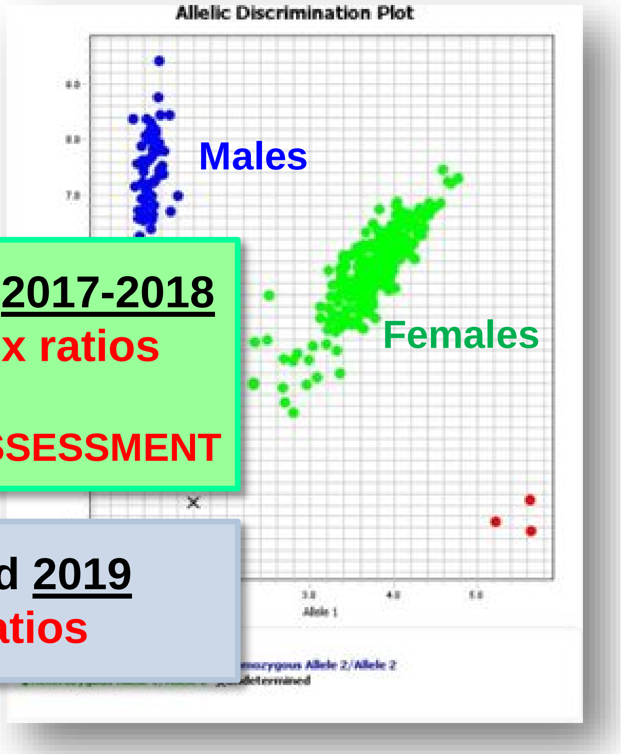
2. Reproduction

1. Identification of sex in the commercial landings

To generate sex-ratio data for use in assessment and policy analysis

Application of genetic techniques (SNPs)





- **Completed**: **Fin clips from entire set of aged <u>2017-2018</u> commercial samples (>10,000 fish/year): sex ratios**

2019 FINAL STOCK ASSESSMENT

- **Completed**: **Fin clips from entire set of aged <u>2019</u> commercial samples (>10,000 fish) : sex ratios**

2. Reproduction

1. Identification of sex in the commercial landings

To generate sex-ratio data for use in assessment and policy analysis

SRB016–Req.16 (para. 42)	**NOTING** the importance of genetically determined sex information to stock assessment, the SRB **REQUESTED** that the IPHC Secretariat conduct a pilot study to determine whether DNA and PCR amplification of sex-linked SNP loci can be obtained from archived otoliths of different collection periods to demonstrate feasibility to develop a more comprehensive spatial and temporal sex ratio data base.	**In Progress**: The IPHC Secretariat is conducting studies to determine whether DNA can be extracted from otoliths and whether sex information can be generated. This information will be presented at the SRB017.

2. Reproduction

1. *Identification of sex in the commercial landings*

DNA Extraction from Archived Otoliths: Current Progress

Storage Type	**n**	**# Successful Genotypes**
Dry	7	7
Glycerin	10	0

Other potential issues:

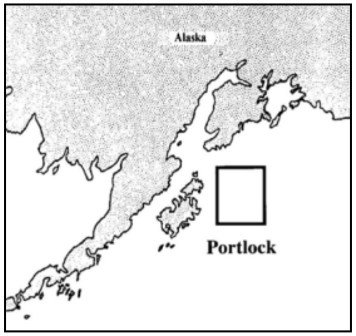
- All otoliths collected prior to 2003 stored in glycerin in batches, not individually
- Glycerin solution sometimes reused
- Some otoliths cleaned in muriatic acid

- Extractions via Qiagen column kits w/ DTT added, low elution volume
- PCR performed w/ BSA, extended cycle number
- No nanodrop signature present for glycerin-stored samples

2. Reproduction

2. Full characterization of the annual reproductive cycle to improve current estimates of maturity

Objective: Revise maturity estimates for male and female Pacific halibut



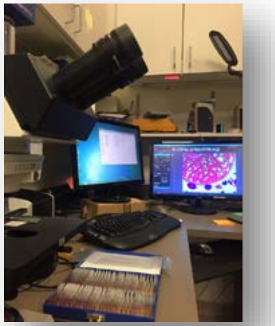
Sept Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug

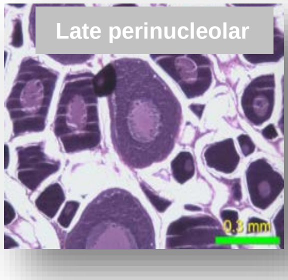
2017 2018

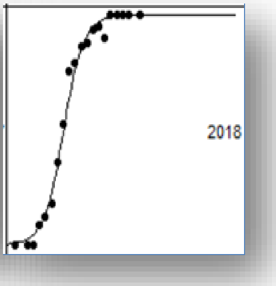
30♀ / 30 ♂

Reproductive cycle

Gonadal growth	Maturation	Spawning





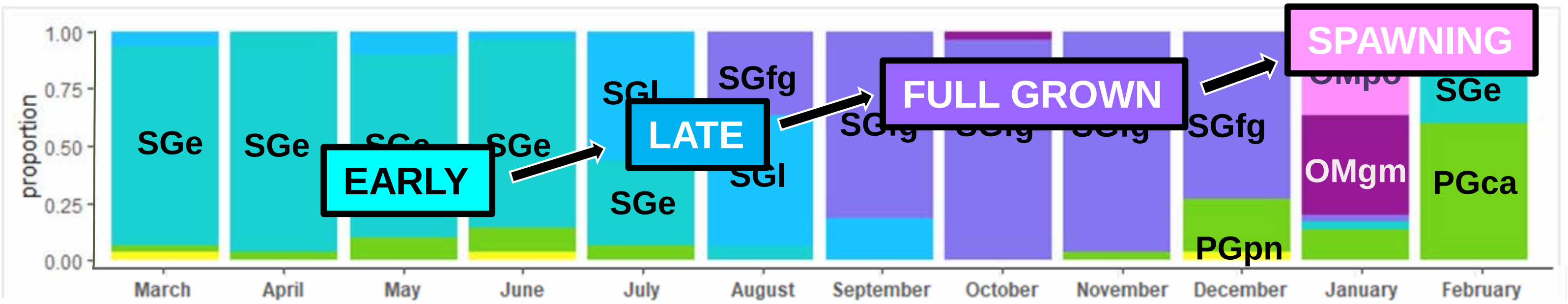


Deliverables:
- Accurate staging of reproductive status
- Updated maturity-at-age estimates
- Estimates of skipped-spawning

2. Reproduction

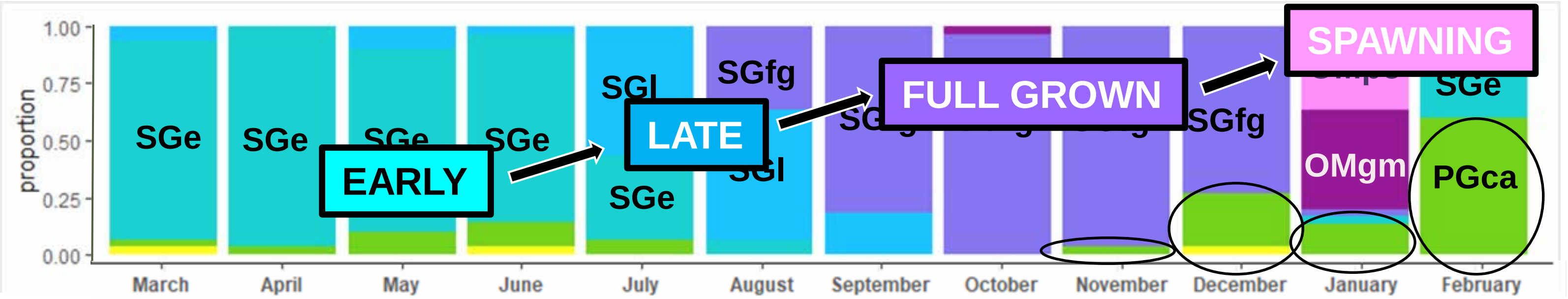
RB016–Req.13 (para. 38)	***Reproductive assessment*** The SRB **REQUESTED** a preliminary analysis of existing data on ‘skipped spawning’.	**In Progress**: Representative histological characteristics of skipped spawning are being investigated. This information will be presented at the SRB017.

Microscopic maturity staging: based on histological oocyte stages



PGpn	**Primary Growth Perinucleolar Stage**
PGca	**Primary Growth Cortical alveoli Stage**
SGe	**Secondary Growth Early Stage**
SGl	**Secondary Growth LateStage**
SGfg	**Secondary Growth Full Grown Stage**
OMgm	**Oocyte maturation Stage**
OMpo	**Postovulatory Stage**

2. Reproduction

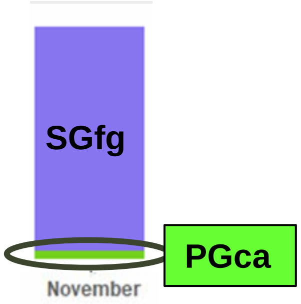


Identification of potential skip-spawners:

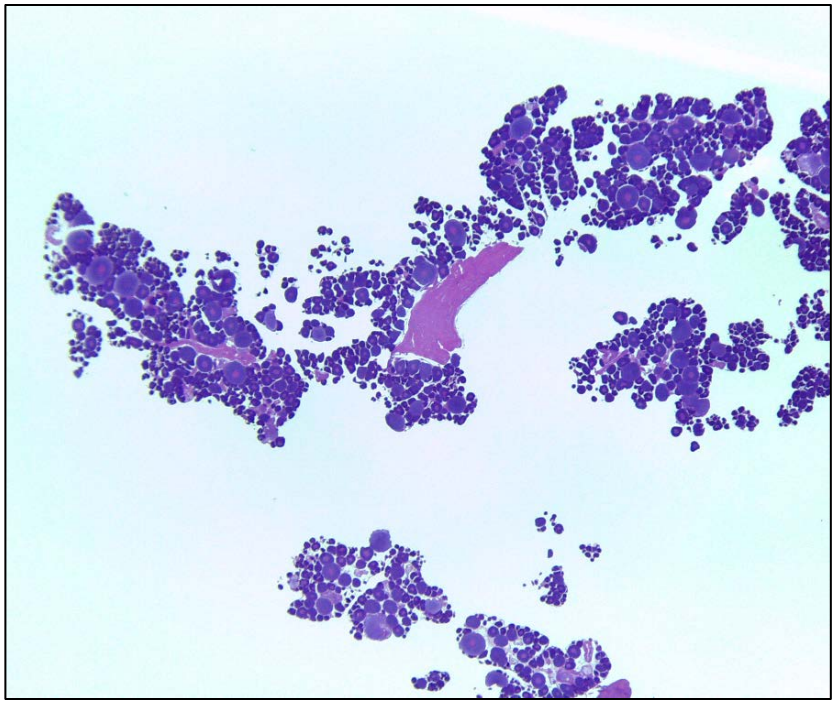
1. Maturity classification prior and during spawning (Nov. – Feb.)
2. Histological examination of aged females at primary growth stages:
   - Presence or absence of post-ovulatory follicles
   - Presence of absence of degenerating follicles
   - General structure of ovarian tissue (compacted versus loose)
3. Examination of additional ovarian parameters:
   - Gonadosomatic index, condition factor, fat content.
   - Endocrine markers in pituitary (luteinizing hormone gene expression) and blood (17β-estradiol and 17α, 20β-dihydroxyprogesterone)

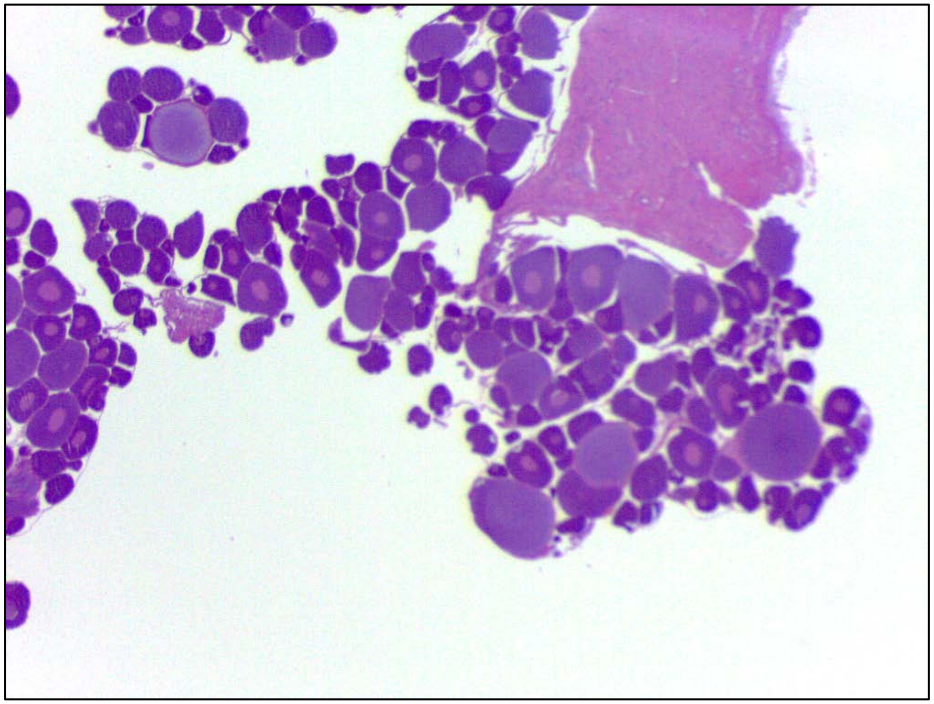
2. Reproduction

Example 1: Potential skip-spawner



Month of collection: November (only female not with full growth vitellogenic oocytes)
Age: 15
Maturity classification: Primary Growth - Cortical Alveoli Stage

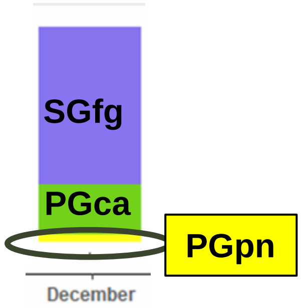


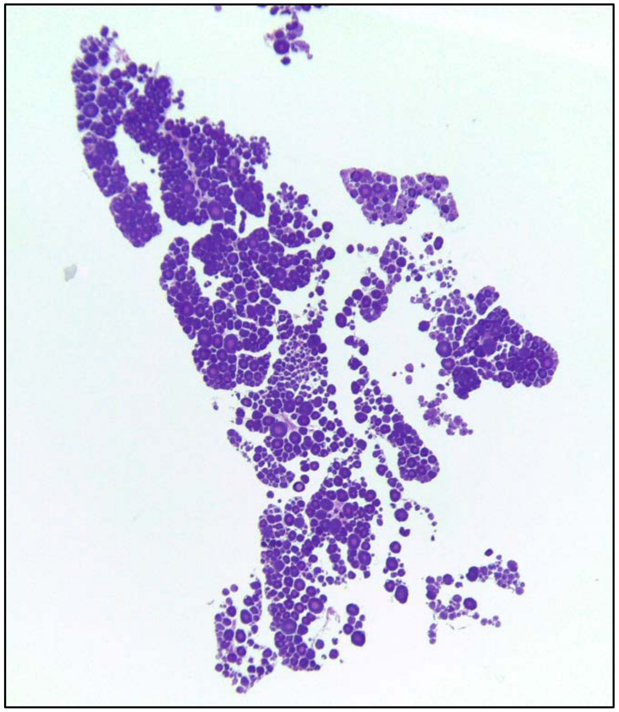


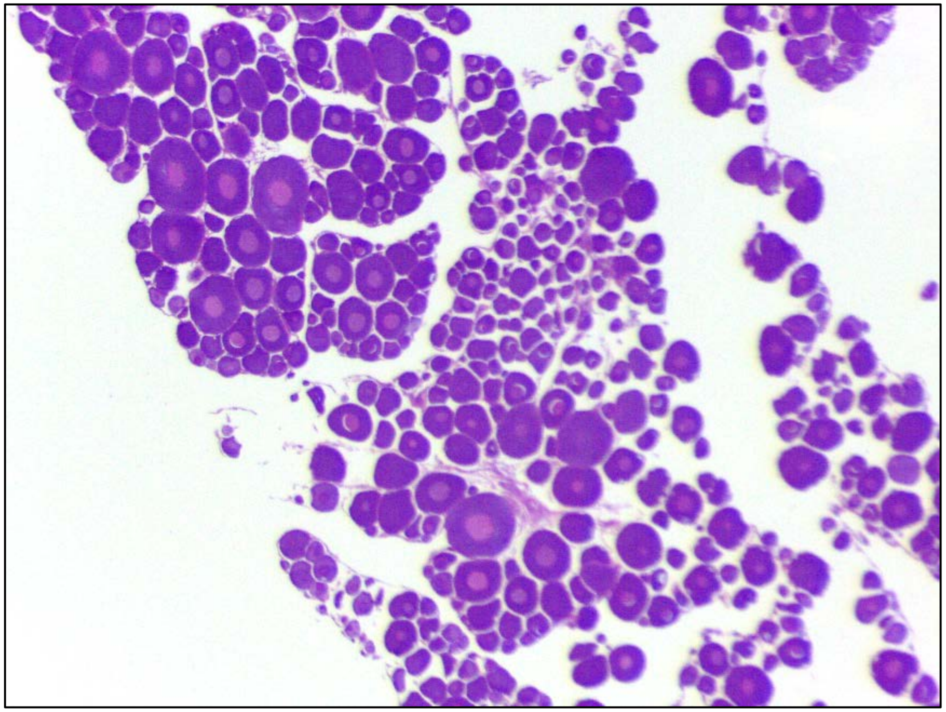
2. Reproduction

Example 2: Immature female during pre-spawning

Month of collection: December
Age: 9
Maturity classification: Primary Growth - Perinuclear Stage







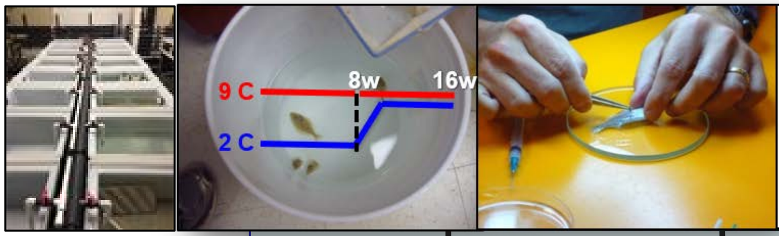
2. Reproduction

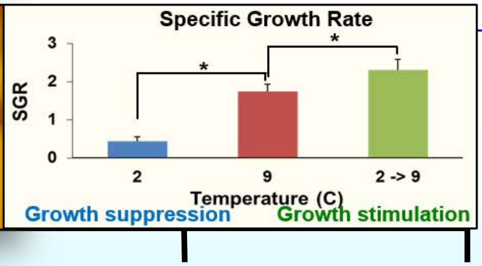
SRB016–Req.14 (para. 39)	The SRB **REQUESTED** that work on size- and age-specific fecundity be incorporated in the next 5-year research plan.	**In Progress**: Studies on size- and age-specific fecundity are being planned for execution in 2021. This information will be presented at the SRB017.

- Objective: establish a fecundity –size (length/weight/age) relationship
- Measure: potential annual fecundity as a measure of annual egg production.
- Important considerations:
  a) Time of sampling. Important to complete annual maturation cycle to select time when individuals are in pre-spawning conditions.
  b) Location of sampling and sample size.
  c) Method: gavimetric versus auto-diametric methods.
- Method testing with ovarian samples collected planned for FISS 2021
- Planned implementation of ovarian collection starting in 2022.

3. Growth

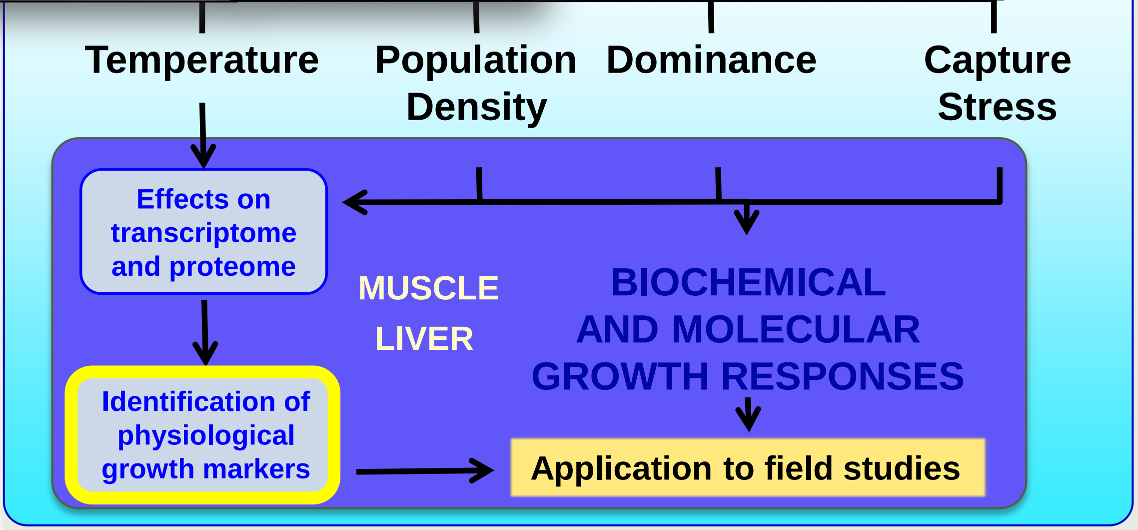
1. Identification and validation of physiological markers for growth





White muscle:

- **Transcriptomics**
- **Proteomics**



Temperature

Population Density

Dominance

Capture Stress

Effects on transcriptome and proteome

Identification of physiological growth markers

MUSCLE

LIVER

BIOCHEMICAL AND MOLECULAR GROWTH RESPONSES

Application to field studies

IPHC / AFSC-NOAA (Newport, OR)

Dr. Josep Planas (PI)

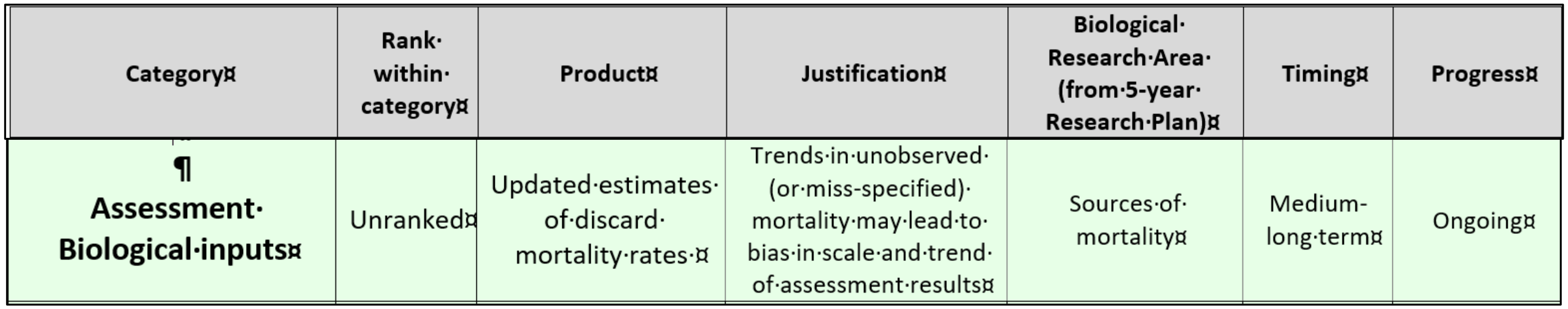
Dr. Thomas Hurst

NPRB Grant 1704 (2017-2020)

NRPB 1704 Final Report

4. Discard mortality rates and survival assessment

Research Priorities



Category	Rank within category	Product	Justification	Biological Research Area (from 5-year Research Plan)	Timing	Progress
Assessment Biological inputs	Unranked	Updated estimates of discard mortality rates	Trends in unobserved (or miss-specified) mortality may lead to bias in scale and trend of assessment results	Sources of mortality	Medium-long term	Ongoing

Projects:

1. ***Improve DMR estimations in the directed longline fishery***

NOAA FISHERIES Saltonstall – Kennedy Grant NA17NMF4270240 ALASKA PACIFIC UNIVERSITY

2. ***Estimate DMRs in the guided recreational fishery***

NFWF National Fish and Wildlife Foundation UAF UNIVERSITY OF ALASKA FAIRBANKS ALASKA PACIFIC UNIVERSITY

4. DMRs and survival assessment

1. <u>Directed longline fishery</u>: A. Relationship between handling practices and injury levels and physiological condition of released Pacific halibut

- **sPAT tagging produced an estimate of 4-8.7% DMR which is consistent with current estimates.**
- **Ongoing investigations into relationships between individual physiological, environmental, and handling practices with respect to final release viability classifications (Masters prgm).**
- **Electronic monitoring (EM) was effective at accurately capturing hook release method**
- **Ongoing investigations into the ability to estimate individual fish lengths from EM video footage (both with post-hoc camera angle/distance calibration, and with pre-calibrated camera angle/distance calibration).**

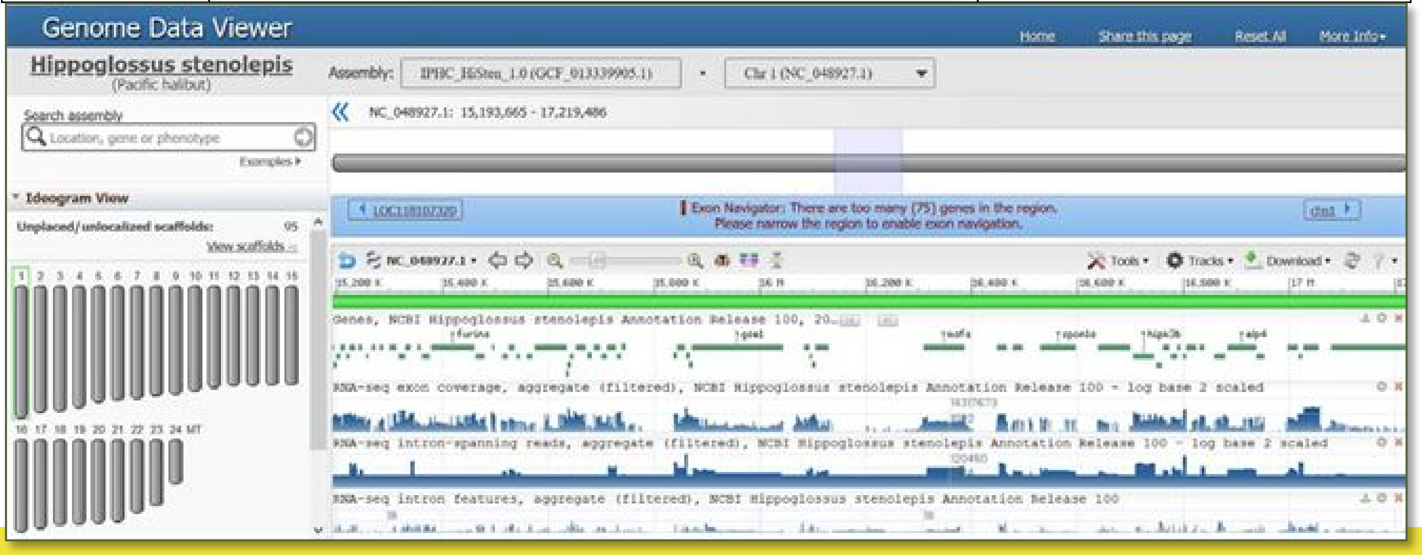
4. DMRs and survival assessment

2. *Guided recreational fishery: Estimation of DMRs*

- **Currently focused on experimental design with experimental field work to occur in Spring 2021. Contemplating two options:**
  - **A. Replicate field treatments based on questionnaire results. This would allow for the generation of an overall DMR for the charter sector, but with lower replicates and confidence for some treatments.**
  - **B. Focus on one set of conditions of predominant interest (circle hook, release vs reversal/twist) to develop a less broad DMR, which would be more transferable to best practices.**
- **Ten variables for testing, several are non-controllable (*Reg Area, Port, Fish Size, Hook Type, Hook Size, Capture conditions, Landing method, Time on Deck, Fish Condition,* and *Release Method*).**
- **This work continues to be the subject of ongoing efforts to secure sufficient external funding for a meaningful number of sPATs.**

5. Genetics and Genomics

SRB016–Req.18 ([para. 49](#))	The SRB **REQUESTED** that the IPHC Secretariat contact the National Center for Biological Information to annotate the genome. Subsequently, existing and newly discovered SNPs be mapped onto the existing Pacific halibut genome. • **Size: 594 million base pairs** • **24 chromosomes** • **27,422 genes** • **91x coverage**	**Completed**: The IPHC Secretariat requested genome annotation from NCBI and the annotation has now been completed and available as [NCBI Hippoglossus stenolepis Annotation Release 100](#).



Exon Navigator: There are too many (75) genes in the region. Please narrow the region to enable exon navigation.

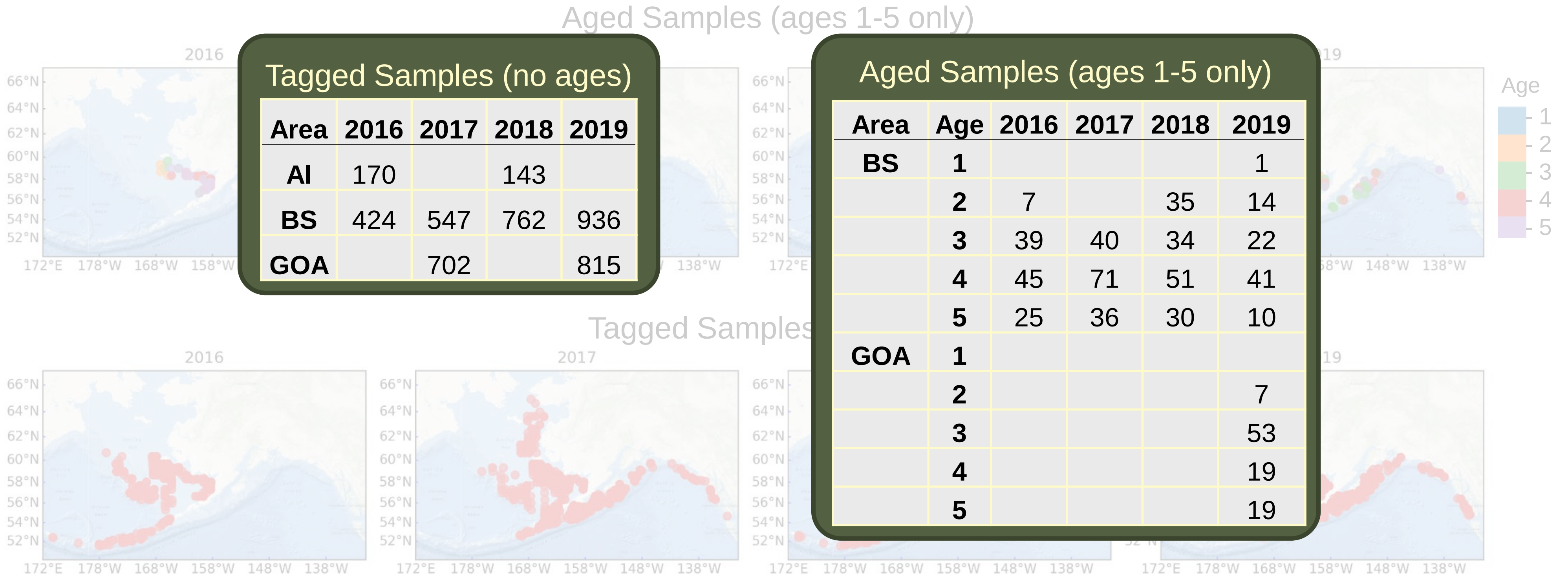
5. Genetics and Genomics

SRB016–Req.12 (para. 37)	**NOTING** the issues of Gulf of Alaska (GOA) and Bering Sea (BS) connectivity relative to juvenile dispersal, the SRB **REQUESTED** that the IPHC Secretariat include individuals of different ages and locations in the GOA and BS in their whole genome sequencing analysis, including individuals from different places in GOA and BS.	**In Progress**: Tissue (fin clip) samples from juvenile Pacific halibut collected in the GOA and BS are currently being selected for age and capture location for whole genome sequencing analysis. A sample summary will be presented at the SRB017.

5. Genetics and Genomics

SRB016-Req. 12

Tissue samples available for genetic analysis



Tagged Samples (no ages)

Area	2016	2017	2018	2019
AI	170		143	
BS	424	547	762	936
GOA		702		815

Aged Samples (ages 1-5 only)

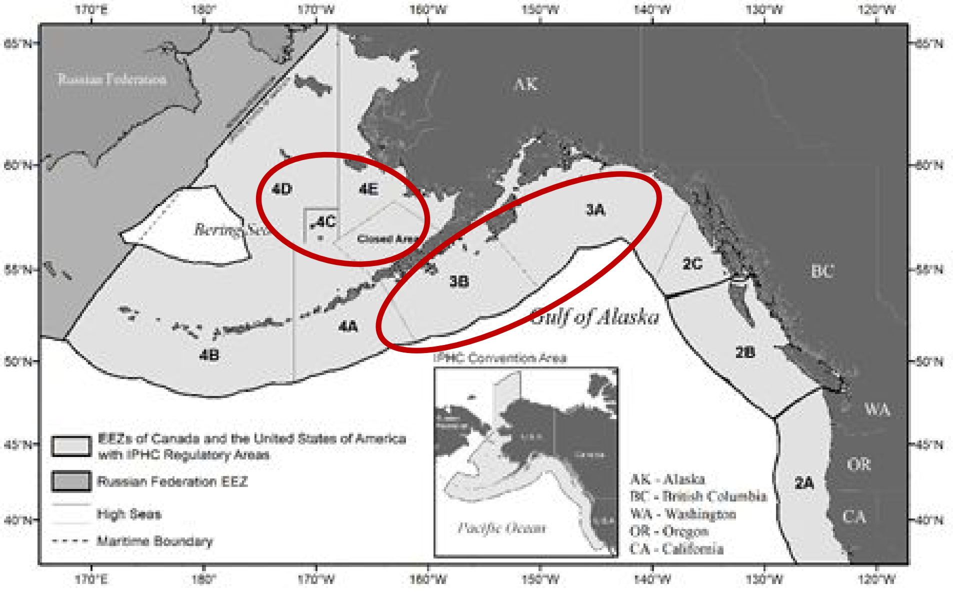
Area	Age	2016	2017	2018	2019
BS	**1**				1
	2	7		35	14
	3	39	40	34	22
	4	45	71	51	41
	5	25	36	30	10
GOA	**1**				
	2				7
	3				53
	4				19
	5				19

5. Genetics and Genomics

Analysis of genetic variability among juvenile Pacific halibut in the Bering Sea and the Gulf of Alaska

- *Infer the potential contribution of fish spawned in different areas to the Gulf of Alaska (GOA) and Bering Sea (BS)*

- Fin clips collected during NMFS trawl surveys
  - – GOA (2017, 2019)
  - – BS (2016-2019)
- Compare genetic diversity metrics between GOA & BS
- Estimate admixture proportions

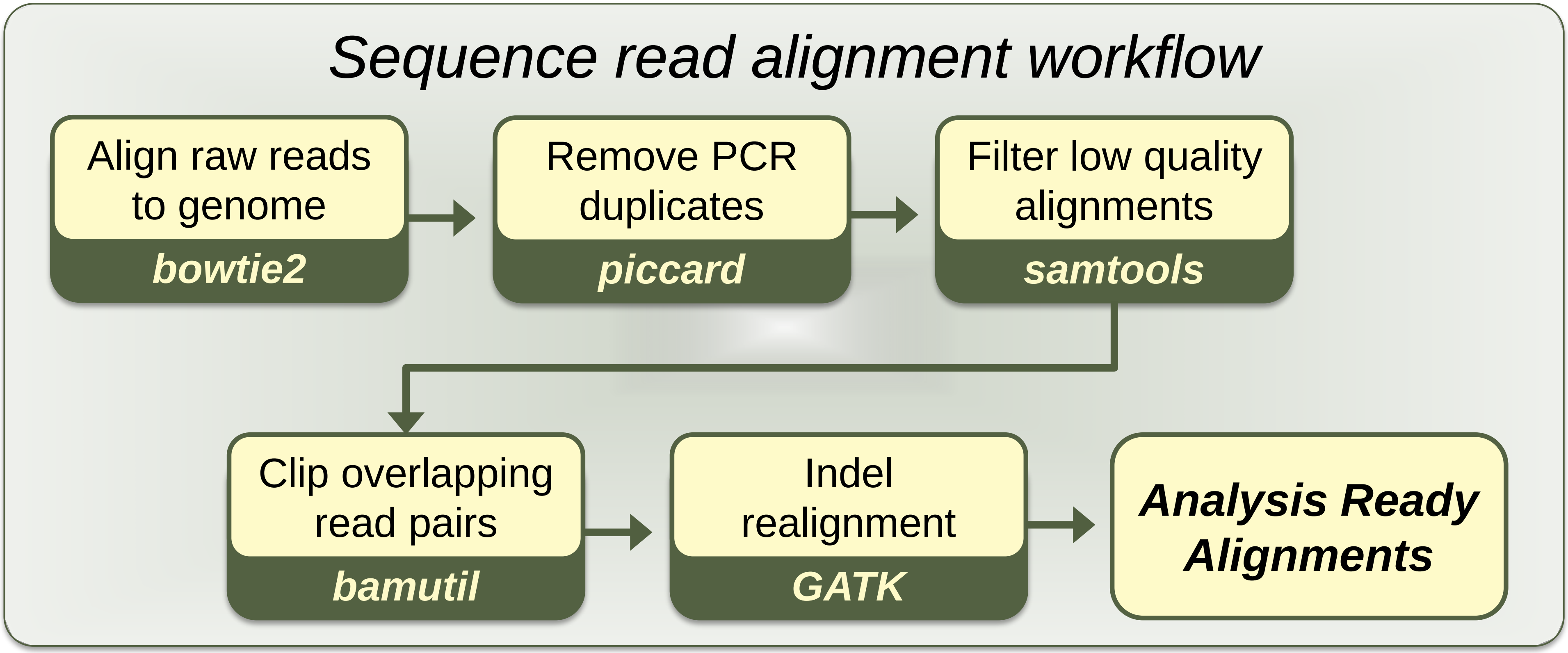


5. Genetics and Genomics

SRB016–Req.15 (para. 41)	***Genetics and genomics*** The SRB **NOTED** that the text in this section of paper IPHC-2020-SRB016-09 was not consistent. A high level of detail was provided in some areas and much less detail was provided in others. At one level, the SRB requires more information on (a) objectives and (b) methods to evaluate study design and the quality of data, however this was not possible given the information provided. For example in the first section on whole genome sequencing there was a major gap in methods. The SRB **REQUESTED** specific information on how the sequence data would be mapped to the reference genome.	**In Progress**: Methods similar to those used by Clucas et al. (2019) will be used to align raw sequence reads to the Pacific halibut reference genome. This information will be presented at the SRB017.

5. Genetics and Genomics

SRB016-Req. 15



Sequence read alignment workflow

Align raw reads to genome
bowtie2

Remove PCR duplicates
piccard

Filter low quality alignments
samtools

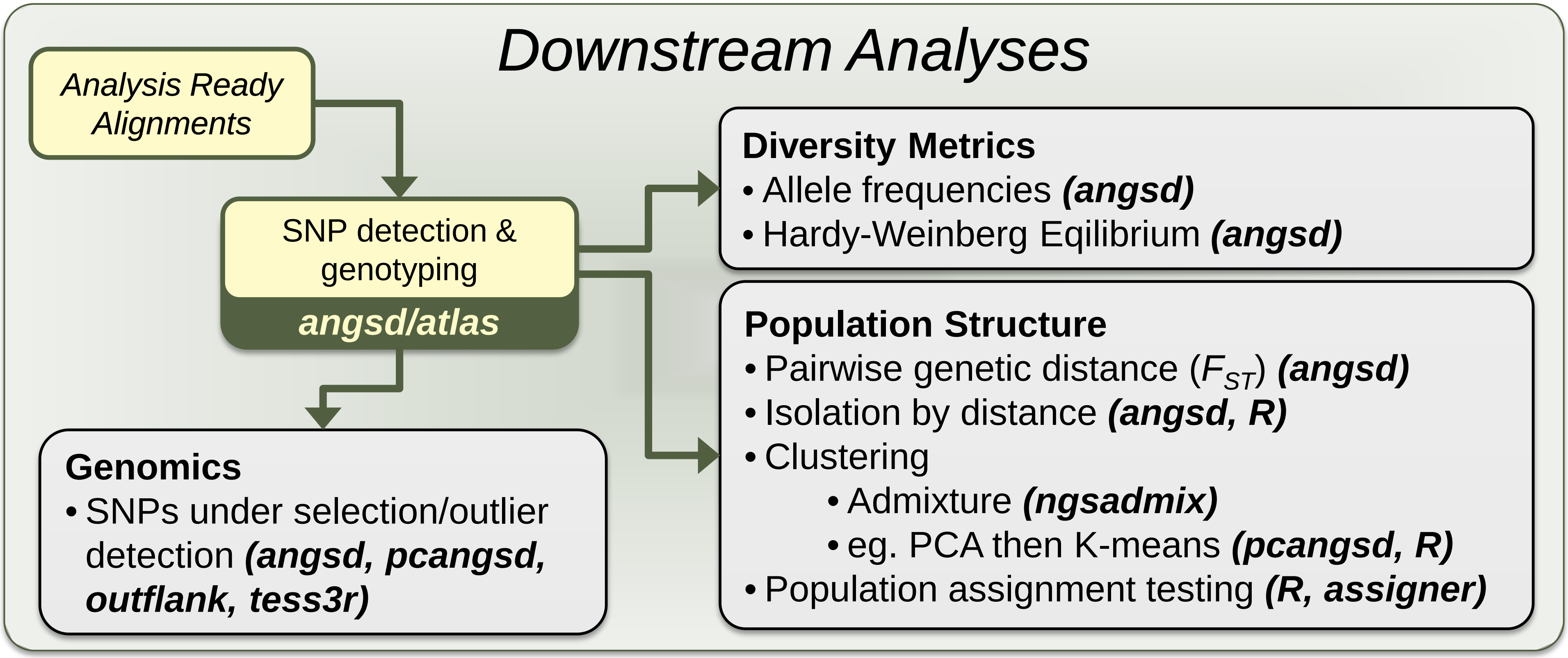
Clip overlapping read pairs
bamutil

Indel realignment
GATK

Analysis Ready Alignments

5. Genetics and Genomics

SRB016-Req. 15



Downstream Analyses

Analysis Ready Alignments

SNP detection & genotyping

angsd/atlas

Diversity Metrics

- Allele frequencies ***(angsd)***
- Hardy-Weinberg Eqilibrium ***(angsd)***

Population Structure

- Pairwise genetic distance (F_{ST}) ***(angsd)***
- Isolation by distance ***(angsd, R)***
- Clustering
  - Admixture ***(ngsadmix)***
  - eg. PCA then K-means ***(pcangsd, R)***
- Population assignment testing ***(R, assigner)***

Genomics

- SNPs under selection/outlier detection ***(angsd, pcangsd, outflank, tess3r)***

5. Genetics and Genomics

Progress

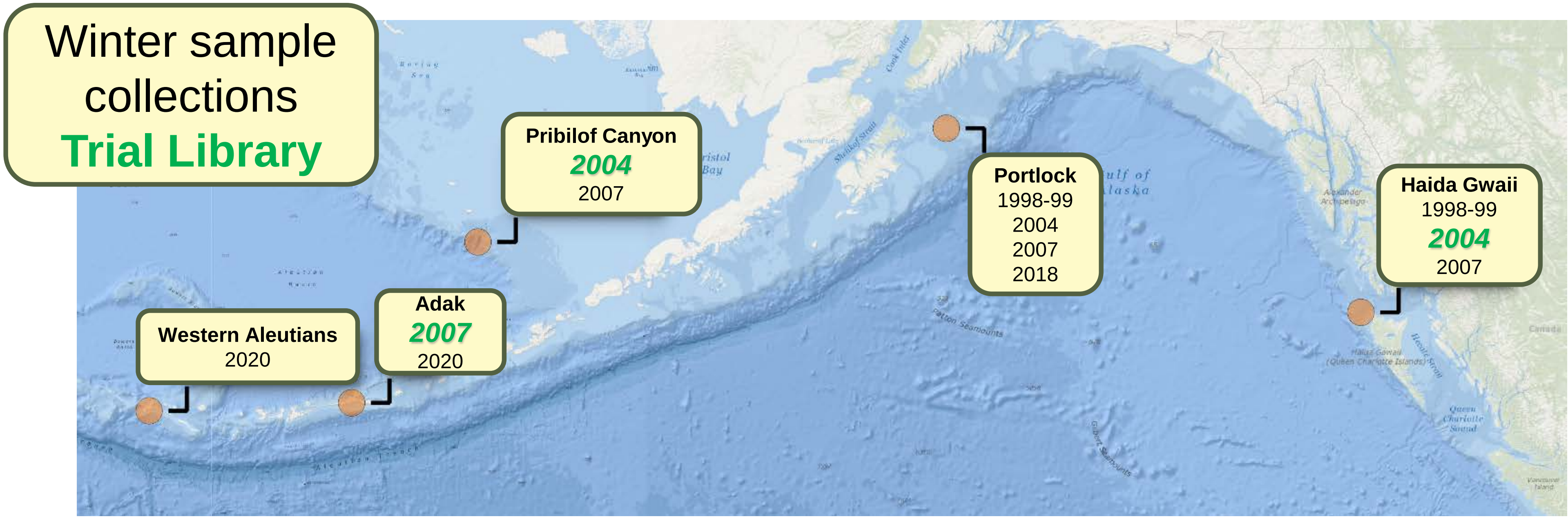
- Submitted a trial library for sequencing 9/8/2020
  - 36 samples (Illumina HiSeq 4000)
- Objectives:
  - Validate library construction methods
  - Assess genomic coverage
  - Genotype accuracy
    - RADseq data for 30 individuals from Drinan *et al.* 2018
  - Test software

Drinan, D. P., T. Loher, and L. Hauser. 2018. Identification of Genomic Regions Associated With Sex in Pacific Halibut. Journal of Heredity 109(3):326–332.

5. Genetics and Genomics

Revise our understanding of genetic structure of the Pacific halibut population in the North-eastern Pacific Ocean

Analysis of structure in IPHC Regulatory Area 4B



Winter sample collections

Trial Library

Pribilof Canyon
2004
2007

Portlock
1998-99
2004
2007
2018

Haida Gwaii
1998-99
2004
2007

Western Aleutians
2020

Adak
2007
2020

INTERNATIONAL PACIFIC

HALIBUT COMMISSION

IPHC-2020-SRB017-08

Report on Current and Future Biological Research Activities

PREPARED BY: **IPHC SECRETARIAT (J. PLANAS, 20 AUGUST 2020)**

PURPOSE

To provide the Scientific Review Board with a description of progress on IPHC's five-year Biological and Ecosystem Science Research Plan (2017-21).

BACKGROUND

The primary biological 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.

UPDATE ON PROGRESS ON THE MAIN RESEARCH ACTIVITIES

1. Migration and Distribution.

Knowledge of Pacific halibut migration throughout all life stages is necessary in order to gain a complete understanding of stock distribution and the factors that influence it.

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

Principal Investigator: Lauri Sadorus (M.Sc.)

Knowledge of the dispersal of Pacific halibut larvae and subsequent migration of young juveniles has remained elusive because traditional tagging methods are not effective on these life stages due to the small size of the animals. This larval connectivity project, in cooperation with NOAA EcoFOCI, used two recently developed modeling approaches to estimate dispersal and migration pathways of larval and young juvenile Pacific halibut in order to better understand the connectivity of populations both within and between the Gulf of Alaska and Bering Sea. A manuscript describing this project is now under second revision in the journal *Fisheries Oceanography* (Sadorus et al., in review).

1.2. Wire tagging of U32 Pacific halibut.
Principal Investigator: Joan Forsberg (B.Sc.)

The patterns of movement of Pacific halibut among IPHC Regulatory Areas have important implications for management of the Pacific halibut fishery. The IPHC Secretariat has undertaken a long-term study of the migratory behavior of Pacific halibut through the use of externally visible tags (wire tags) on captured and released fish that must be retrieved and returned by workers in the fishing industry. In 2015, with the goal of gaining additional insight into movement and growth of young Pacific halibut (less than 32 inches [82 cm]; U32), the IPHC began wire-tagging small Pacific halibut encountered on the National Marine Fisheries Service (NMFS) groundfish trawl survey and, beginning in 2016, on the IPHC fishery-independent setline survey (FISS). In 2019, a total of 821 Pacific halibut were tagged and released during the NMFS Gulf of Alaska trawl survey and 885 tags were released during the NMFS Bering Sea survey. Through 2019, a total of 6,536 tags have been released in the NMFS groundfish trawl survey and, to date, 52 tags have been recovered. On the IPHC FISS, a total of 3,112 U32 Pacific halibut had been wire tagged are released and 90 of those have been recovered to date. The wire tagging effort on the FISS was not implemented in 2019 due to work load commitments on the FISS operation. However, 54 U32 Pacific halibut were wire-tagged as part of other research projects in 2019. Recoveries by release and recovery Regulatory Area are reported in Table 1 and numbers recovered by release Regulatory Area and years at liberty are shown in Table 2. Wire-tagging efforts on U32 Pacific halibut are continuing in 2020 on IPHC's FISS but not on the NMFS groundfish trawl survey because of its cancellation due to COVID-19.

Table 1. Recoveries of tagged Pacific halibut from U32 wire tagging conducted between 2015 and 2019 by release and recovery Regulatory Area.

Release Reg Area	**Total Releases**	**Recovery Regulatory Area**										
		2A	**2B**	**2C**	**3A**	**3B**	**4A**	**4B**	**4D**	**4E**	**CLS**	**Total**
2A	34	1	3									**4**
2B	636	1	27									**28**
2C	747		8	22	1							**31**
3A	2,005				31	1						**32**
3B	2,309		1		3	25	1			1	1	**32**
4A	1,096				2		6	1		1		**10**
4B	369							5				**5**
4C	244						1					**1**
4D	469						1		2	1		**4**
4E	1,420								1	2	3	**5**
CLS	544				2	1	1			1		**5**
Total	**9,873**	**2**	**12**	**6**	**29**	**6**	**8**	**1**	**2**	**4**	**4**	**158**

Table 2. Number of Pacific halibut recovered by years at liberty and by release Regulatory Area from U32 wire tagging conducted between 2015 and 2019 (includes recoveries for which recovery area is not known).

Years at liberty	Number recovered by release Regulatory Area											
	2A	**2B**	**2C**	**3A**	**3B**	**4A**	**4B**	**4C**	**4D**	**4E**	**CLS**	**Total**
0		7	2	3	1	1	1	1	1	1		**18**
1	2	14	17	14	12	3	2		1	4	2	**71**
2	2	7	9	7	12	3	2		1	1		**44**
3		1	3	7	5	2	1		1		1	**21**
4			1	1	3	1					2	**8**
5				1								**1**
Total	**4**	**29**	**32**	**33**	**33**	**10**	**6**	**1**	**4**	**6**	**5**	**163**

2. Reproduction.

Efforts at IPHC are currently underway to address two critical issues in stock assessment for estimating the female spawning biomass: the sex ratio of the commercial landings and maturity assessment.

2.1. Sex ratio of the commercial landings.
Principal Investigator: Anna Simeon (M.Sc.)

The IPHC Secretariat has recently completed the processing of genetic samples from the 2019 commercial landings and results indicate that the percentage of females coastwide in the commercial catch is approximately 78%, showing a decline in all regulatory regions since 2017. Additional years of commercial catch sex-ratio information are likely to further inform selectivity parameters and cumulatively reduce uncertainty in future estimates of stock size.

The IPHC Secretariat is also working towards providing information regarding the sex ratios in years previous to 2017 through the use of genotyping techniques using historical otolith samples. The IPHC Secretariat has recently tested whether DNA can be extracted from otoliths and whether the extracted DNA is of sufficient quantity and quality to be used in the genotyping assays currently used with DNA derived from fin clips. Preliminary results using recently collected otoliths with visible residue indicate that DNA can be extracted from otoliths, albeit at low concentration, and that the genotyping assays can successfully be used on otolith DNA for sex identification. Further studies will be completed by the SRB meeting regarding the viability of this protocol on clean archived otoliths.

2.2. Maturity assessment.
Principal Investigator: Josep Planas (Ph.D.)

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). These results highlight the need for a better understanding of factors influencing reproductive biology and success for 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) accurate description of oocyte developmental stages and their use to classify female maturity stages; 2) comparison of macroscopic (based on field observations) and microscopic (based on histological assessment) maturity stages and revision of maturity criteria; 3) revision of current estimates of female age-at-maturity; and 4) investigation of skip-spawning in females.

The IPHC Secretariat has described for the first time the different oocyte stages that are present in the ovary of female Pacific halibut and how these are used to classify females histologically to specific maturity stages. This information is contained in a manuscript that is currently in preparation for submission to a peer-reviewed journal (Fish et al., in preparation). Currently underway is a study assessing temporal changes in female maturity, as assessed by microscopic observations of ovarian samples collected throughout an entire annual reproductive cycle, and the comparison with macroscopic staging of maturity status as conducted in the field.

In addition, the IPHC Secretariat is conducting temporal and spatial analyses of female maturity schedules through the collection of ovarian samples in FISS. For the temporal analysis of maturity, ovarian samples have been collected in the Portlock region (central Gulf of Alaska) during the same period (June-July) for 30 females (>90 cm length) for four consecutive years: 2017, 2018, 2019 and 2020. These ovarian samples are being processed for histology and microscopic maturity staging will be conducted to compare the maturity status over time. Furthermore, for the spatial analysis of maturity, ovarian samples from 30 females (>90 cm length) are currently being collected in the FISS in 5 different regions in the Gulf of Alaska in order to determine potential spatial differences in maturity.

The IPHC Secretariat is also investigating the possible presence of skip spawning females by focusing on the histological characteristics of ovaries of females of reproductive age (older than 12 years of age) and that are classified as immature by macroscopic and microscopic staging at a time of the year when most females have oocytes at stages in late vitellogenesis or in later stages.

Plans are underway to measure fecundity in 2021 in order to be able to relate fecundity to age and size in female Pacific halibut.

3. Growth.
   Principal Investigator: Josep Planas (Ph.D.)

   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 use of growth markers for evaluating growth patterns in the Pacific halibut population and the effects of environmental factors on somatic growth. In order to pursue these objectives, the IPHC Secretariat has conducted investigations on the effects of temperature variation on growth performance, as well as on the effects of density, hierarchical dominance and handling stress on growth in juvenile Pacific halibut in captivity. These studies have been partially funded by a grant from the North Pacific Research Board to the IPHC (Appendix II) and the preliminary results have been described in the final report of the project and a manuscript for publication is currently in preparation (Planas et al., in preparation).

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 for 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. 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.
        Principal Investigator: Claude Dykstra (B.Sc.)

        In order to better estimate post-release survival of Pacific halibut caught incidentally in the directed longline fishery, the IPHC Secretariat is conducting investigations to understand the relationship between fish handling practices and fish physical and physiological condition and survival post-capture as assessed by electronic archival tagging with funding by a grant from the Saltonstall-Kennedy Grant Program NOAA (Appendix II). Currently, investigations are devoted to decipher potential relationships between individual physiological characteristics, environmental conditions, and handling practices, and final viability release classifications.

Electronic monitoring (EM) systems were proven to be effective at accurately capturing the release method applied to each animal. Ongoing work has focused on investigating the ability to estimate individual Pacific halibut lengths from EM systems in the longline fishery. The previously captured footage has been used to generate lengths for ~300 fish., Fish lengths are being compared to the actual measurement of fish from the same skates of gear. Additionally, efforts are currently underway to do a similar comparison from a current FISS operation, with a pre-calibrated camera, using imagery of the fish when they are located in the area of the screen where the fish would normally be shaken if not of legal size. .

4.2. <u>Quantification of handling practices and physiological stress in Pacific halibut released in the charter recreational fishery</u>.
<u>Principal Investigator</u>: Claude Dykstra (B.Sc.)

The IPHC has begun 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 (<u>Appendix II</u>). As previously reported, results show that the guided recreational fleet predominantly uses circle hooks (75-100%), followed by jigs. Predominant hook release methods included reversing the hook (54%), or twisting the hook out with a gaff (40%), fish are landed with the line and hook, followed by hand netting, and while aboard the fish were generally handled by supporting both the head and tail (65%), while other common techniques included handling by the operculum (10%) or by the tail alone (10%). We are now developing experimental designs for a field project that is being planned for the Spring of 2021 and in which fish condition and stress will be evaluated to identify best practices intended to minimize discard mortality in this fishery. The design effort is considering whether it is best to replicate field treatments in a way that reflects the questionnaire results in their entirety, generating an overall DMR estimate for that sector to be derived, or to focus on one set of conditions of a particular predominant interest and to develop a DMR that is less broad, but more transferable for best practices. Replicating questionnaire results involves many variables, several with uncontrollable features (10 variables: Reg Area, Port, Fish Size, Hook Type, Hook Size, Capture conditions, Landing method, Time on Deck, Fish Condition, and Release Method) allowing for an overall generic DMR estimate to be derived, with minimal parsing as to the influences of each variable. Selecting the more focused route would refine estimates for a specific hook type, and allow for fine tuning of one portion of the overall estimates of mortality (for instance circle hook effect of most predominant hook size, which is nested within several hook types contributing to an overall DMR estimate in a region). This work continues to be the subject of ongoing efforts to secure sufficient funding for a meaningful number of sPAT tags to estimate discard mortality.

5. <u>Genetics and genomics</u>. The IPHC Secretariat is exploring avenues for incorporating genetic approaches for a better understanding of population structure and distribution and is also building genomic resources to assist in genetics and molecular studies on Pacific halibut.

5.1. Genetics.
Principal Investigator: Andy Jasonowicz (M.Sc.)

The primary objective of the proposed studies is to investigate the genetic structure of the Pacific halibut population and to conduct genetic analyses to inform on Pacific halibut movement and distribution in the eastern North Pacific Ocean. Two specific objectives will be pursued:

5.1.1. Determine the genetic structure of the Pacific halibut population in the North-eastern Pacific Ocean. Understanding population structure is imperative for sound management and conservation of natural resources (Hauser, 2008). Pacific halibut in US and Canadian waters are managed by the International Pacific Halibut Commission (IPHC) as a single coastwide unit stock since 2006 (Stewart and Martell, 2014). The rationale behind this management approach is based on our current knowledge of the highly migratory nature of Pacific halibut as assessed by tagging studies (Webster et al., 2013) and of past analyses of genetic population structure that failed to demonstrate significant differentiation in the North-eastern Pacific Ocean population of Pacific halibut by allozyme (Grant, 1984) and small-scale microsatellite analyses (Bentzen, 1998; Nielsen et al., 2010). However, more recent studies have reported slight genetic population structure on the basis of genetic analysis conducted with larger sets of microsatellites suggesting that Pacific halibut captured in the Aleutian Islands may be genetically distinct from other areas (Drinan et al., 2016). These findings of subtle genetic structure in the Aleutian Island chain area are attributed to limited movement of adults and exchange of larvae between this area and the rest of the stock due to the presence of oceanographic barriers to larval and adult dispersal (i.e. Amchitka Pass) that could represent barriers to gene flow. Unfortunately, genetic studies suggesting subtle genetic structure (Drinan et al., 2016) were conducted using a relatively limited set of microsatellite markers and, importantly, using genetic samples collected in the summer (i.e. non-spawning season) that may not be representative of the local spawning population. With the recent collection of winter (i.e. spawning season) genetic samples in the Aleutian Islands by the IPHC in early 2020, winter collected samples from 5 different geographic areas across the North-eastern Pacific Ocean (i.e. British Columbia, Central Gulf of Alaska, Bering Sea, Central and Western Aleutian Islands) are now available to re-examine the genetic structure of the Pacific halibut population. Using low-coverage whole genome resequencing (Therkildsen and Palumbi, 2017; Clucas et al., 2019), and the recently sequenced Pacific halibut genome (deposited at DDBJ/ENA/GenBank under the accession JABBIT000000000), the IPHC Secretariat's main objective is to revise our current understanding of population genetic structure using novel, high-resolution genomic technology. The IPHC Secretariat will expand on previous work by including additional samples that have not yet been analyzed (winter collections from 2007, 2018, and 2020) and scanning the genome for signatures of natural selection. By including samples collected over multiple years, we can examine how spatial genetic variation and signatures of natural selection may change over time. The results from the proposed genomic studies would provide important information on spawning structure and provide management advice regarding the relative justifiability for considering the western Aleutians as a genetically-distinct substock.

Methods

Collected fin clips preserved in ethanol from Pacific halibut during the spawning season (i.e. winter) will be processed for DNA extraction and purification using Qiagen kits. The available samples correspond to the following geographic areas and dates of winter collection: British Columbia (Haida Gwaii; 1998-1999, 2004, 2007), Central Gulf of Alaska (Portlock region; 1998-1999, 2004, 2007, 2018), Bering Sea (Pribilof Canyon; 2004, 2007), Central Aleutian Islands (Adak; 2007, 2020) and Western Aleutian Islands (Attu; 2020). Samples from 50 individuals from each of these collections, totaling 600 individuals, will be processed for genetic analyses. Libraries for low-coverage whole-genome resequencing will be prepared according to published protocols (Clucas et al. 2019) and sequencing will be conducted using the Illumina NovaSeq platform. With an output of 2.5 billion reads (750Gb) per NovaSeq S4 lane, we estimate that sequencing could be carried out in 3 lanes to achieve 5x sequencing coverage per individual. An initial sequencing run of 36 samples will be carried out using a single Illumina HiSeq 4000 lane to validate these numbers and library preparation methods.

An approach similar to the one used by Clucas et al. (2019) will be used to process the raw sequence reads prior to genotyping. Bowtie2 (Langmead and Salzberg 2012) will be used in end-to-end mode to align the raw sequence reads to the Pacific halibut genome. Samtools (Li et al. 2009) will be used to filter out alignments with a mapping quality score less than 20 (99% change of a correct alignment) and reads aligned to multiple locations in the genome. Polymerase chain reaction (PCR) duplicates will be removed using Piccard (https://broadinstitute.github.io/picard) and overlapping read pairs will be clipped using bamutil (Jun et al. 2015). Local realignment will be will be performed using GATK (Poplin et al. 2018) to improve alignments around insertion/deletion elements.

The software ANGSD (Korneliussen et al. 2014) and ATLAS (Link et al. 2017) will be used detect SNPs through the Pacific halibut genome. ANGSD will also be used to estimate measures of genetic diversity (allele frequencies and heterozygosity) for each sample collection. We expect to identify millions of SNPs taking this approach (Therkildsen and Palumbi 2017; Clucas et al. 2019). Measures of genetic differentiation (F_{ST}) will be estimated among the sample collections to examine levels of divergence between them and test for patterns of isolation by distance. To investigate the possibility of cryptic population structure, clustering methods will be used. The software ngsAdmix (Skotte et al. 2013), will be used to infer the number of genetic clusters across the range of Pacific halibut without making a priori assumptions about sample origin. This program also attempts to estimate the ancestry of individual fish and therefore will be useful in the identification of potential migrants. Additionally, outlier tests will also be used to scan the genome for SNPs showing signals of divergent selection. These SNPs showing potential signatures of selection may offer more power to resolve population structure in highly migratory marine fish (Grewe et al. 2015; Anderson et al. 2019). We will compare the results of multiple methods of SNP outlier detection, in particular both F_{ST} based methods (eg. OutFLANK (Whitlock and Lotterhos 2015), tess3r (Caye et al. 2016)) and PCA based methods (PCAngsd (Meisner and Albrechtsen 2018)) will be used.

Furthermore, SNPs showing signals of selection may be functionally relevant and linked to local adaptations. Transcriptomic resources currently under development by the IPHC Secretariat will be very useful in interpreting the functional significance of the many SNPs that we expect to identify in this study.

5.1.2. Analysis of genetic variability among juvenile Pacific halibut in the Bering Sea and the Gulf of Alaska. The aim of this objective is to evaluate the genetic variability or genetic diversity among juvenile Pacific halibut in a given ocean basin in order to infer information on the potential contribution from fish spawned in different areas to that particular ocean basin. We hypothesize that genetic variability among juvenile Pacific halibut captured in one particular ocean basin (e.g. eastern Bering Sea) may be indicative of mixing of individuals originating in different spawning grounds and, therefore, of movement. By comparing the genetic variability of fish between two ocean basins (i.e. eastern Bering Sea and Gulf of Alaska), we will be able to evaluate the extent of the potential contribution from different sources (e.g. spawning groups) in each of the ocean basins and provide indications of relative movement of fish to these two different ocean basins. The use of genetic samples from juvenile Pacific halibut collected in the National Marine Fisheries Service trawl survey in the eastern Bering Sea and in the Gulf of Alaska, aged directly by otolith reading or indirectly through a length-age key, will allow us to provide information on genetic variability among fish that are at or near their settlement or nursery grounds.

Methods

Fin clips from 150 fish from the eastern Bering Sea and from 150 fish from the Gulf of Alaska will be selected for genetic analysis. Fin clips have been collected in these areas between 2016-2019 (Table 3). Sample selection will be distributed among sampling years and age class. When possible, otolith reading will be used to directly age fish and an length-age key will be used to indirectly age fish that do not have otoliths samples available. For fish of unknown sex, genetic sex will be determined using SNPs to two sex-linked loci developed (Drinan et al., 2018) and used for determining the genetic sex of commercial Pacific halibut captures.

A similar technical approach with respect to sequencing and bioinformatics in section 5.1.1 will be used for this analysis. The software ANGSD and ATLAS will be used to estimate measures of genetic diversity (allele frequencies and heterozygosity) for sample collections made in the eastern Bering Sea and the Gulf of Alaska. Tests for Hardy-Weinberg equilibrium will also be performed using ANGSD. Clustering methods such as discriminant analysis of principal components (DAPC) (Jombart et al. 2010) and the estimation of admixture proportions (using ngsAdmix) will also be used to identify background population structure and identify individuals that may have originated in different ocean basins.

Table 3. Number of genetic samples available per year, aged or non-age, collected in the NMFS trawl survey.

All Samples by Year

Area		2016	2017	2018	2019
BS	**Total**	622	746	943	1,074
	Aged	188	195	167	138
GOA	**Total**		702		1,155
	Aged				340

Aged Samples (ages 1-5 only)

Area	Age	2016	2017	2018	2019
BS	**1**				25
	2	7		35	11
	3	39	40	34	10
	4	45	71	51	4
	5	25	36	30	4
GOA	**1**				57
	2				38
	3				28
	4				28
	5				19

5.2. Generation of genomic resources.
Principal Investigator: Josep Planas (Ph.D.)

The IPHC Secretariat has conducted studies aimed at generating genomic resources for Pacific halibut that are instrumental for a more in-depth understanding the genetic make-up of the species: a reference genome and a comprehensive collection of expressed sequence tags (ESTs). The generated genomic resources will greatly assist current studies on the genetic structure of the Pacific halibut population, on the application of genetic signatures for assigning individuals to spawning populations and for a thorough characterization of regions of the genome or genes responsible for important traits of the species.

5.2.1. Genome sequencing. The IPHC Secretariat has recently completed the first draft sequence of the Pacific halibut genome in collaboration with the French National Institute for Agricultural Research (INRA, Rennes, France). The Pacific halibut genome has a size of 594 Mb and contains 24 chromosome-size scaffolds covering 98.6% of the complete assembly with a N50 scaffold length of 25 Mb at a coverage of 91x. The Pacific halibut whole genome sequence has been deposited at DDBJ/ENA/GenBank under the accession JABBIT000000000. In addition, the Pacific halibut genome has been annotated and is available in NCBI as NCBI Hippoglossus stenolepis Annotation Release 100.

5.2.2. Expressed Sequence Tags. The IPHC Secretariat has completed transcriptome (i.e. RNA) sequencing of a wide variety of tissues (12) in Pacific halibut including white and red skeletal muscle, liver, heart, ovary, testis, head kidney, brain, gill, pituitary, spleen and retina. The functional annotation of these transcriptomes to describe tissue-specific gene expression complements the genome sequencing efforts and represents a resource that will provide biological insights at a molecular level for ongoing and future IPHC research.

The IPHC Secretariat reported previously on the results of Illumina sequencing and assembly of the 12 individual tissues as well as the resulting combined assembly. 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.

The transcript assemblies for each tissue were annotated using the Trinotate pipeline. TransDecoder (v5.5.0) was used to identify open reading frames longer than 100 codons and used to predict likely protein coding sequences. Transcripts and predicted proteins were queried against the Swiss-Prot database using BLASTx (Figure 1) and BLASTp, respectively.

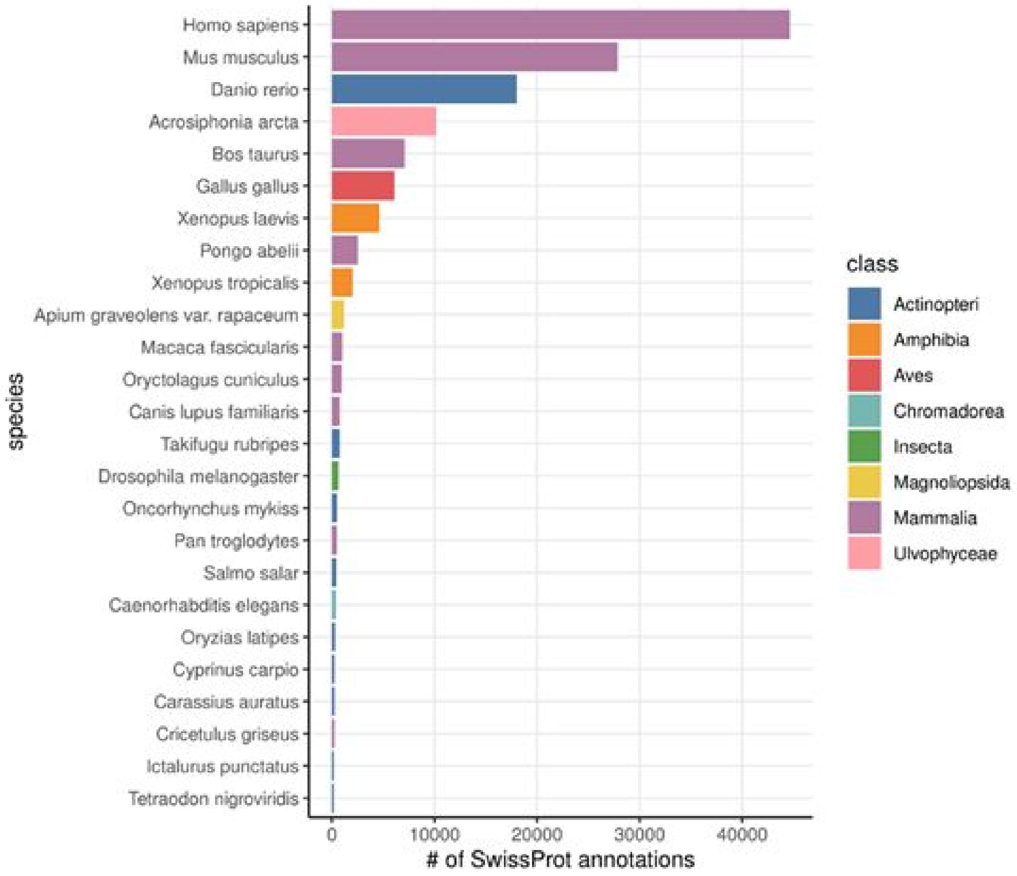


Figure 1. Most represented species assigned to top blastx match in the Swiss-Prot database.

Filtered reads were mapped back to the combined transcriptome assembly and differential gene expression analysis was performed by RSEM (v1.2.28) (Li and Dewey 2011). The raw RNA-seq read counts for each gene were normalized using the trimmed mean of M-values (TMM) method (Robinson and Oshlack 2010). The R package TissueEnrich (v1.6.0) (Jain and Tuteja 2019) was used to identify tissue-specific genes according to the expression categories defined by the Human Protein Atlas (HPA) (Uhlén et al. 2015), with the ‘Tissue-enriched” category indicating genes with an expression level greater than or equal to 1 (TPM or FPKM) that also have at least five-fold higher expression levels in a particular tissue compared to all other tissues. Analysis of the three HPA expression categories across the 12 individual Pacific halibut tissues evidenced differences in the number of tissue-specific transcripts, with retina and pituitary containing the highest number of tissue-specific transcripts, followed by gill, testis and brain (Figure 2). Spleen and white muscle were the two tissues with the lowest number of tissue-specific transcripts.

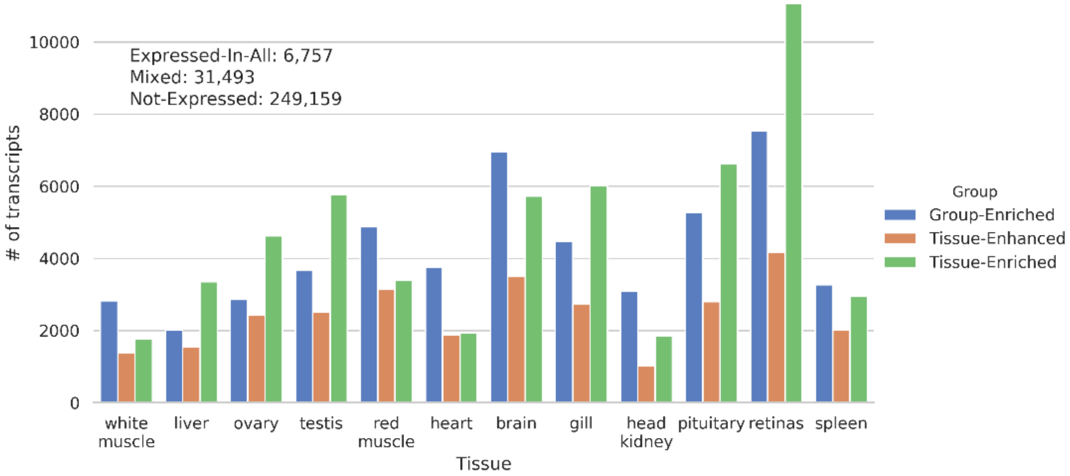


Figure 2. Number of transcripts in each expression category as defined by Uhlen et al. (2015).

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APPENDIX I

Integration of biological research, stock assessment and harvest strategy policy


Biological Research

Stock assessment

MSE

Policy Decisions

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

Summary of awarded research grants

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 (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
5	**National Fish & Wildlife Foundation**	Improving the characterization of discard mortality of Pacific halibut in the recreational fisheries	IPHC	Alaska Pacific University, U of A Fairbanks, charter industry	$98,902	Bycatch estimates	April 2019 – June 2021
Total awarded ($)					**$516,914**		


L. Boitor

INTERNATIONAL PACIFIC
HALIBUT COMMISSION

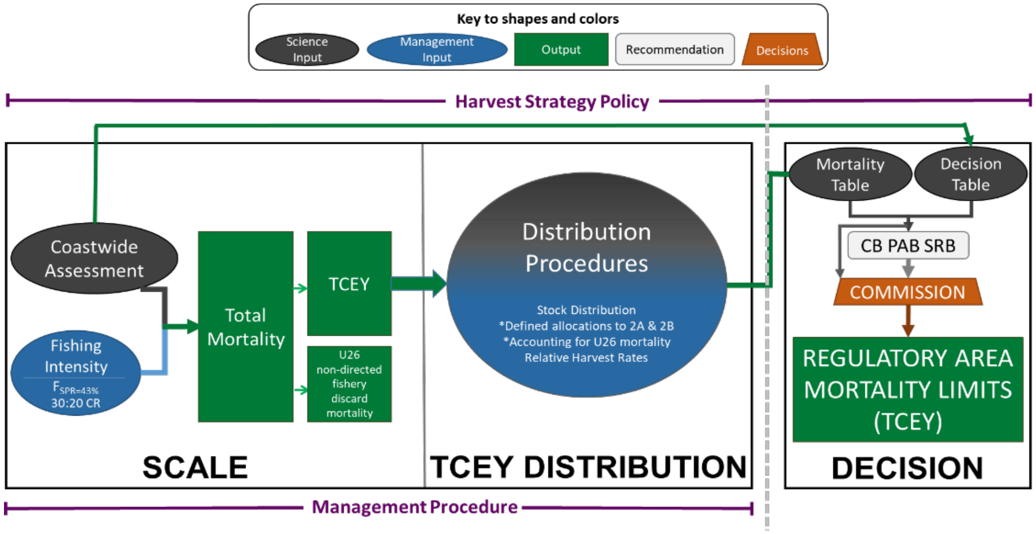
Management Strategy Evaluation Update

Agenda Item 7.1

IPHC-2020-SRB017-09

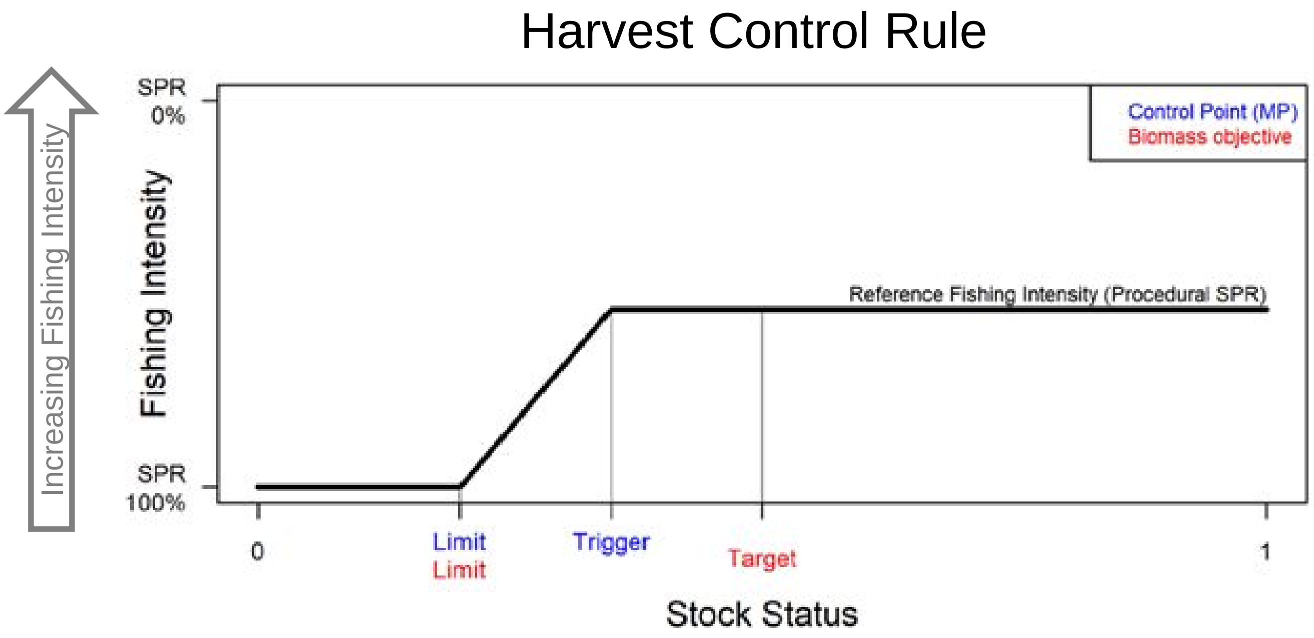
IPHC Harvest Strategy Policy

1. Coastwide target fishing intensity (science-based & management-derived)
2. Regional Stock Distribution (science-based & management-derived)
3. Regulatory Area Allocation (science-based & management-derived)
4. Annual Regulatory Area Adjustment (policy-based)



Coastwide Scale (fishing intensity)

- SPR
  - Various values
- Control rule
  - 30:20
- Constraint
  - Maximum change in TCEY of 15%
  - Slow-up, fast-down

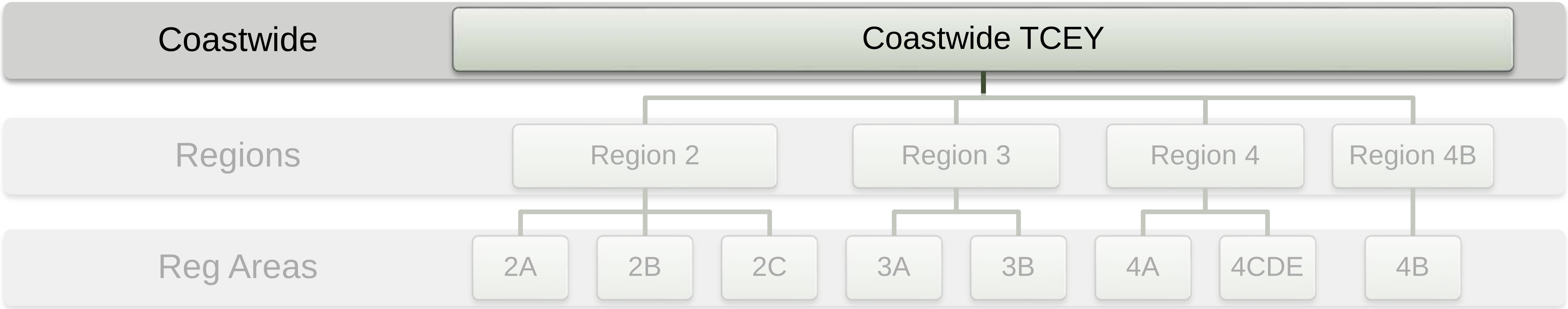


A procedure for distributing the TCEY (2)

1. Coastwide Target Fishing Intensity

Required

- Determine coastwide Total Mortality from Scale MP
- Separate TM into O26 (TCEY) and U26 components



Coastwide
Coastwide TCEY

Regions
Region 2
Region 3
Region 4
Region 4B

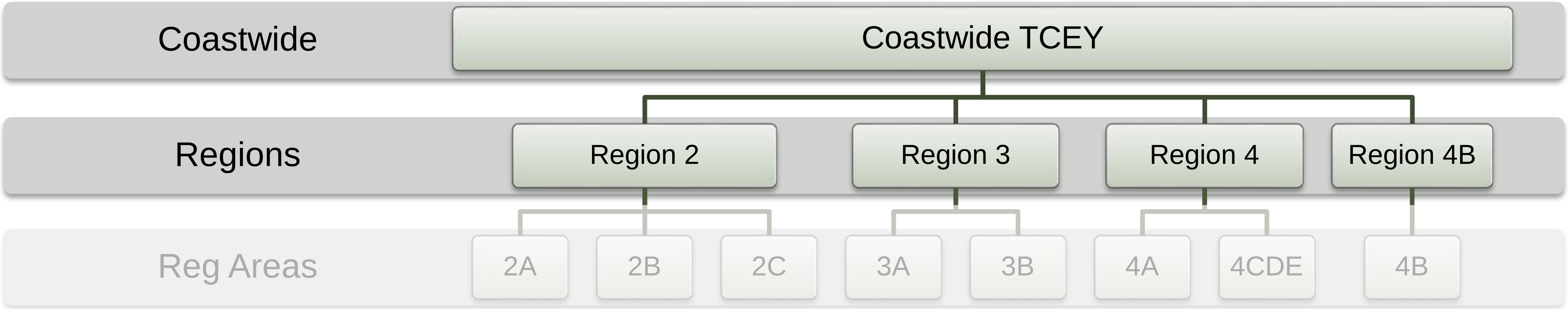
Reg Areas
2A
2B
2C
3A
3B
4A
4CDE
4B

A procedure for distributing the TCEY (3)

2. Regional Stock Distribution

Optional

- Stock distribution using proportion of the stock estimated from the WPUE index.
- Relative fishing intensity to adjust the distribution in account of migration, productivity, etc…
- Regional Allocation adjustment to account for other factors.

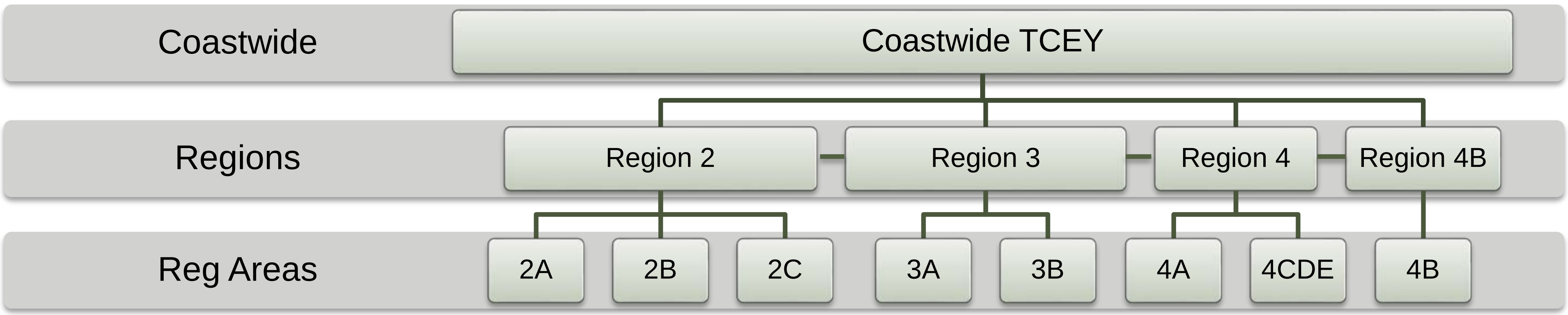


A procedure for distributing the TCEY (4)

3. Regulatory Area Allocation

- Stock distribution using proportion of the stock estimated from the WPUE index.
- Relative harvest rates

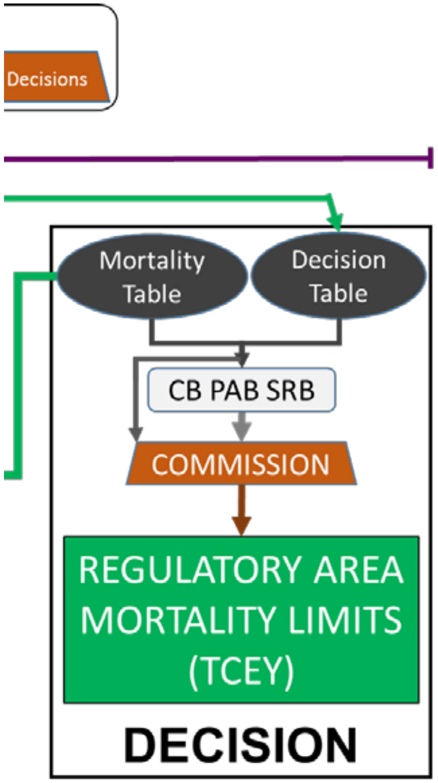
Required



A procedure for distributing the TCEY (5)

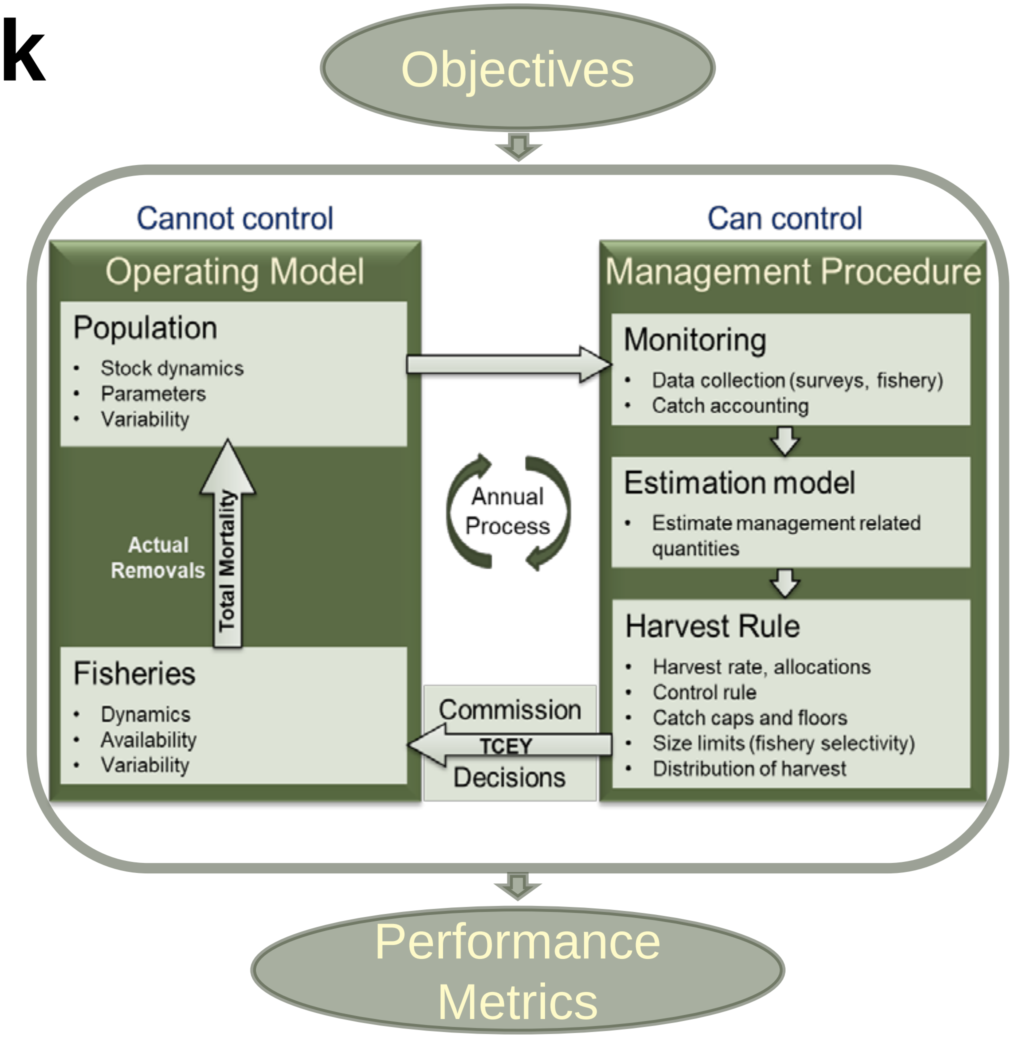
4. Annual Regulatory Area Adjustment

- Adjust Regulatory Area TCEY's to account for other factors as needed
- May deviate from the management procedure
  - Will have unpredictable consequences



Simulation Framework

- The framework contains
  - The elements of the closed-loop simulations
  - The input of objectives and output of performance metrics



Objectives

Cannot control

Operating Model

Population
- Stock dynamics
- Parameters
- Variability

Actual Removals

Total Mortality

Fisheries
- Dynamics
- Availability
- Variability

Annual Process

Commission

TCEY

Decisions

Can control

Management Procedure

Monitoring
- Data collection (surveys, fishery)
- Catch accounting

Estimation model
- Estimate management related quantities

Harvest Rule
- Harvest rate, allocations
- Control rule
- Catch caps and floors
- Size limits (fishery selectivity)
- Distribution of harvest

Performance Metrics

General Objectives

- Primary biological sustainability objectives
- Primary fishery objectives
    - Target Spawning Biomass to optimise fishing activities
    - Stability in mortality limits
    - Provide directed fishing yield

MSAB014: https://www.iphc.int/uploads/pdf/msab/msab014/iphc-2019-msab014-r.pdf

Commission: https://iphc.int/uploads/pdf/cir/2020/iphc-2020-cr-007.pdf

Primary Performance Metrics

Biological Sustainability

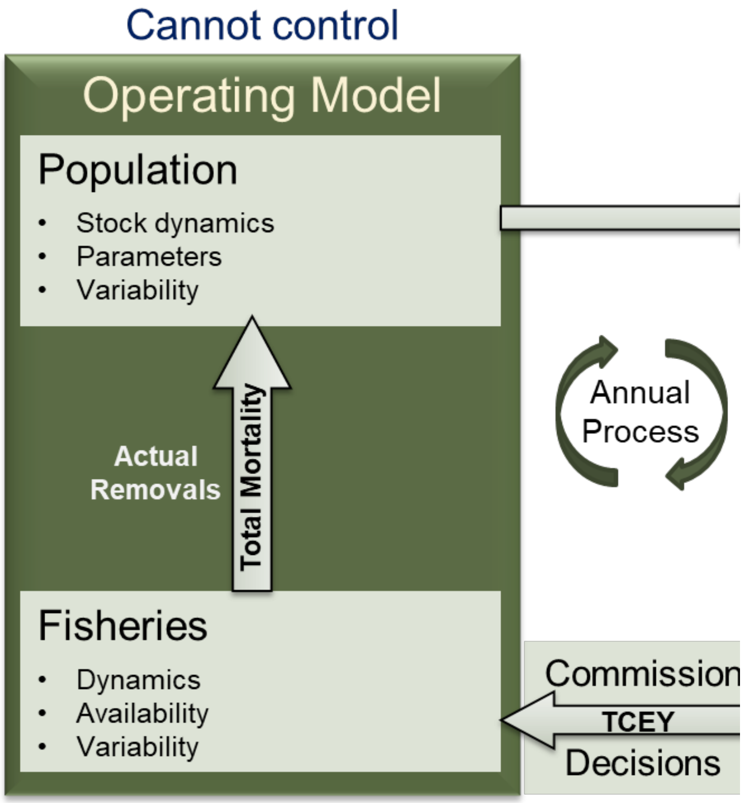
- Probability female SB > 20% of B0
- Probability female SB in R2 > 5% of coastwide SB
- Probability female SB in R3 > 33% of coastwide SB
- Probability female SB in R4 > 10% of coastwide SB
- Probability female SB in R4B > 2% of coastwide SB

Primary Performance Metrics

Fishery

- Probability coastwide female SB > 36% of B0
- Probability Annual Change in TCEY > 15% in any 3 yrs of 10
  - coastwide and by IPHC Regulatory Area
- Median AAV
  - coastwide and by IPHC Regulatory Area
- Median TCEY
  - coastwide and by IPHC Regulatory Area
- Median %TCEY in each IPHC Regulatory Area
- Minimum TCEY in each IPHC Regulatory Area
- Mininum %TCEY in IPHC Regulatory Area

Operating Model (OM)



For technical details, see:

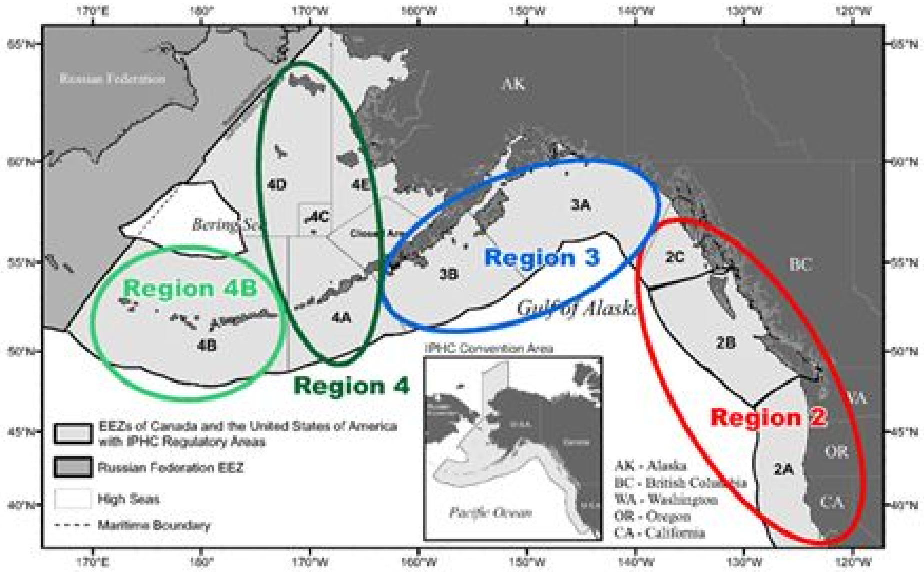
https://www.iphc.int/venues/details/16th-session-of-the-iphc-scientific-review-board-srb016

MSAB015 Report

https://www.iphc.int/uploads/pdf/msab/msab015/iphc-2020-msab015-r.pdf

OM specifications: Regions

- Four Biological Regions to model biological processes
- Eight IPHC Regulatory Areas for fisheries



OM specifications: Fishing Sectors

- Five sectors
  1. Directed commercial fishery
     - O32 mortality from directed fisheries
  2. Directed commercial discard mortality (*directed discards*)
     - U32 mortality from directed fisheries
  3. Non-directed commercial discard mortality (*non-directed*)
     - Mortality from non-directed fisheries
  4. Recreational
     - Mortality from recreational landings and discards
  5. Subsistence
     - Mortality from non-commercial, customary and traditional use

OM specifications: 33 Fisheries

Fishery	IPHC Reg Areas	2019 Mortality
Directed Commercial 2A	2A	0.89
Directed Commercial 2B	2B	5.22
Directed Commercial 2C	2C	3.67
Directed Commercial 3A	3A	8.16
Directed Commercial 3B	3B	2.31
Directed Commercial 4A	4A	1.45
Directed Commercial 4B	4B	1.00
Directed Commercial 4CDE	4CDE	1.65

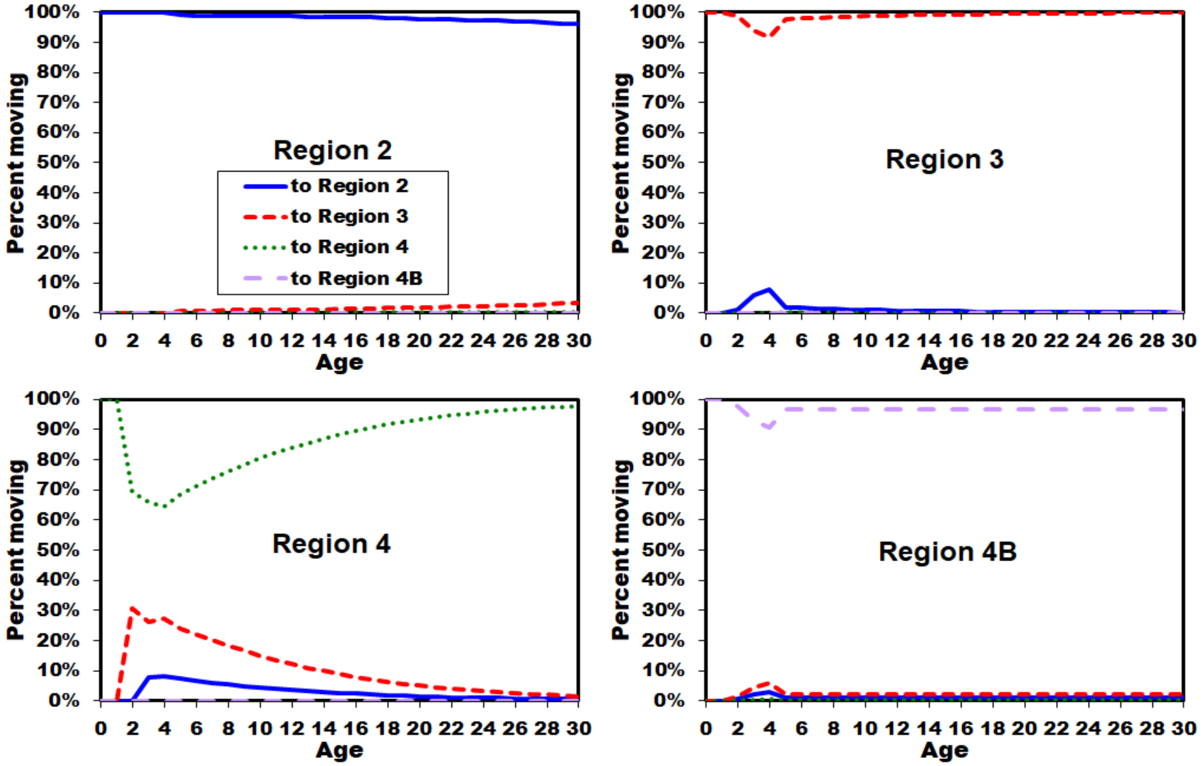
Fishery	IPHC Reg Areas	2019 Mortality
Directed Commercial Discards 2A	2A	0.03
Directed Commercial Discards 2B	2B	0.13
Directed Commercial Discards 2C	2C	0.06
Directed Commercial Discards 3A	3A	0.32
Directed Commercial Discards 3B	3B	0.15
Directed Commercial Discards 4A	4A	0.09
Directed Commercial Discards 4B	4B	0.03
Directed Commercial Discards 4CDE	4CDE	0.07

Fishery	IPHC Reg Areas	2019 Mortality
Non-Directed Comm Discards 2A	2A	0.13
Non-Directed Comm Discards 2B	2B	0.24
Non-Directed Comm Discards 2C	2C	0.09
Non-Directed Comm Discards 3A	3A	1.65
Non-Directed Comm Discards 3B	3B	0.48
Non-Directed Comm Discards 4A	4A	0.35
Non-Directed Comm Discards 4B	4B	0.15
Non-Directed Comm Discards 4CDE	4CDE	3.5

Fishery	IPHC Reg Areas	2019 Mortality
Recreational 2B	2B	0.86
Recreational 2C	2C	1.89
Recreational 3A	3A	3.69
Subsistence 2B	2B	0.41
Subsistence 2C	2C	0.37
Subsistence 3A	3A	0.19
Recreational/Subsistence 2A	2A	0.48
Recreational/Subsistence 3B	3B	0.02
Recreational/Subsistence 4	4A,4CDE	0.06

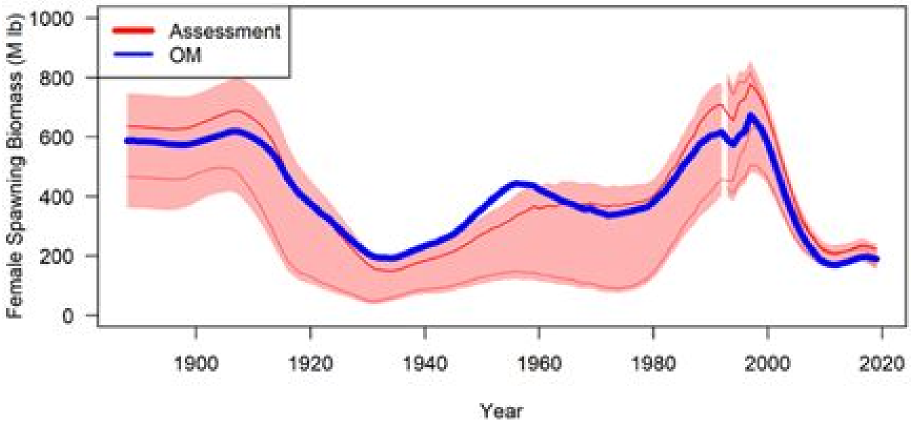
Movement

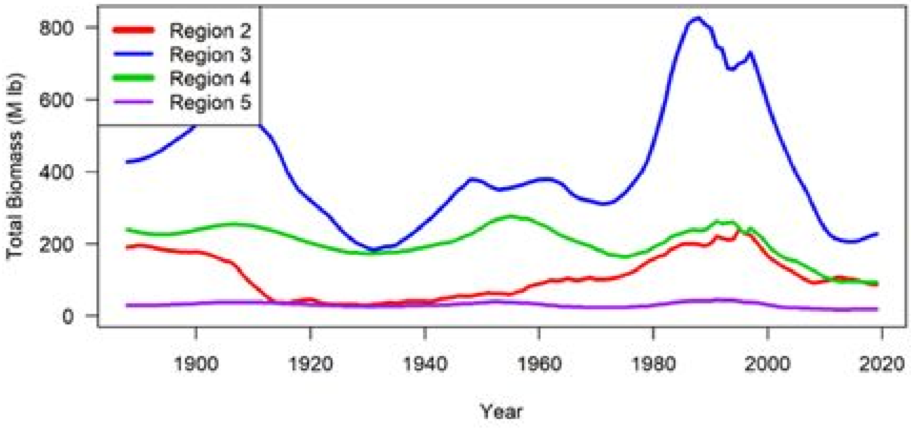
- Integration of information from many sources
  - Recent review of halibut movement
  - Estimated annual movement rates
  - Tuned to observations

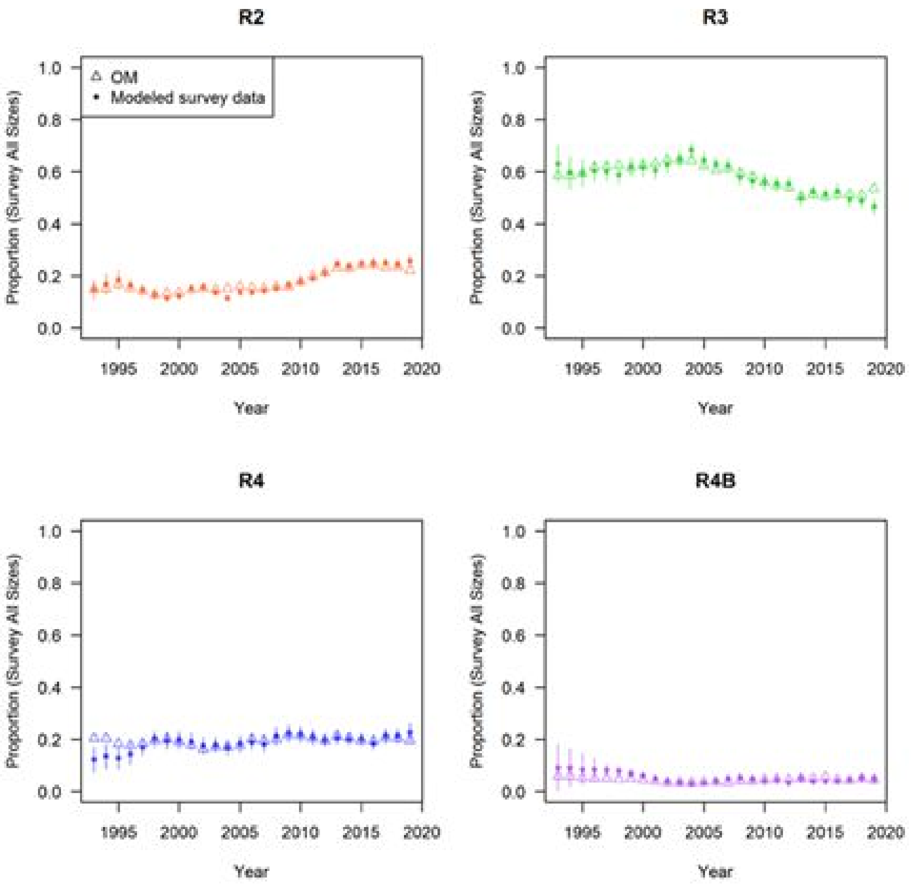


Estimated aggregate annual movement rates by age from Biological Regions (panels) based on currently available data

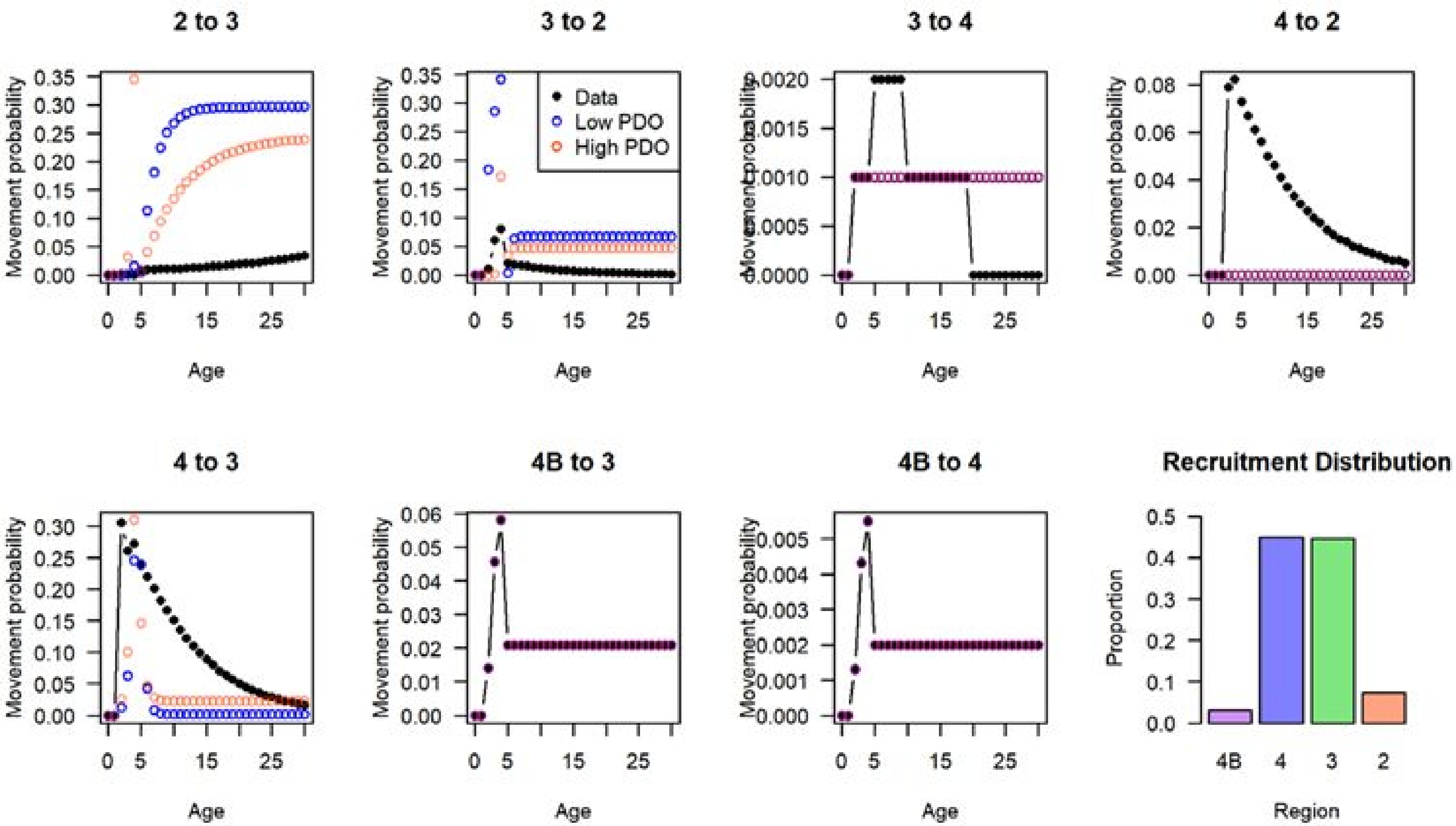
Conditioned model







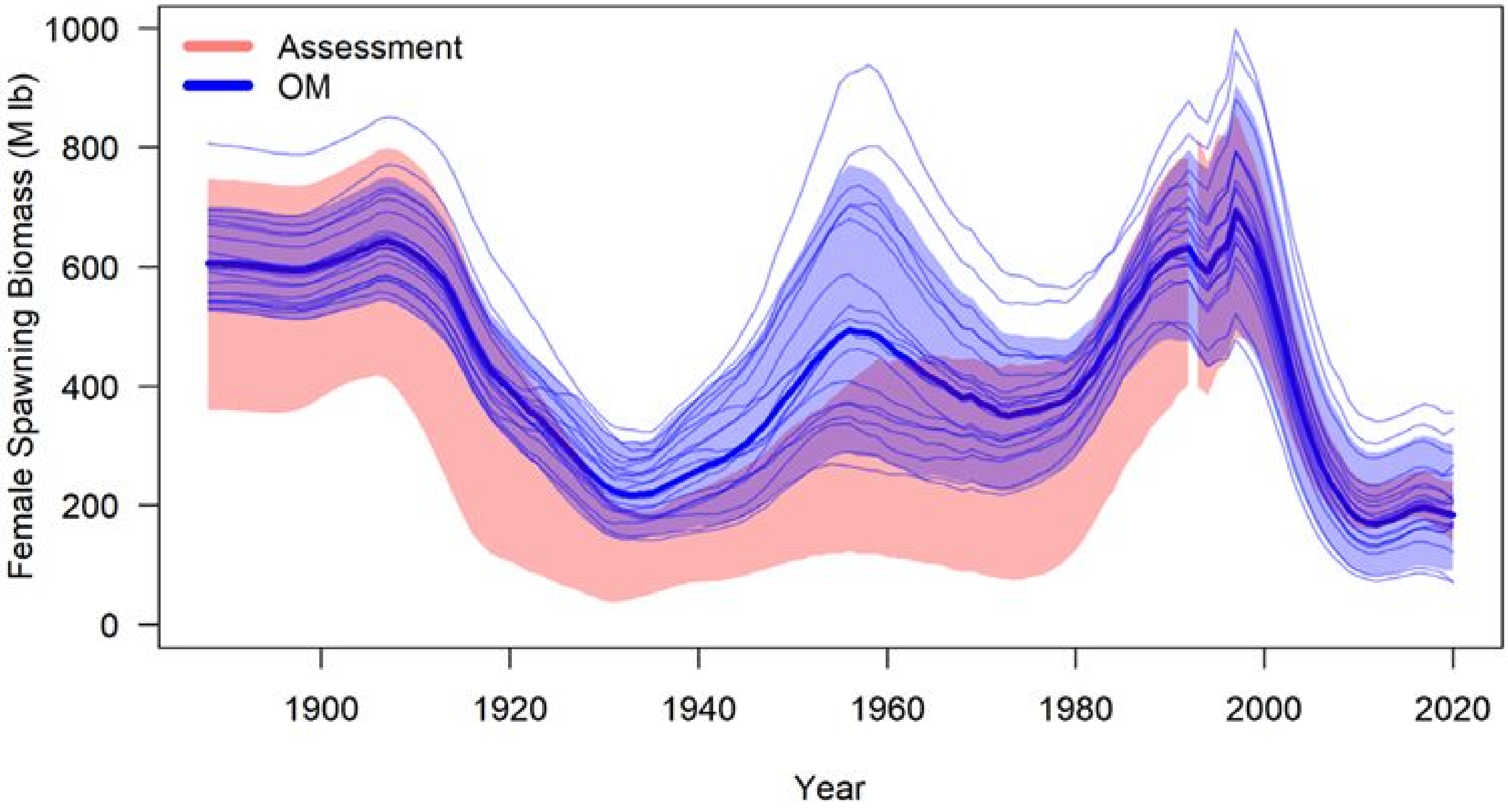
Conditioned Model



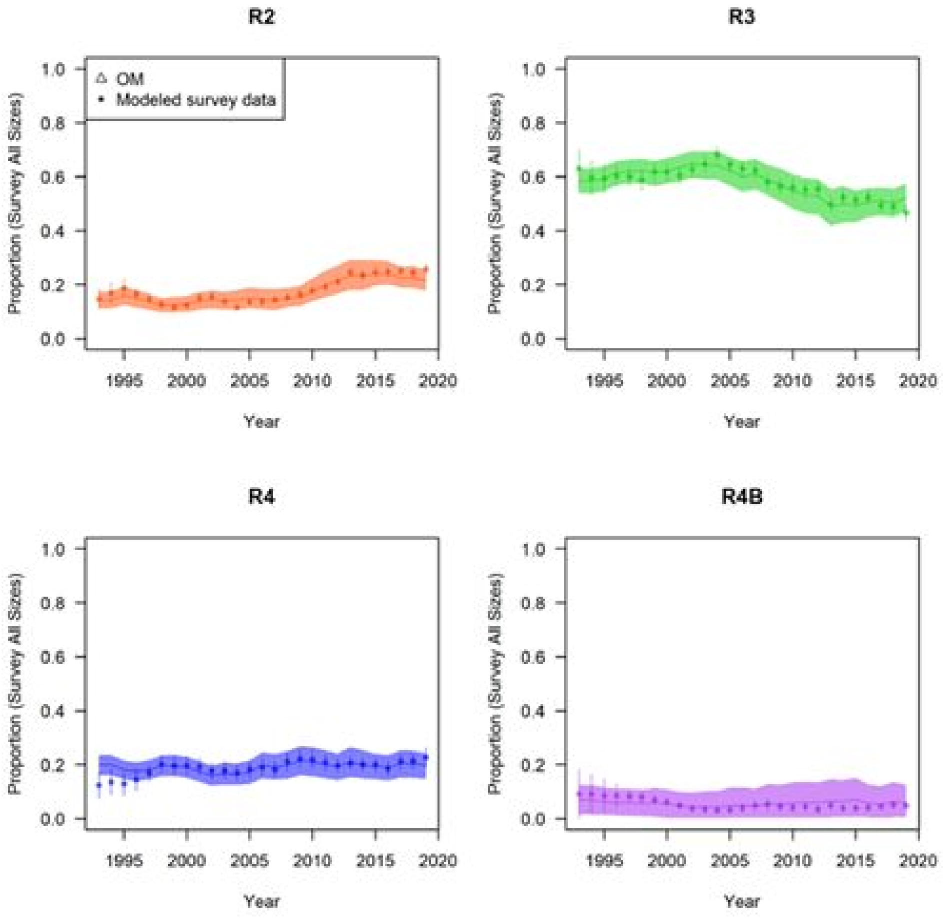
Uncertainty and variability

1. Integrated uncertainty
   - Uncertain parameters
     - M, steepness, R_0, movement, selectivity parameters
   - Variability in projections
     - selectivity, weight-at-age, recruitment, movement
2. Scenarios
   - Specific case to investigate departure in an assumption
     - Weight-at-age at a specified level
     - Non-directed mortality at a specific amount
     - Movement
   - May or may not be integrated into results

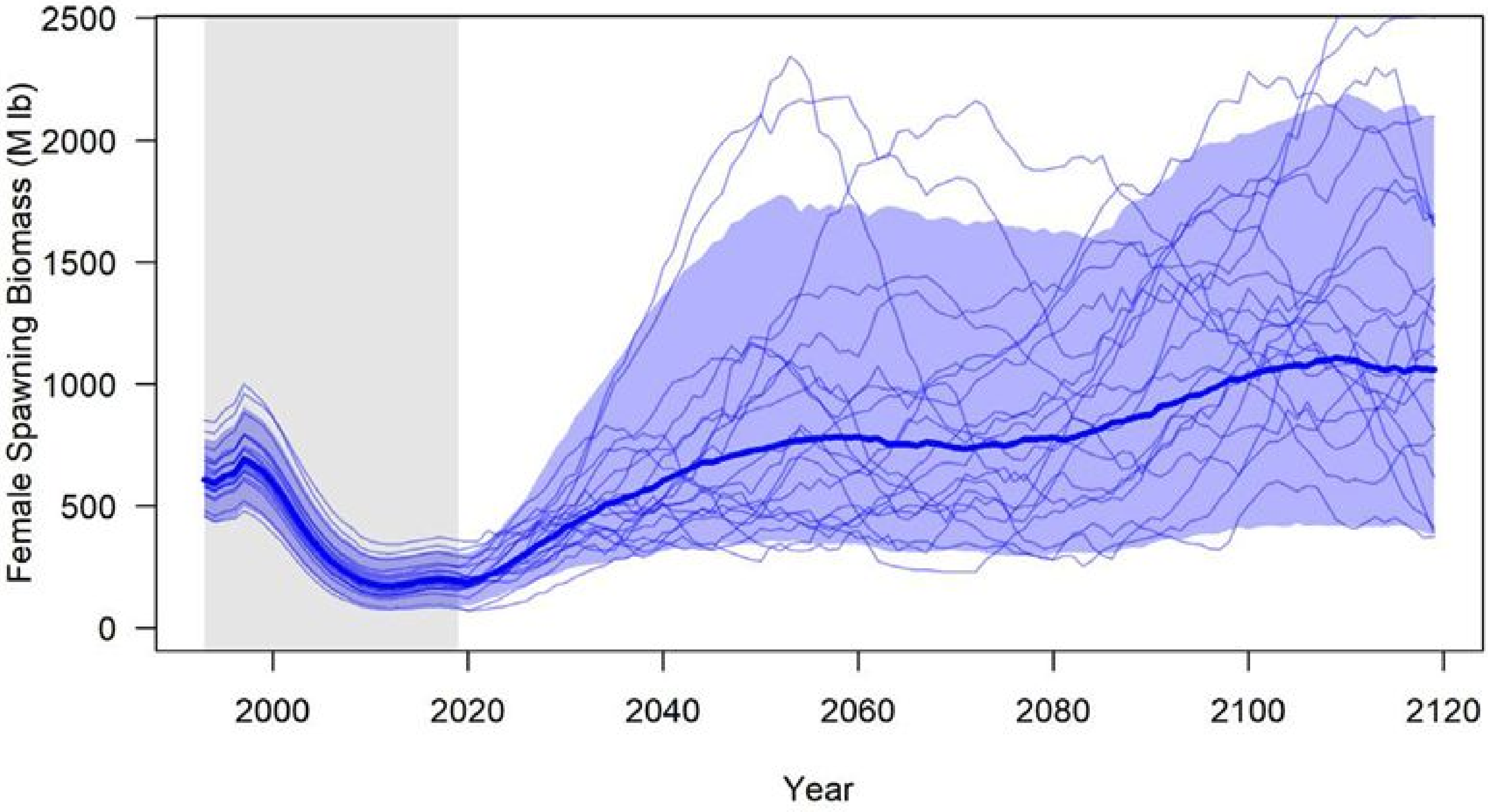
Variability in conditioned model trajectories



Variability in conditioned distribution



Projections without fishing

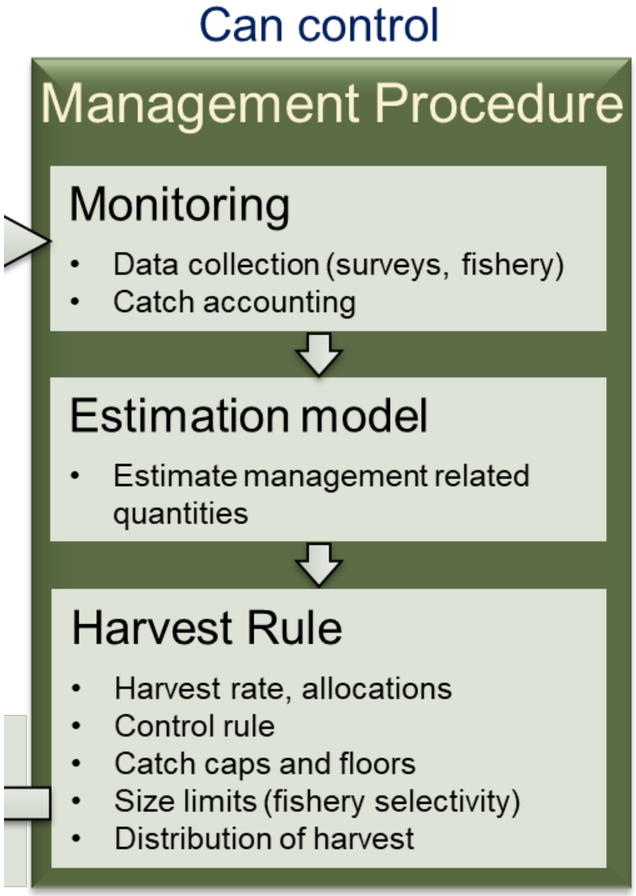


Implementation variability

1. Decision-making
    - Adopted TCEYs may depart from the MP outcomes
2. Actual fishing mortality
    - Fisheries do not exactly catch the set limit
3. Uncertainty in the estimated amount of variability

- Will look at past observations to determine reasonable methods

Management Procedures



Can control

Management Procedure

Monitoring

- Data collection (surveys, fishery)
- Catch accounting

Estimation model

- Estimate management related quantities

Harvest Rule

- Harvest rate, allocations
- Control rule
- Catch caps and floors
- Size limits (fishery selectivity)
- Distribution of harvest

MSAB015

- ***IPHC-2020-MSAB015-R, para. 42***.*The MSAB* ***AGREED*** *that the following elements of interest for defining constraints on changes in the TCEY, and distribution procedures be considered for the Program of Work in 2020:*
  - *constraints on the change in the TCEY can be applied annually or over multiple years at the coastwide or IPHC Regulatory Area level. Constraints on the change in TCEY currently considered include a maximum annual change in the TCEY of 15%, a slow-up fast down approach, multi-year mortality limits, and multi-year averages on abundance indices;*
  - *indices of abundance in Biological Regions or IPHC Regulatory Area (e.g. O32 or All sizes from modelled survey results);*
  - *a minimum TCEY for an IPHC Regulatory Area;*
  - *defined shares by Biological Region, Management Zone, or IPHC Regulatory Area;*
  - *maximum coastwide fishing intensity (e.g. SPR equal to 36% or 40%) not to be exceeded when distributing the TCEY;*
  - *relative harvest rates between Biological Regions or IPHC Regulatory Areas.*

Monitoring and estimation models

Monitoring

- Simulation of survey and fishery data
  - Indices, age compositions, stock distribution

Three types of estimation error

1. No estimation error
   - RSB, TM, and stock distribution known without error
2. Simulated estimation error
   - RSB and TM simulated from bivariate normal distn
   - Stock distribution determined from generated data
3. SS assessment model
   - RSB and TM estimated from long coastwide SS model
   - Stock distribution determined from generated data

MPs for evaluation in 2020

MP	Coastwide	Regional	IPHC Regulatory Area	Priority
MP 15-A	SPR 30:20		• O32 stock distribution • Proportional relative harvest rates (1.0 for 2-3A, 0.75 for 3B-4) • 1.65 Mlbs floor in 2A • Formula percentage for 2B	1
MP 15-B	SPR 30:20 MaxChange15 %		• O32 stock distribution • Proportional relative harvest rates (1.0 for 2-3A, 0.75 for 3B-4) • 1.65 Mlbs floor in 2A • Formula percentage for 2B	1
MP 15-C	SPR 30:20 MaxChange15 %	O32 stock distn Rel HRs: R2, R3=1, R4, R4B=0.75,	• O32 stock distribution • Relative harvest rates not applied • 1.65 Mlbs floor in 2A • Formula percentage for 2B	2
… K				

https://www.iphc.int/uploads/pdf/msab/msab015/iphc-2020-msab015-r.pdf

MP comparison

Element	MP-A	MP-B	MP-C	MP-D	MP-E	MP-F	MP-G	MP-H	MP-I	MP-J	MP-K
maxChange15%		■	■	■	■	■	■	■	■	■	■
max FI buffer (36%)				■							
O32 stock distribution	■	■	■	■	■	■	■	■			
O32 stock distribution (5-year moving avg)										■	
All sizes stock distribution									■		
5-year shares form O32 stock distribution									■		■
Relative harvest rates 1 for 2-3A, 0.75 for 3B-4	■	■		■	■	■	■		■	■	
Relative harvest rates 1 for 2-3, 4A, 4CDE, 0.75 for 4B								■			
1.65 Mlbs floor in 2A	■	■	■	■	■						
Formula percentage for 2B	■	■	■	■							
National Shares (2B=20%)						■					

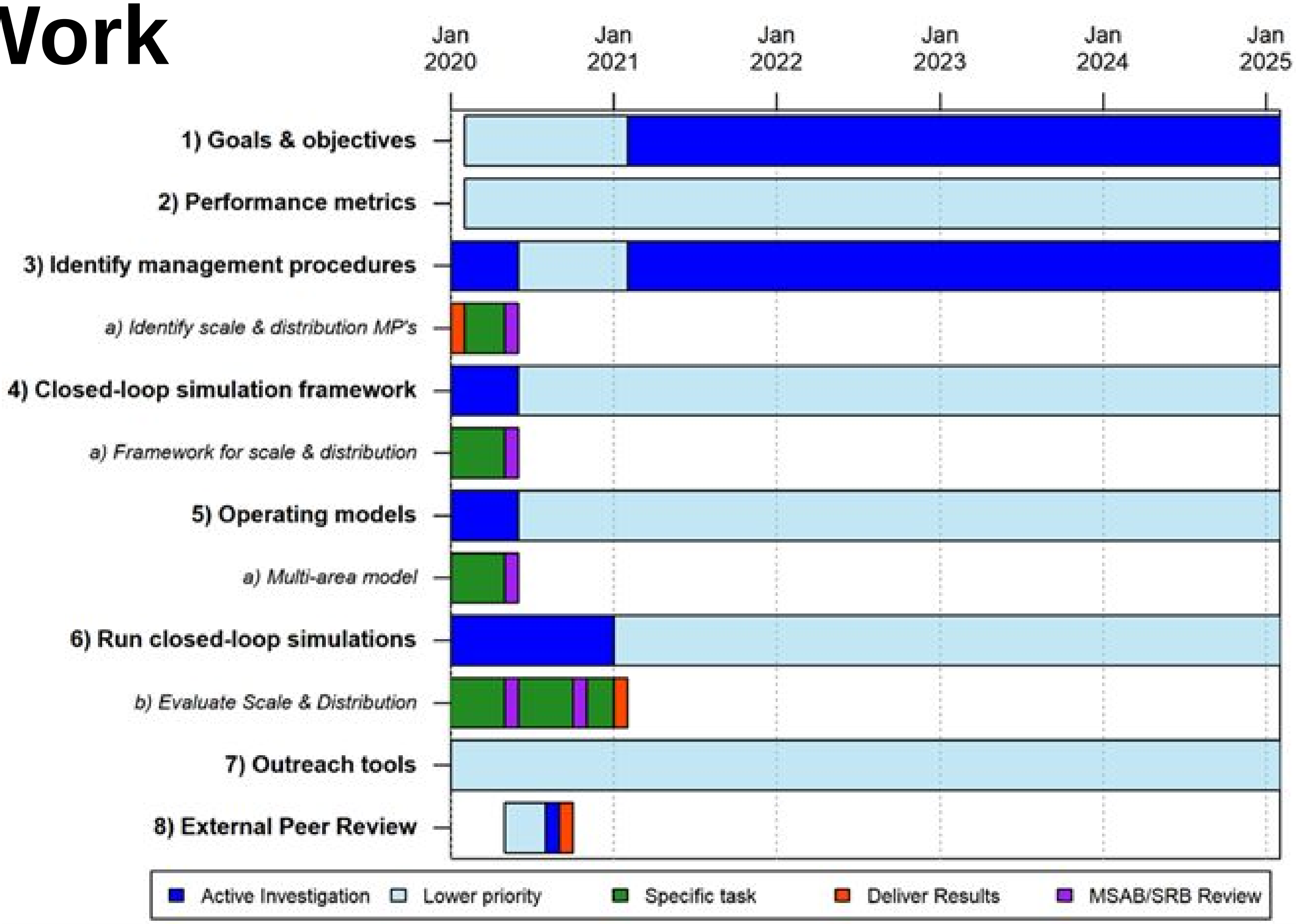
Simulations and Results

- Three assumptions about estimation error
  1. No estimation error
  2. Simulated estimation error (as with coastwide MSE)
  3. Modelled estimation error (a stock assessment model)

http://shiny.westus.cloudapp.azure.com/shiny/sample-apps/MSE-Explorer/

Program of Work

- Eight tasks



Program of Work

May 2020 MSAB Meeting (MSAB015)	**Progress**
Review Goals and Objectives (Distribution & Scale)	Completed
Review simulation framework	Completed
Review multi-area model	Completed
Review preliminary results	
Identify MPs (Distribution & Scale)	Completed
June 2020 SRB Meeting (SRB016)	
Review simulation framework	Completed
Review multi-area model	Completed
Review preliminary results	
August 2020 MSAB Special Session	
Examine preliminary results	Completed
September 2020 SRB Meeting (SRB017)	
Review penultimate results	On schedule
October 2020 MSAB Meeting (MSAB016)	
Review final results	On schedule
Provide recommendations on MPs for scale and distribution	
Annual Meeting 2021	
Presentation of first complete MSE product to the Commission Recommendations on Scale and Distribution MP	

Recommendations

a) **NOTE** paper IPHC-2020-SRB017-09 which provides a description of the IPHC MSE framework, a description of the specifications of the multi-area operating model, results from conditioning the multi-area operating model, and an overview of the implementation of management procedures.

b) **RECOMMEND** the use of the MSE framework to evaluate management procedures incorporating scale and distribution elements.

c) **RECOMMEND** improvements for the MSE framework including data generation, estimation models, multi-region operating models, and methods to simulate processes.

INTERNATIONAL PACIFIC

HALIBUT COMMISSION

An update of the IPHC Management Strategy Evaluation process for SRB017

PREPARED BY: IPHC SECRETARIAT (A. HICKS, P. CARPI, S. BERUKOFF, & I. STEWART; 21 AUGUST 2020)

PURPOSE

To provide an update of International Pacific Halibut Commission (IPHC) Management Strategy Evaluation (MSE) activities including updates to the framework and preliminary results on the evaluation of management procedures for distributing the TCEY.

1 INTRODUCTION

The Management Strategy Evaluation (MSE) at the International Pacific Halibut Commission (IPHC) has completed an initial phase of evaluating management procedures (MPs) relative to the coastwide scale of the Pacific halibut stock and fishery, and has developed a framework to investigate MPs related to distributing the Total Constant Exploitation Yield (TCEY) to IPHC Regulatory Areas. The TCEY is the mortality limit composed of mortality from all sources except under-26-inch (66.0 cm, U26) non-directed commercial discard mortality, and is determined by the Commission at each Annual Meeting for each IPHC Regulatory Area (Figure 1).

The development of an MSE framework aims to support the scientific, forecast-driven study of the trade-offs between fisheries management scenarios. Crafting this tool requires:

- the definition and specification of a multi-area operating model;
- an ability to condition model parameters using historical catch and survey data and other observations;
- identification and development of management procedures with closed-loop feedback into the operating model;
- definition and calculation of performance metrics and statistics based on defined objectives to evaluate the efficacy of applied management procedures.

Updates on the recent efforts in these areas are outlined below.

2 FRAMEWORK ELEMENTS

The MSE framework includes elements that simulate the Pacific halibut population and fishery (Operating Model, OM) and management procedures (MPs) with a closed-loop feedback (Figure 2). Specifications of some elements are described below, with additional technical details in document IPHC-2020-SRB017-10.

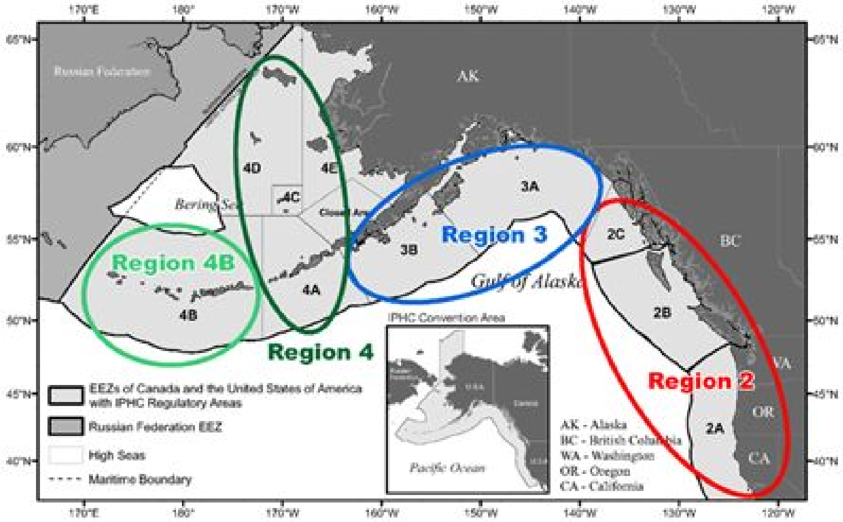


Figure 1. Biological Regions overlaid on IPHC Regulatory Areas. Region 2 comprises 2A, 2B, and 2C, Region 3 comprises 3A and 3B, Region 4 comprises 4A and 4CDE, and Region 4B comprises solely 4B.

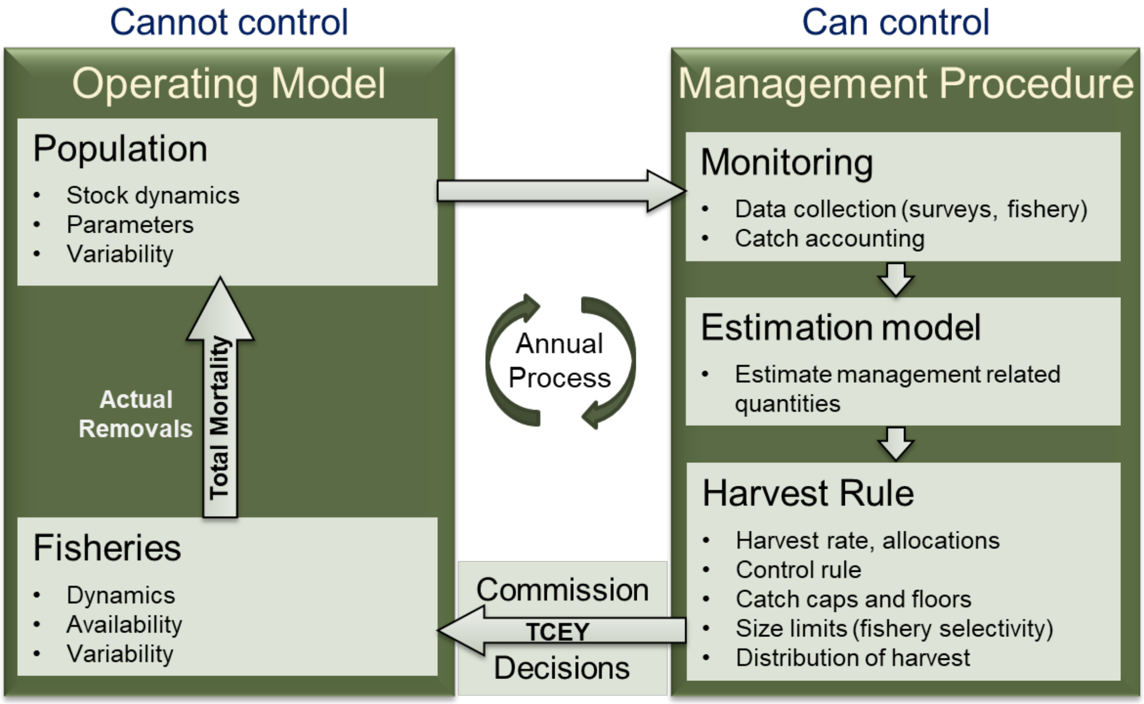


Figure 2. Illustration of the closed-loop simulation framework with the operating model (OM) and the Management Procedure (MP). This is the annual process on a yearly timescale.

2.1 Multi-area operating model

The generalized operating model is able to model multiple spatial components, which is necessary because mortality limits are set at the IPHC Regulatory Area level (Figure 1) and some objectives (Appendix I) are defined at that level. Written in the programming language C++ with JavaScript Object Notation (JSON) input files, the OM is flexible, fast, modular, and easily adapted to many different assumptions. The operating model is a simulation tool and uses external optimisation tools for estimation of parameters. It will be a useful tool for many investigations of the Pacific halibut fishery in the future.

The technical details of the multi-area operating model, which continues to be under development, are supplied in document IPHC-2020-SRB017-10. Some background information on specific components and the incorporation of uncertainty is supplied below.

2.1.1 General process of running the operating model

The use of multiple input JSON-formatted files allows for the simulation of many configurations of the Pacific halibut population and associated fisheries. Any number of areas/regions can be specified along with any number of fisheries that operate in those areas at a specified time in the year. Various parameters, such as natural mortality, movement probabilities, selectivity, etc., are inputs and most can vary over time, region, sex, fishery, and age where relevant.

The OM is called from a script written in the R statistical language (R Core Team 2020) that defines the number of simulations (i.e., unique individual projections), creates all the necessary folders, copies all necessary files over to the new folders, and sets the number of projection years. This script also calls the OM which begins by calculating the unfished equilibrium population given an input set of biological parameters. It then simulates the annual process during what is called an “initial period” which allows for the stock to distribute across modelled areas to an equilibrium state given recruitment deviations and fishing mortality. During a subsequent “main period”, the population and dynamics are simulated using the input annual fishing mortality and time-varying parameters such as selectivity, recruitment variability, and annual movement between areas. The parameterized model that is run through these three periods is called the conditioned model. At the end of the main period the projection period begins.

An R script containing all the details of the management procedure being evaluated as well as changes in weight-at-age is called during the projection period, which does the following. It reads the current OM state from ‘csv’ files written by the OM. It projects weight-at-age as a random process, as described below. It generates data with observation error that are needed for estimation models (EMs) and MPs. It runs the estimation models if required to determine mortality limits and realized mortality for each fishery. The mortalities for each fishery are written to a JSON file and read back into the OM along with other projected annual processes (e.g., weight-at-age) to simulate the fish population one year forward.

2.1.2 Population and fishery spatial specification

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 1) were defined with boundaries that matched some of the IPHC Regulatory Area boundaries for the following reasons. First, data for stock assessment and other analyses are most often reported at the IPHC Regulatory Area scale and are largely unavailable for sub-Regulatory Area evaluation. Particularly for historical sources, there is little information to partition data to a portion of a Regulatory Area. Second, it is necessary to distribute TCEY to IPHC Regulatory Areas for quota management. If a Region is not defined by boundaries of IPHC Regulatory Areas (i.e. a single IPHC Regulatory Area is in multiple Regions) it will be difficult to create a distribution procedure that accounts for biological stock distribution and distribution of the TCEY to Regulatory Areas for management purposes. Further, the structure of the current directed fisheries does not delineate fishing zones inside individual IPHC Regulatory Areas, so there would be no way to introduce management at that spatial resolution.

To a certain degree, Pacific halibut within the same Biological Region share common biological traits different from adjacent Biological Regions. These traits include sex ratios, age composition, and size-at-age, and historical trends in these data may be indicative of biological diversity within the greater Pacific halibut population. Furthermore, tagging studies have indicated that within a year, larger Pacific halibut tend to undertake feeding and spawning migrations within a Biological Region, and movement between Biological Regions typically occurs between years (Loher and Seitz 2006; Seitz et al. 2007; Webster et al. 2013).

Given the goals to divide the Pacific halibut stock into somewhat biologically distinct regions and preserve biocomplexity across the entire range of the Pacific halibut stock, Biological Regions are considered by the IPHC Secretariat, and supported by the SRB (paragraph 31 IPHC-2018-SRB012-R), to be the best option for biologically-based areas to meet management needs. They also offer a parsimonious spatial separation for modeling inter-annual population dynamics.

However, as mentioned earlier, mortality limits are set for IPHC Regulatory Areas and thus directed fisheries operate at that spatial scale. Furthermore, since some fishery objectives have been defined at the IPHC Regulatory Area level (Appendix I), the TCEY will need to be distributed to that scale. Even though the population is modelled at the Biological Region scale, fisheries can be modelled at the IPHC Regulatory Area scale by using an areas-as-fleets approach within Biological Regions. This requires modelling each fleet with separate selectivity and harvest rates that operate on the biomass occurring in the entire Biological Region in each year. The following is a discussion of the pros and cons of this method.

First, modelling the population dynamics at the IPHC Regulatory Area scale would require intra-annual dynamics to be modelled, dividing the year into seasons to model movement between IPHC Regulatory Areas. There is evidence that such intra-annual movements occur (Loher and Seitz, 2006) and fisheries in adjacent IPHC Regulatory Areas may intercept the same pool of fish (Loher 2011). Using Biological Regions assumes that all fisheries within a Region have access to the pool of Pacific halibut in that Region in that year. This greatly simplifies the calculations and eliminates the need to parameterize intra-annual movement.

Additionally, calculating statistics specific to IPHC Regulatory Areas requires assumptions about mechanisms determining future distribution of biomass within each Biological Region. For example, simulating the observed proportion of biomass in each IPHC Regulatory Area (e.g., to mimic the current interim management procedure) requires simulating a survey biomass for each IPHC Regulatory Area. Likewise, determining some performance metrics related to IPHC Regulatory Area objectives may be difficult to calculate (such as the proportion of O26 fish in each IPHC Regulatory Area). The distribution of the population within a Biological Region is currently approximated assuming specified proportions of the population in each IPHC Regulatory Area within a Biological Region that are based on historical observations. These proportions are constant over ages and allows for the calculation of statistics specific to IPHC Regulatory Areas. Future improvements to the framework will allow for different options such as modelling proportions based on population attributes and accounting for year to year variability.

Fisheries were defined by IPHC Regulatory Areas (or combinations of areas if fishing mortality in that area was small) and for five general sectors consistent with the definitions in the recent IPHC stock assessment (IPHC-2020-AM096-09 Rev_2):

- **directed commercial** representing the O32 mortality from the directed commercial fisheries including O32 discard mortality;
- **directed commercial discard** representing the U32 discard mortality from the directed commercial fisheries, comprised of Pacific halibut that die on lost or abandoned fishing gear, and Pacific halibut discarded for regulatory compliance reasons;
- **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.

Table 1 shows the summed mortality realized from 1992 through 2019 for each of these sectors by IPHC Regulatory Area or Biological Region. Thirty-three (33) fisheries were defined as a sector/area combination based on the amount of mortality in the combination, data availability, and MSAB recommendations (Table 2).

The Fishery-Independent Setline Survey (FISS) is included as a fishery with no mortality to output summaries of observations such as indices and observed proportions-at-age in the population available to the survey at a specific time and in a specific region. Mortality from the FISS is included with the directed commercial fishery mortality, although it could be kept separate.

Table 1. Summed mortality (millions of net pounds) from 1992 through 2019 by fisheries and IPHC Regulatory Area or Biological Region.

Year	2A	2B	2C	3A	3B	4A	4CDE	4B
Directed commercial	17.5	259.8	205.5	551.2	252.4	78.2	72.5	62.8
Directed commercial discard mortality	0.5	7.1	5.2	16.7	10.7	2.1	1.3	0.8
Non-directed commercial discard mortality	11.8	12.0	4.5	73.6	36.2	39.2	16.2	128.6
Recreational	13.7	31.8	71.1	152.2	0.5	1.4	<0.1	<0.1
Subsistence	0.7	9.6	10.3	7.6	1.0	0.6	<0.1	2.4

2.1.3 Fishery and survey selectivity and retention

Selectivity and retention determine the age composition of fishery mortality and ensure the removal of appropriate numbers-at-age from the population when mortality occurs in the annual time-step. Selectivity represents the proportion at each age that is captured by the gear. Retention represents the proportions-at-age that are retained and landed if caught (i.e., 1 - retention is the proportion-at-age that is released). The product of selectivity and retention is called the “keep curve” and represents the proportions-at-age from the population that are landed. Some fish that are not retained may survive; thus, a discard mortality rate is used to indicate the proportion of fish that are not retained and die after release.

Retention is not modelled specifically at this time because directed commercial discard mortality is modelled as a separate sector, and discard mortality for other sectors is included in the total mortality for those sectors. Parameters for selectivity when conditioning models were determined from the estimated parameters from the long AAF model in the recent stock assessment (IPHC-2020-SA-01) including annual deviations in selectivity for the directed fisheries and the survey. These parameters could be modified as necessary to improve fits to data and to reflect differences in implied availability of a spatially explicit model compared to the coastwide stock assessment, but were not at this time.

2.1.4 Weight-at-age

Empirical weight-at-age by region for the population, fisheries, and survey are determined using observations from the FISS and the fisheries, as is done with the stock assessment models (IPHC-2020-SA-02) and as described in detail in Stewart and Martell (2016). Smoothed observations of weight-at-age from NMFS trawl surveys were used to augment weight-at-age for ages 1–6 in the fishery sectors and survey. Population weight-at-age is smoothed across years to reduce observation error. Finally, survey and population weight-at-age prior to 1997 is scaled to fishery data because survey observations are limited if present at all.

Table 2. The thirty-three fisheries in the OM, the IPHC Regulatory Areas they are composed of, and the 2019 mortality (millions of net pounds and tonnes) for each.

Fishery	IPHC Regulatory Areas	2019 Mortality Mlbs	2019 Mortality tonnes
Directed Commercial2A	2A	0.89	404
Directed Commercial 2B	2B	5.22	2,368
Directed Commercial 2C	2C	3.67	1,665
Directed Commercial 3A	3A	8.16	3,701
Directed Commercial 3B	3B	2.31	1,048
Directed Commercial 4A	4A	1.45	658
Directed Commercial 4B*	4B	1.00	454
Directed Commercial 4CDE	4CDE	1.65	748
Directed Commercial Discards 2A	2A	0.03	14
Directed Commercial Discards 2B	2B	0.13	59
Directed Commercial Discards 2C	2C	0.06	27
Directed Commercial Discards 3A	3A	0.32	145
Directed Commercial Discards 3B	3B	0.15	68
Directed Commercial Discards 4A	4A	0.09	41
Directed Commercial Discards 4B	4B	0.03	14
Directed Commercial Discards 4CDE	4CDE	0.07	32
Non-directed Commercial Discards 2A	2A	0.13	59
Non-directed Commercial Discards 2B	2B	0.24	109
Non-directed Commercial Discards 2C	2C	0.09	41
Non-directed Commercial Discards 3A	3A	1.65	748
Non-directed Commercial Discards 3B	3B	0.48	218
Non-directed Commercial Discards 4A	4A	0.35	159
Non-directed Commercial Discards 4CDE	4CDE	3.50	1,588
Non-directed Commercial Discards 4B	4B	0.15	68
Recreational 2B	2B	0.86	390
Recreational 2C	2C	1.89	857
Recreational 3A	3A	3.69	1,674
Subsistence 2B	2B	0.41	186
Subsistence 2C	2C	0.37	168
Subsistence 3A	3A	0.19	86
Recreational/Subsistence 2A	2A	0.48	218
Recreational/Subsistence 3B	3B	0.02	9
Recreational/Subsistence 4	4A, 4CDE	0.06	27

*The small amount of recreational and subsistence mortality from IPHC Regulatory Area 4B is included in Directed Commercial 4B

2.1.5 Movement

Many data sources are available to inform Pacific halibut movement. Decades of tagging studies and observations have shown that important migrations characterize both the juvenile and adult stages and apply across all regulatory areas. The conceptual model of halibut ontogenetic and seasonal migration, including main spawning and nursery grounds, as per the most current knowledge, was presented in IPHC-2019-MSAB014-08 and was used to assist in parameterizing movement rates in the OM.

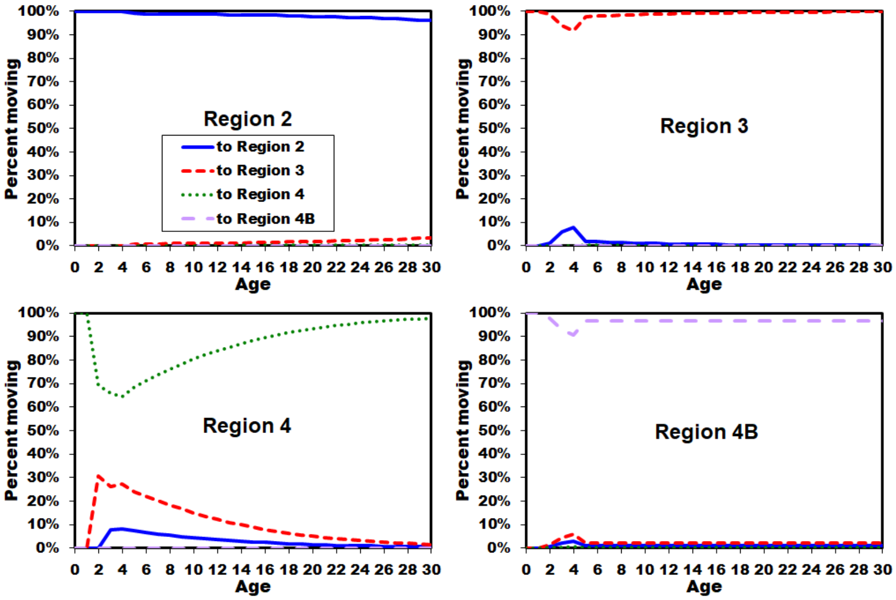


Figure 3. Estimated aggregate annual movement rates by age from Biological Regions (panels) based on currently available data (from IPHC-2019-AM095-08).

In 2015, the many sources of information were assembled into a single framework representing the IPHC's best available information regarding movement-at-age among Biological Regions. Key assumptions in constructing this hypothesis included:

- ages 0-1 do not move (most of the young Pacific halibut reported in Hilborn et al. (1995) were aged 2-4),
- movement generally increases from ages 2-4,
- age-2 Pacific halibut cannot move from Region 4 to Region 2 in a single year, and
- relative movement rates of Pacific halibut of age 2-4 to/from Region 4 are similar to those observed for 2-4-year-old Pacific halibut in Region 3, relative to older Pacific halibut.

Based on these assumptions, appreciable emigration is estimated to occur from Region 4, decreasing with age. Pacific halibut age-2 to age-4 move from Region 3 to Region 2 and from Region 4B to Regions 3 and 2, and some movement of older Pacific halibut is estimated to occur from Region 2 back to Region 3 (Figure 3).

The conceptual model and assembled movement rates were used to inform the development of the MSE operating model framework and were used as a starting point to incorporate variability and alternative movement hypotheses in Pacific halibut movement dynamics. Movement in the OM is modelled using a transition matrix as the proportion of individuals that move from one Biological Region to another for each age class in each year.

The transition matrix with movement probabilities from one region to another (including staying in the region of origin) can either be entered directly or parameterized using several functional forms. Current functional forms include *constant*, *exponential*, and *double exponential*, as shown in equations 1-4, and can closely mimic the movement probabilities described in IPHC-2019-AM095-08 that are based on data.

Constant

$$\omega_{a|j\to k} = \begin{cases} 0 & a \le lastAge0 \\ c & a > lastAge0 \end{cases} \tag{1}$$

Exponential

$$\omega_{a|j\to k} = \begin{cases} 0 & a \le lastAge0 \\ \dfrac{e^{\lambda(a-lastAge0+1)}}{\max(\omega_{a|j\to k})} \times (\gamma_2 - \gamma_1) & a > lastAge0 \end{cases} \tag{2}$$

Double-exponential

$$\omega_{a|j\to k} = \begin{cases} 0 & a \le lastAge0 \\ \dfrac{e^{\lambda(a-lastAge0)} - 1}{\max(\omega_{a|j\to k})} \times \gamma_2 & lastAge0 < a < peak \\ (\gamma_2 - \alpha)e^{-\lambda(a-lastAge0+1)} + \alpha & a > peak \end{cases} \tag{3}$$

Values

$$\omega_{a|j\to k} = \begin{cases} v_a & a \le lastAge \\ v_{lastAge} & a > lastAge \end{cases} \tag{4}$$

where $lastAge0$ is the oldest age with a movement probability of zero before the first non-zero movement probability, α is the asymptote, γ_1 is the minimum probability in that range of ages, and γ_2 is the maximum probability in that range of ages. These parameters are used to scale the relationship to the appropriate range and λ determines the rate of increase or decrease.

These parameterizations overcome an impediment identified in the development of the spatially explicit stock assessment model using stock synthesis. The functional forms allow for efficient and easy modifications to input files to depart from the estimated movement rates based on data, which occurs when conditioning the models. This is useful because there are many assumptions in the estimates, especially for young ages, and the OM will need to include uncertainty as well as possibly time-varying aspects.

2.1.6 Maturity

Spawning biomass for Pacific halibut is currently calculated from weight-at-age and a maturity-at-age ogive that is assumed to be constant over years. There is currently no evidence (IPHC-2020-SA-02) for skip spawning or maternal effects (increased reproductive output or offspring survival for larger/older females) and therefore are not modelled, but could be added. Stewart & Hicks (2017) examined the sensitivity of the estimated biomass to a trend in declining spawning potential (caused by a shift in maturity or increased skip spawning) and found that under that condition there was a bias in both scale and trend of recent estimated spawning biomass. The

SRB document IPHC-2020-SRB016-07 tested maternal effects on estimates of recruitment and concluded “there appears to be no evidence in the current data that the addition of a simple age-based maternal effects relationship improves the ability of the current stock assessment models to explain the time-series of estimated recruitments.” Ongoing research on maturity and skip spawning will help to inform future implementations of the basis for and variability in the determination of spawning output.

2.1.7 Uncertainty and variability in the operating model

Uncertainty and variability are important to consider, as the goal of an MSE is to develop management procedures that are robust to both. The OM should simulate potential states of the population in the future, uncertainties within the management procedure, and variability when implementing the management procedure.

2.1.7.1 Uncertainty in the conditioned OM

The conditioned OM is a representation of the Pacific halibut population and matches observations from the fishery, survey, and research. Uncertainty in these observations are included in the OM by varying parameters in two different ways. First, parameters vary between simulated trajectories and are drawn from correlated probability distributions that are derived from estimation procedures (e.g., the stock assessment). Second, specific parameters are fixed at different values representing potential states. Trajectories may be simulated using both methods and then integrated appropriately to produce distributions of potential outcomes. At this time, the second method of fixing specific parameters at alternative values is not being used but can easily be implemented in the future.

Table 3: Major sources of parameter uncertainty and variability in the conditioned operating model (OM).

Process	**Uncertainty**
Natural Mortality (M)	Variability determined from assessment
Average recruitment (R_0)	Effect of the coastwide environmental regime shift and variability determined from conditioning
Recruitment	Random lognormal deviations. Variability on distribution to Biological Regions determined from conditioning
Movement	Change in parameters synchronized with PDO regime shift

2.1.7.2 Projected population variability

Variability in the projected population is a result of initializing the population with a range of parameters to recreate a range of historical trajectories and including additional variability in certain population processes in the projection. The major sources of variability in the projections are shown in Table 4 and some are described in more detail below.

Table 4: Major sources of projected variability in the operating model (OM).

Process	**Variability**
Average recruitment (R_0)	Effect of the coastwide environmental regime shift, modelled as an autocorrelated indicator based on properties of the PDO
Recruitment	Random lognormal deviations. Variability on distribution to Biological Regions.
Movement	Variability on movement parameters determined from conditioning process
Size-at-age	Annual and cohort deviations in weight-at-age by Biological Region, with approximate historical bounds
Sector mortality	Sector mortality allocation variability on non-directed commercial discard mortality, directed discard mortality, and unguided recreational mortality within an area
Movement	Change in parameters synchronized with PDO regime shift

2.1.7.3 Linkage between average coastwide recruitment and environmental conditions

The average recruitment (R_0) is related to the Pacific Decadal Oscillation index[1], expressed as a positive or negative regime (IPHC-2020-SA-02). R_0 is multiplied by $e^{I\delta}$, where I is an indicator of the negative (0) or positive (1) regime, and δ is a parameter determining the magnitude of that multiplier. The parameter δ, and uncertainty, was determined from the stock assessment.

The regime was simulated in the MSE by generating a 0 or 1 to indicate the regime of each future year, as described in IPHC-2018-MSAB011-08. To encourage regimes between 15 and 30 years in length (assuming a common periodicity, although recent years have suggested less), the environmental index was simulated as a semi-Markov process, where each subsequent year depends on recent years. However, the probability of changing to the opposite regime was a function of the length of the current regime, with a change probability equal to 0.5 at 30 years, and a probability near 1 at 40 or greater years. This default parameterization results in simulated regime lengths most often between 20 and 30 years, with occasional runs between 5 and 20 years or greater than 30 years. However, this can be modified to test other scenarios.

2.1.7.4 Projected weight-at-age

Weight-at-age varies over time historically, and the projections capture that variation using a random walk from the previous year. 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 was implemented using the same ideas as in the coastwide MSE (IPHC-2018-MSAB011-08), but was modified to incorporate autocorrelation in a more straightforward manner, and allow for slight departures between regions and fisheries.

The method used to simulate weight-at-age was described in IPHC-2020-SRB016-08 Rev1. Two example projections are shown in Figure 4.

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[1] https://oceanview.pfeg.noaa.gov/erddap/tabledap/cciea_OC_PDO.htmlTable?time,PDO

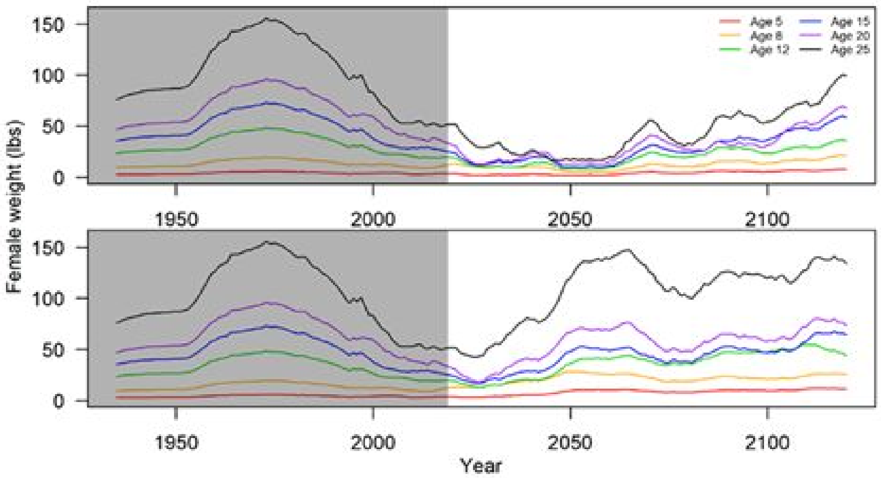

Figure 4: Past observed (shaded area) and two examples of possible one-hundred-year projections of weight at ages 5, 8, 12, 15, 20, and 25.

2.2 Management Procedures for coastwide scale and distribution of the TCEY

The management procedure consists of three elements (Figure 2). Monitoring (data generation) is the code that simulates the data from the operating model that are used by the estimation model as well as O32 or all-sizes stock distribution, which is needed for the distribution procedure. It simulates the sampling process and can introduce variability, bias, and any other properties that are desired. The Estimation Model (EM) is analogous to the stock assessment and includes estimation error in the simulation. Using the data generated, it produces an annual estimate of stock size and status and provides the advice for setting the catch levels for the next time step. Two methods were investigated for mimicking the estimation procedures to determine a coastwide total mortality limit, as described below. Finally, the Harvest Rule contains additional procedures when determining the mortality limits, such as the application of a control rule and distribution of the limits to IPHC Regulatory Areas.

The first EM was to use an approach to simulate estimation error, as was done in the coastwide MSE. The OM determines the stock status and the TM consistent with the input fishing intensity (i.e., F_{SPR}). Correlated deviates randomly generated with a bivariate normal distribution including an autocorrelation of 0.4 with previous deviates was applied to the stock status and TM. Details of this method can be found in Section 4.2.2. of IPHC-2018-SRB012-08. This method is useful to provide perfect information, bridge the multi-region MSE to the coastwide MSE, and speed up simulations while providing a reasonable approximation of the assessment process. Additionally, it may be used to test the effects of different levels of estimation error.

A second approach was to use estimation models based on stock synthesis (SS). Initial investigations showed biases with the models as additional data were added. The assessment models that these EMs were based on are complicated and developed for short-term forecasts using currently available data. Increasing the number of years of data in the models, possibly not simulated with the exact processes that the assessment was tuned to, can cause the models to perform less than optimal. However, the use of EMs based on the assessment models provides a more accurate representation of the assessment process and of the bias associated with it. Additional details are described below.

2.2.1 Estimation models using stock synthesis

The short and long coastwide models used in the ensemble stock assessment require between one and seven minutes to estimate parameters without a Hessian. Two approaches were used to speed up these two estimation models for use in the MSE simulations: reducing the reading time and reducing the computation time.

To reduce the reading time, the amount of data included in the model was reduced compared to the full assessment, while ensuring similar trajectories in the estimated quantities such as spawning stock biomass, exploitation and virgin biomass. Once this condition was met, the trend in dynamic B0 for the most recent period and the forecasted TM were also verified. The number of years of age composition data was shortened, and for each additional year of age data added during the projection period, an early year in the time series was removed. A minimum of at least 50 years of age composition for the directed commercial fleet is required before the removal of historical data begins. For the long coastwide estimation model, only the beginning of the CPUE time series was maintained, removing all subsequent years starting from 1994. Additionally, the start year of the long coastwide estimation model was set to 1935 instead of 1888.

The major change to the data is the use of an absolute index of abundance to replace the NPUE from the survey. The index is generated with error from the numbers at age and the survey selectivity at age for the whole time series. The catchability is fixed to 1.

To reduce the computation time, the ‘opt’ (optimized) version of stock synthesis was used, and the number of estimated parameters was reduced, mostly by removing some time-varying options. The remaining annual deviations in selectivity parameters were fixed at the values estimated by the original assessment model, and only the deviations for the most recent 10 or 20 years (depending on the parameter) were left free to be estimated. In the first projected year, optimization was initiated using the parameters estimated by this streamlined version of the assessment model (i.e., the ‘ss.par’ file). For each subsequent year in the projection, the ‘ss.par’ file from the previous year was used, manually adding one extra parameter where necessary. The parameter estimation was also set to start from the last phase.

Finally, the convergence criterion was set to 0.1, the Hessian was not estimated (therefore uncertainty is not calculated), and the amount of information printed on screen was reduced to a minimum. The number of iterations for a model to reach convergence was fixed to a maximum of 800. If the model did not converge after 800 iterations (i.e., convergence > 0.1), the initial value for the R0 parameter was increased by 5% and the model was restarted. If the model still did not converge, it was restarted for a third time, but estimation was started from phase 1. The replacement of the NPUE with an absolute index of abundance has reduced the computation time of both models and initial investigations did not show any convergence issues.

For each OM, data for the historical period were generated and input files for both the short and long coastwide assessment models were created, so to have each set of estimation models consistent with the historical period of the correspondent OM. The initial parameter files used are the same across all simulations.

The observation model generates the data for the EMs during projections from the OM with error. In particular, deviates to the absolute index of abundance and the stock distribution are generated by region from a lognormal distribution with standard deviation equal to the average standard error by region from the last 5 years. Age composition data are simulated using a Dirichlet distribution. The nominal sample size is used as the scale parameter of the Dirichlet distribution, to control the variance of the distribution, i.e. a higher sample size implies lower variance. The nominal sample size is generated using an average fixed proportion of the sector mortality. The resulting sample size values are bounded between a minimum and a maximum which varies between sectors: these limits have been chosen looking at the historical minimum and maximum sample size and help both to stabilize the EMs, as well as to avoid unrealistic distribution in the simulated age composition.

The two estimation models are called in parallel from an R script that is called by the C++ OM code.

2.2.2 Harvest rule and distribution procedures

The harvest rule for distributing the TCEY begins with the coastwide TCEY determined from the stock assessment and fishing intensity defined by the reference SPR (with application of the control rule). Figure 5 is an illustration of the harvest strategy policy at IPHC, which includes the harvest rule as part of the management procedure. The TCEY may be distributed to Biological Regions first and then to IPHC Regulatory Areas, or directly to IPHC Regulatory Areas. Relative adjustments can be applied in each step of the distribution process. Typically, the distribution procedure does not appreciably alter the coastwide fishing intensity (although a slight change may occur due to different selectivity patterns accessing the population), however there is interest in management procedures that are only limited to being less than a maximum fishing intensity (i.e., above a minimum SPR) that would account for modifications in the TM during the distribution procedures.

The Coastwide TCEY is calculated from the TM by removing the U26 portion of the non-directed discard mortality, which is approximated by a fixed length-at-age key determined from historical observations applied to non-directed discard mortality observed the previous year.

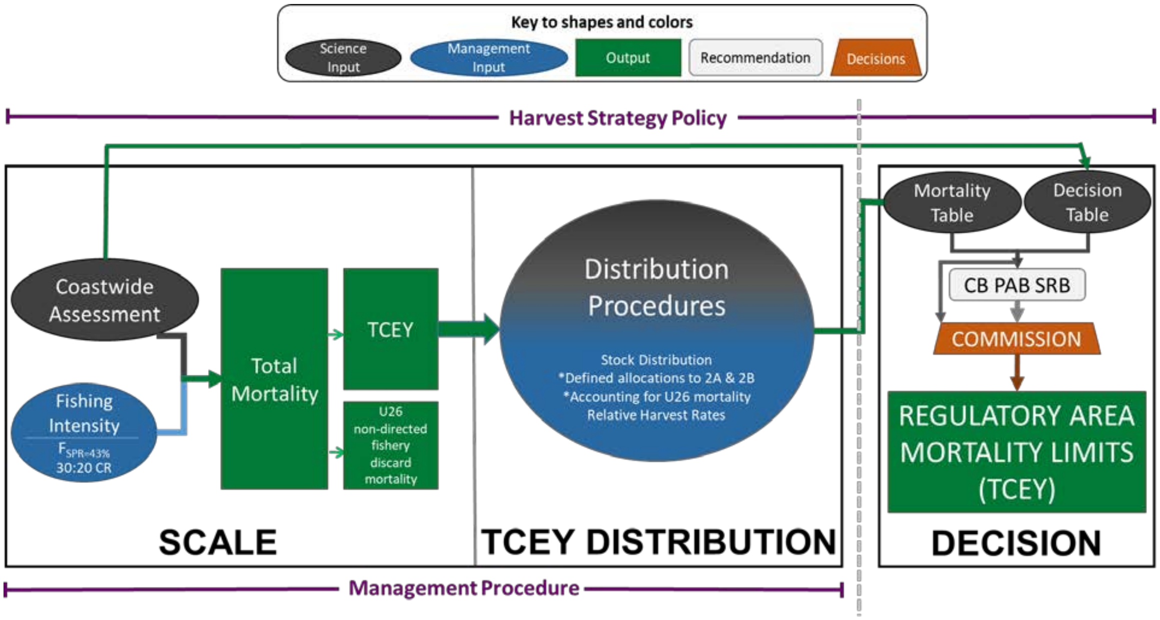

Figure 5: Illustration of the Commission interim IPHC harvest strategy policy (reflecting paragraph ID002 in IPHC CIRCULAR 2020-007) showing the coastwide scale and TCEY distribution components that comprise the management procedure. Items with an asterisk are three-year interim agreements to 2022. The decision component is the Commission decision-making procedure, which considers inputs from many sources.

The MSAB has defined coastwide and distribution elements of management procedures that are important for future evaluation, including the following listed in paragraph 42 of IPHC-2020-MSAB015-R.

> ***IPHC-2020-MSAB015-R, para. 42****.The MSAB* ***AGREED*** *that the following elements of interest for defining constraints on changes in the TCEY, and distribution procedures be considered for the Program of Work in 2020:*
>
> a) *constraints on the change in the TCEY can be applied annually or over multiple years at the coastwide or IPHC Regulatory Area level. Constraints on the change in TCEY currently considered include a maximum annual change in the TCEY of 15%, a slow-up fast down approach, multi-year mortality limits, and multi-year averages on abundance indices;*
>
> b) *indices of abundance in Biological Regions or IPHC Regulatory Area (e.g. O32 or All sizes from modelled survey results);*
>
> c) *a minimum TCEY for an IPHC Regulatory Area;*
>
> d) *defined shares by Biological Region, Management Zone, or IPHC Regulatory Area;*
>
> e) *maximum coastwide fishing intensity (e.g. SPR equal to 36% or 40%) not to be exceeded when distributing the TCEY;*
>
> f) *relative harvest rates between Biological Regions or IPHC Regulatory Areas.*

At MSAB014 and MSAB015, elements specifying candidate management procedures were defined for simulation and subsequent evaluation (Table II.1 in Appendix II, reproduced from IPHC-2020-MSAB015-R).

The estimated values from the data generation and estimation model/estimation error steps are used in the application of the harvest rule to determine mortality limits by IPHC Regulatory Area. The simulated application of the harvest rule will therefore include errors in the status as well as the size of the population, both of which will be propagated into management quantities.

2.2.3 Allocating simulated total mortality to sectors

The outputs of the management procedure are TCEY limits for each IPHC Regulatory Area, which then need to be allocated to the different sectors specific to the IPHC Regulatory Area. See Table 2 for a complete list of the fishing sectors by IPHC Regulatory Area.

There are two parts to the allocation procedure: the calculation of the upcoming mortality limits by sector, and the calculation of the realized mortality by sector. The calculation of mortality limits is necessary because some sector's mortality limits are determined from the limits for other sectors. In the current framework, the calculation of the realized mortality differs from the calculation of the mortality limits for the non-directed discard, directed discard, subsistence, and unguided recreational mortalities. Mortality limits and realized mortality for the recreational and directed commercial sectors are assumed to be equal (i.e., no implementation error for these sectors).

The allocation procedure begins by subtracting the non-directed commercial O26 discard mortality by IPHC Regulatory Area from the corresponding IPHC Regulatory Area TCEY. The remainder is referred to as the directed TCEY for convenience (it is not used as a management quantity). The directed TCEY is then allocated to directed fishery sectors. Each IPHC Regulatory Area has a unique catch-sharing plan (CSP) or allocation procedure, and these CSPs were matched as closely as possible. When the TCEY for an IPHC Regulatory Area is low, the CSP may deteriorate and alternative decisions may be necessary. It is unknown what the allocation procedure may be at low TCEYs, so working with MSAB members, an appropriate assumption will be made. One simple assumption is to assume that the sum of the directed non-FCEY components would not exceed the directed TCEY, and the FCEY components would be set to zero.

Non-directed commercial discard mortality: the O26 component of the non-directed discard mortality limit is calculated as an average of the previous three years non-directed discard mortality for each IPHC Regulatory Area. However, the realized non-directed discard mortality is determined from a linear relationship between the non-directed discard mortality by region and the total biomass in that region. Given changes in non-directed commercial discard mortality in recent years the fit was forced through the last observed year (2019). The realized non-directed discard mortality was then randomly drawn from the value determined from total biomass by region using a log normal distribution with a 20% CV (Figure 6). The non-directed commercial discard mortality by region is then distributed to IPHC Regulatory Area using the proportion of non-directed commercial discard mortality recently observed in each IPHC Regulatory Area.

Directed commercial discard mortality: directed commercial discard mortality limits are calculated using the ratio of directed discard mortality to directed commercial mortality from the previous year. The realized directed discard mortality is modelled as a function of the directed commercial plus directed discard mortality and the weight at age 8 for a male Pacific halibut. The resulting proportion of directed discard mortality relative to different values of the commercial plus directed discard mortality is shown in Figure 7. A minimum of 0.05% of directed discard mortality over commercial plus directed discard mortality is applied.

Subsistence: subsistence mortality limits are set equal to the values observed in the previous year, except for IPHC Regulatory Area 2A, for which the subsistence value is set to 30,000 pounds (13.6 t). The realized subsistence mortality is randomly drawn from a lognormal distribution with a median equal to the limit subsistence mortality and a CV of 15%. The coastwide subsistence is then compared to the coastwide TCEY: if the allocation to the subsistence sector is higher than half of the overall TCEY, then the subsistence mortality in each regulatory area is adjusted so that the coastwide value will not exceed 50% of the coastwide TCEY.

Unguided recreational mortality: unguided recreational mortality is relevant only for IPHC Regulatory Areas 2C and 3A and it is randomly drawn from a lognormal distribution with a median equal to an average historical value (1.257 Mlb or 570 t for 2C and 1.579 Mlb or 716 t for 3A) and a 5% CV.

Recreational mortality: recreational mortality follows the catch sharing plans (CSPs) for IPHC Regulatory Areas in Region 2 and IPHC Regulatory Area 3A, noting that guided recreational mortality limits are only under the CSP in IPHC Regulatory Areas 2C and 3A and the total recreational mortality is the sum of guided and unguided. In IPHC Regulatory Areas 3B, 4A, 4B, and 4CDE, recreational mortality is included with subsistence because almost negligible.

Commercial mortality: is the remainder of the total mortality after subtracting all other sources of mortality.

Figure 8 and Figure 9 illustrate the results of the allocation procedure for each IPHC Regulatory Area when non-directed commercial discard mortality and unguided recreational are held constant at an average value. The recreational and subsistence allocations for IPHC Regulatory Areas 4A and 4CDE are fixed at low values and aggregated to Biological Region in the OM. For this reason, these two sectors are not shown in Figure 9.

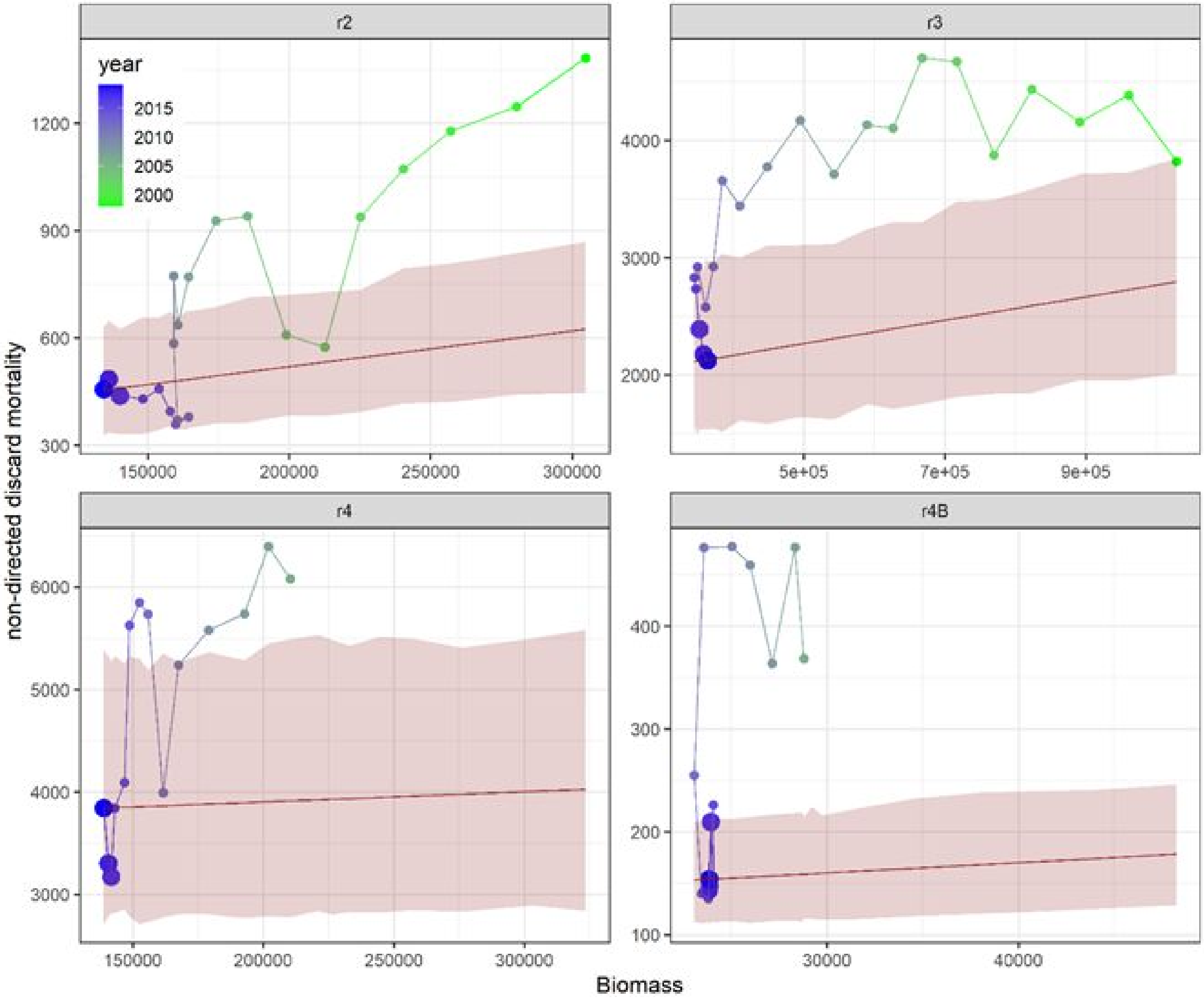

Figure 6: Non-directed commercial discard mortality plotted against total biomass from the conditioned multi-region OM. The colors in the points represent the sequence of time from 1998 to 2019. The years 2017–2019 are represented by larger dots. The red line represents the linear relationship used for predicting the non-directed discard mortality from the biomass. The shaded red area around it represents the 0.05 and 0.95 quantiles of the non-directed discard mortality simulated from a log-normal distribution with a 20% CV.

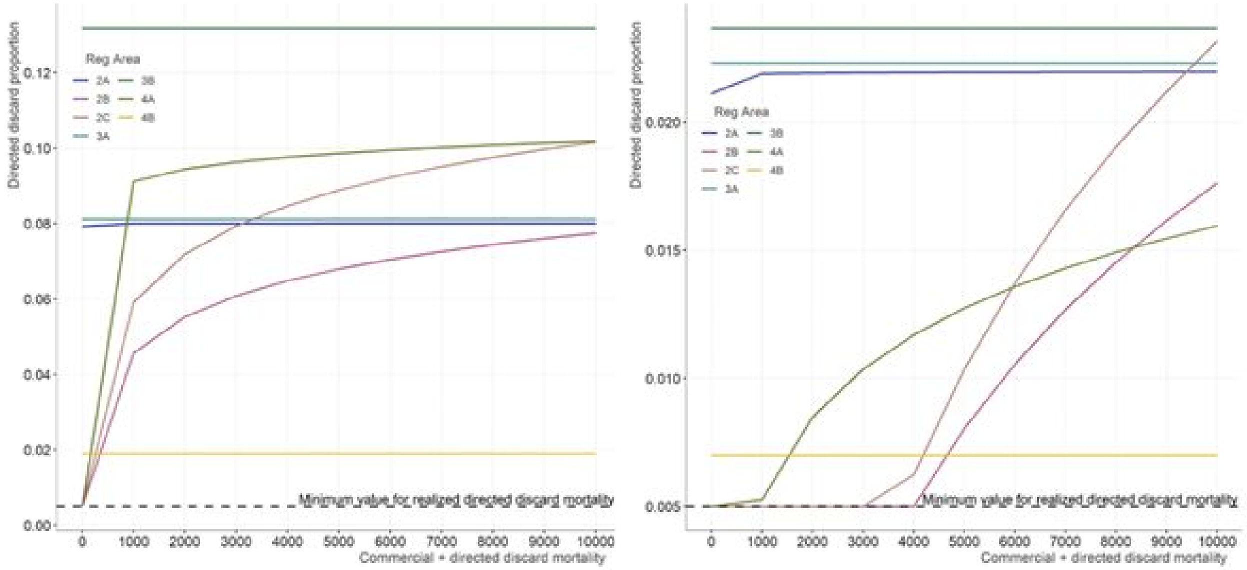

Figure 7: Proportion of directed discard mortality by IPHC Regulatory Area relative to different values of the commercial plus directed discard mortality with a male weight at age 8 equal to 4 lb (left) and 8 lb (right). The dashed line shows the 0.5% minimum.

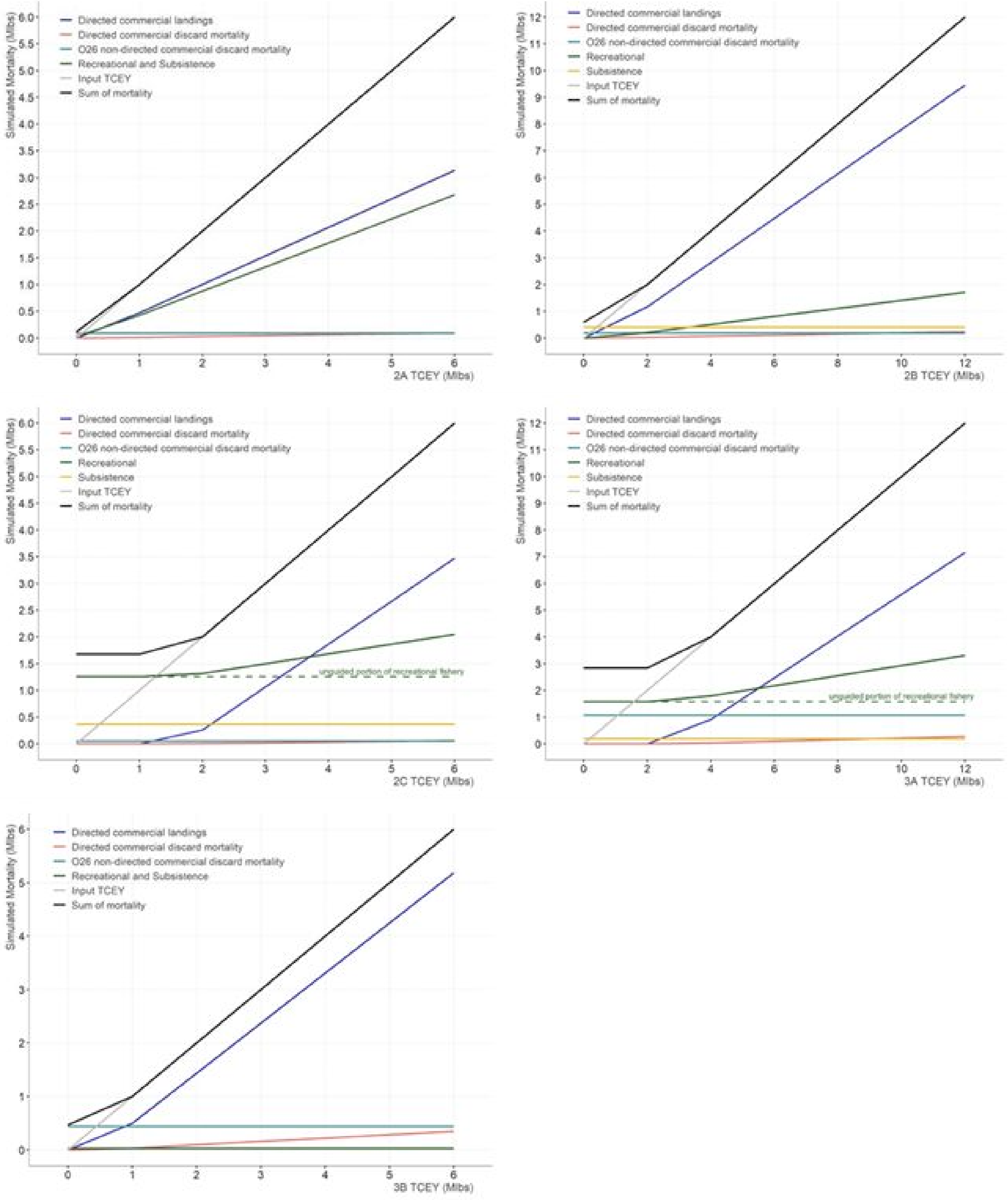

Figure 8: Allocation of the TCEY to sectors for IPHC Regulatory Areas 2A (top left) to 3B (bottom left) when O26 non-directed commercial discard mortality and unguided recreational are is assumed constant at average values. The input TCEY provided to the allocation function is shown in light gray, while the sum of mortalities after allocation is shown in black.

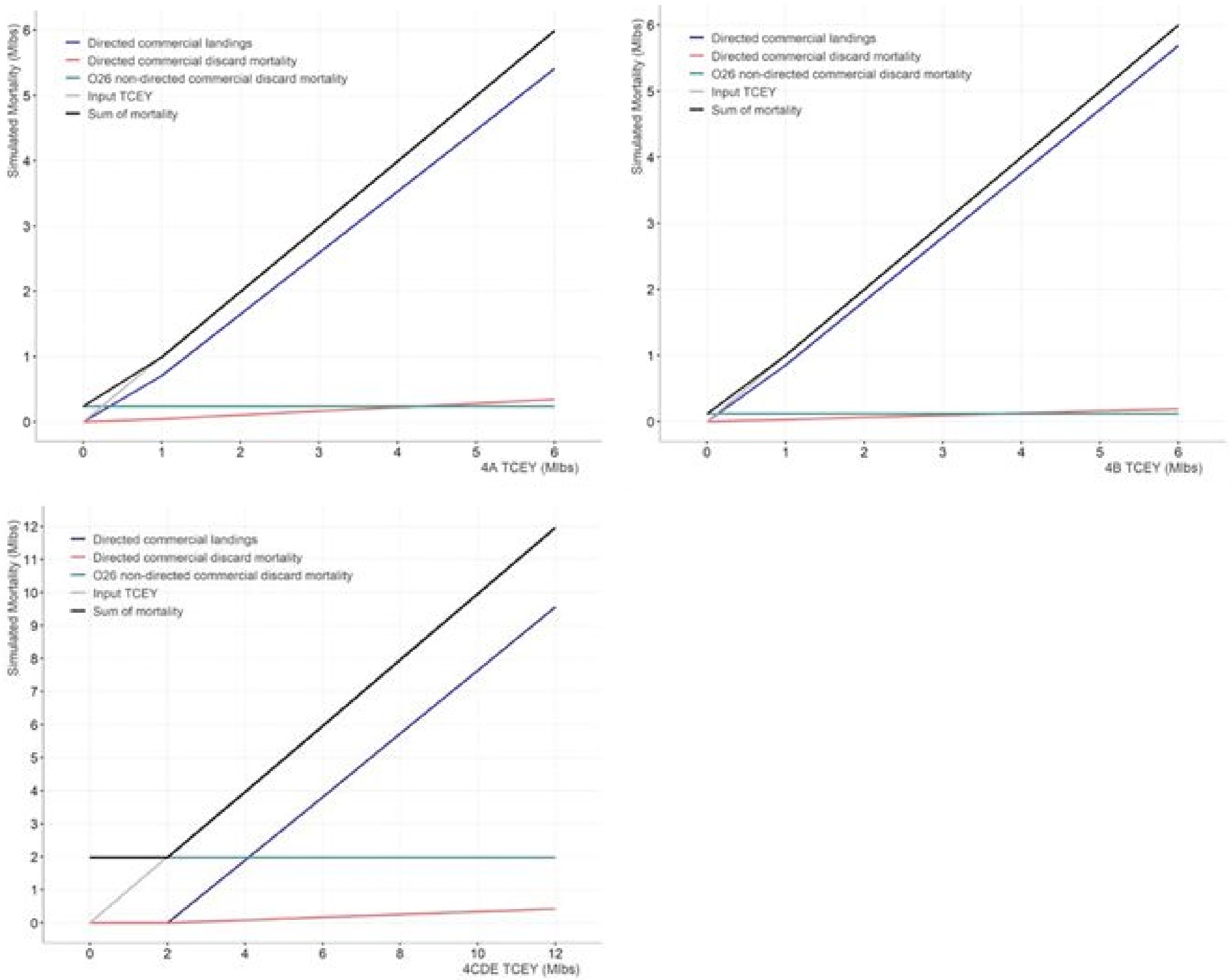

Figure 9: Allocation of the TCEY to sectors for IPHC Regulatory Areas 4A (top left), 4B (top right), and 4CDE (lower left) when O26 non-directed commercial discard mortality is assumed constant at an average value. The input TCEY provided to the allocation function is shown in light gray, while the sum of mortalities after allocation is shown in black.

3 RESULTS

Results of testing the conditioning of a four-region operating model are presented below.

3.1 Four-region operating model

A multi-area OM was specified with four Biological Regions (2, 3, 4, and 4B; Figure 1), thirty-three (33) fisheries (Table 2), and four (4) surveys. The model was initiated in 1888 and initially parameterized using estimates from the long areas-as-fleets (AAF) assessment model. Selectivity was kept the same as the regional estimates from the long AAF assessment model except that the directed commercial and survey selectivities were made asymptotic (i.e., no descending limb) since movement in the spatially explicit OM accounted for availability among the Biological Regions.

Parameters for R0, proportion of recruitment to each Biological Region, movement from 2 to 3, 3 to 2, and 4 to 3 were estimated by minimizing an objective function based on lognormal likelihoods for spawning biomass predictions and region-specific modelled survey indices, robustified multivariate normal likelihoods for the proportion of survey biomass in each region, and observed proportions at age from the FISS. Other movement parameters were fixed to estimates from data (Figure 3) except that movement probabilities from 4 to 2, 2 to 4, 4B to 2, and 2 to 4B were set to zero for all ages. This makes the assumption that a Pacific halibut cannot travel between these areas in an annual time step even though significant probabilities of movement-at-age from 4 to 2 are predicted to occur from the data (Figure 3).

The OM was conditioned using five sets of observations: the average predicted spawning biomass from the long AAF and long coastwide stock assessment models (1888–1992), predicted spawning biomass from the stock assessment ensemble (1993–2019), survey indices of abundance for each Biological Region, survey proportions-at-age for each Biological Region, and the proportion of “all selected sizes” modelled survey biomass in each Biological Region (stock distribution). The lognormal likelihood (assuming that the observed value was the median) was used to fit to the predicted stock assessment spawning biomass and the survey indices.

$$-\ln(L) = \sum \left(\frac{\ln\left({O_y}/{E_y} \right)}{\sigma_y} \right)^2 \tag{5}$$

where O_y is the predicted spawning biomass from the stock assessment, E_y is the predicted spawning biomass from the OM, and σ_y is the standard deviation of the stock assessment spawning biomass on a natural log scale calculated as $\sigma_y = \sqrt{ln(1+cv^2)}$.

A robustified multivariate normal (Fournier et al 1990, Starr et al 1999) was used to fit to the survey proportions-at-age and the regional stock distribution estimates.

$$-\ln(L) = -\sum \ln\left[\exp\left(\frac{-\left(O_y - E_y\right)^2}{2O'_y/N'} + 0.01 \right) \right] \tag{6}$$

where $O_y^{'} = (1-O_y)O_y + 0.1/n$ and N' is the effective sample size as entered in the stock assessment (before data weighting). Estimates of uncertainty were available for the proportion of survey biomass in each Biological Region, thus the denominator was the standard deviation instead of O'_y/N'.

A subset of all possible parameters was used for conditioning by estimating the parameters that minimized the summed weighted negative log likelihood components for each observation type. The parameters estimated are listed in Table 5.

Table 5: Descriptions of the parameters estimated when conditioning the OM. Separate sets of parameters were estimated for movement in poor and good PDO regimes.

Parameters	# parameters	Description
$\ln(R_0)$	1	Natural log of unfished equilibrium recruitment. Determines the scale of the population trajectory.
$p^R_{y,r}$	3	Proportion of R_0 distributed to each Biological Region. Only three of the four parameters need to be estimated to sum to 1.
$\Psi_{2\to3}$	5 + 5	Probability of movement-at-age from Region 2 to Region 3, modelled using a double exponential function (equation 3). The left and right λs, left maximum probability, right maximum probability, and right asymptote were estimated.
$\Psi_{3\to2}$	5 + 5	Probability of movement-at-age from Region 3 to Region 2, modelled using a double-exponential function (equation 3). The left and right λs, left maximum probability, right maximum probability, and right asymptote were estimated.
$\Psi_{4\to3}$	5 + 5	Probability of movement-at-age from Region 4 to Region 3, modelled using a double-exponential function (equation 3). The left and right λs, left maximum probability, right maximum probability, and right asymptote were estimated.

The parameters in Table 5 were fit to the five data sources individually to determine similarities and differences in the estimates of parameters and derived quantities that each data source implied. This was done for different parameterizations of movement to understand how changes to the structure affected the fit to the different data sets. Those results (not shown here) identified that fitting to the modelled survey distribution of biomass in each Biological Region was important because fitting to no other single data source resulted in a close prediction of the distribution. Stock distribution is an important component of many management procedures to be tested, thus must be represented accurately by the conditioned OM. Secondly, fitting to index data resulted in predicted spawning biomass trajectories that were generally in the envelope of predicted spawning biomass from the stock assessment models. Index data are an important data source as they reflect trends in abundance by Biological Region. Fitting to proportion-at-age did not greatly improve the overall general trends in recent estimates of proportion-at-age in each region but did result in low predicted spawning biomass. Therefore, the final model was fit to the modelled survey proportion of biomass in each Biological Region, the modelled survey indices of abundance (NPUE) as used in the stock assessment, the estimated spawning biomass from 1888 to 1992 from the two long assessment models, and the estimated spawning biomass from the ensemble assessment from 1993–2019 with each given *ad hoc* weights of 1.0, 0.1, 0.4, and 0.4, respectively, in the joint likelihood.

The predicted spawning biomass fell mostly within the range of estimated spawning biomass from the four stock assessment models in the ensemble (Figure 10). The multi-region operating model predicted a female spawning biomass at the upper part and slightly above the 90% credible interval from about 1930 to 1960 for the long assessment models due to a large amount of predicted total biomass in Biological Regions 3 and 4. The predicted stock distribution matched closely for most years, although the end of the time-series in Biological Regions 2 and 3 and beginning of the time-series in Biological Regions 4 and 4B showed departures. These departures from the observed stock distribution were consistent for all models examined and suggest that the current structural specifications cannot capture these trends.

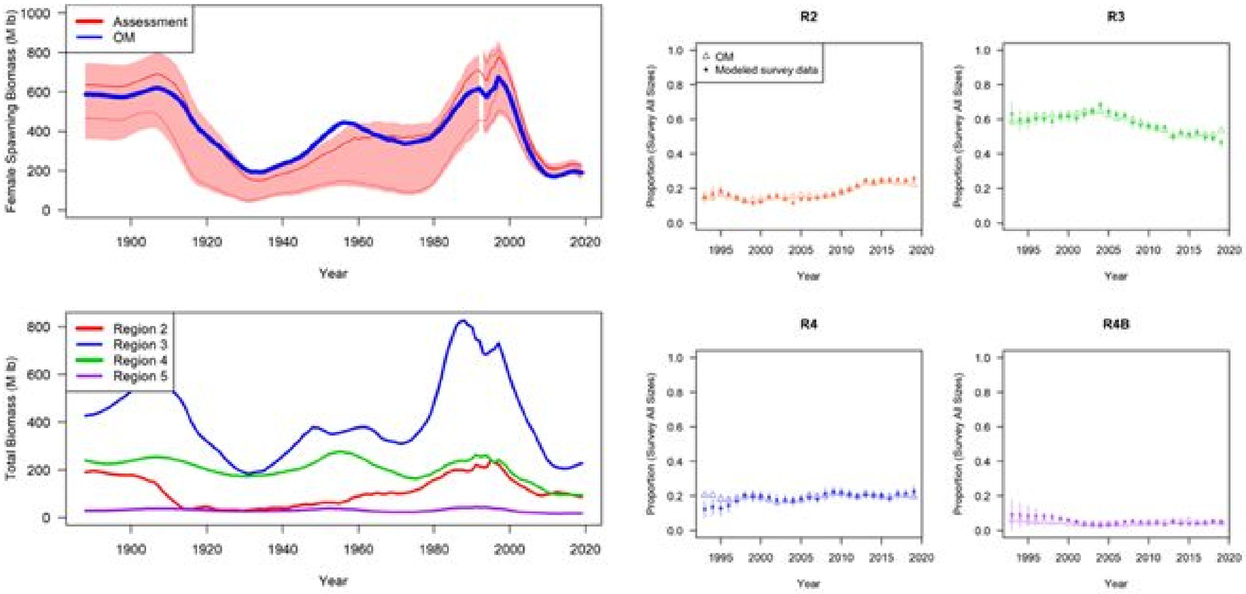

Figure 10: Predicted coastwide spawning biomass (top left), total biomass by Biological Region (bottom left), and the proportion of biomass in each Biological Region (right plots; Region 4B is denoted by "Region 5") from the final OM. The blue line is predicted spawning biomass from the OM and red lines are the predicted spawning biomass from each model in the stock assessment ensemble and the red shaded area in the 90% credible interval from the ensemble stock assessment (top left). The proportion of biomass from the modelled survey results by year and Biological Region (filled circles) with estimated uncertainty are compared to the predicted proportion of biomass from the OM by year and Biological Region in the plots on the right.

Fits to the modelled survey index were reasonable for all Biological Regions, but showed some patterns in residuals in Biological Region 2 (Figure 11). Few models that were examined were able to fit the time-series in Biological Region 2 much better, and those that did show an improved fit had poor fits to stock distribution.

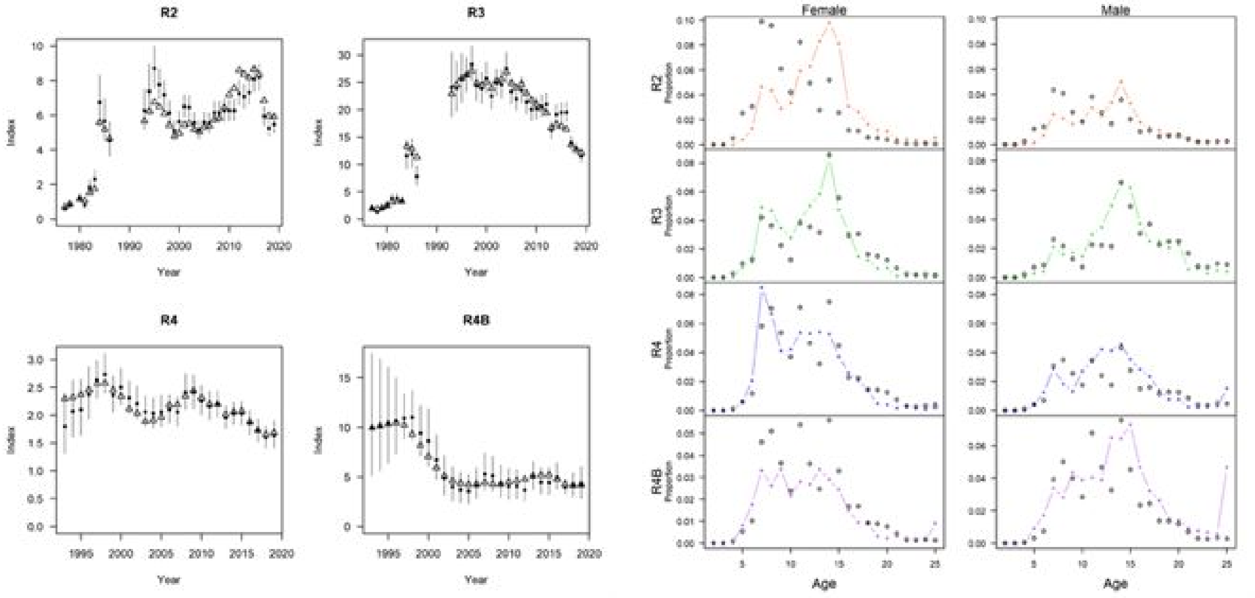

Figure 11: Fits to modelled survey NPUE index data (four panels on the top left), fits to proportions-at-age by sex and Biological Region from the year 2019 (eight panels on the top right), and estimated movement-at-age for the final OM (bottom row). Filled circles in the index plots are modelled survey NPUE with 95% credible intervals and the open triangles are predictions from the final OM. Filled circles connected by lines are the proportions-at-age determined from FISS data and the open circles are predictions from the final OM.

Estimated and assumed movement probabilities-at-age from one Biological Region to another are shown in Figure 12. Movement from 2 to 3 is estimated to be much greater than the data suggest with higher movement of very young fish and lower movement rates of older fish during high PDO regimes. The generally higher movement of older fish from 2 to 3 may be to counter-balance the high movement rates of young fish from 3 to 2. The OM has movement rates near 5% for movement of older fish from 3 to 2. Younger fish tend to move at higher rates from 4 to 3 with little movement once they are age 8 and older. The OM assumes that this is a closed population with no movement in or out of the four Biological Regions, which may explain some of the differences observed from the movement rates based on observations.

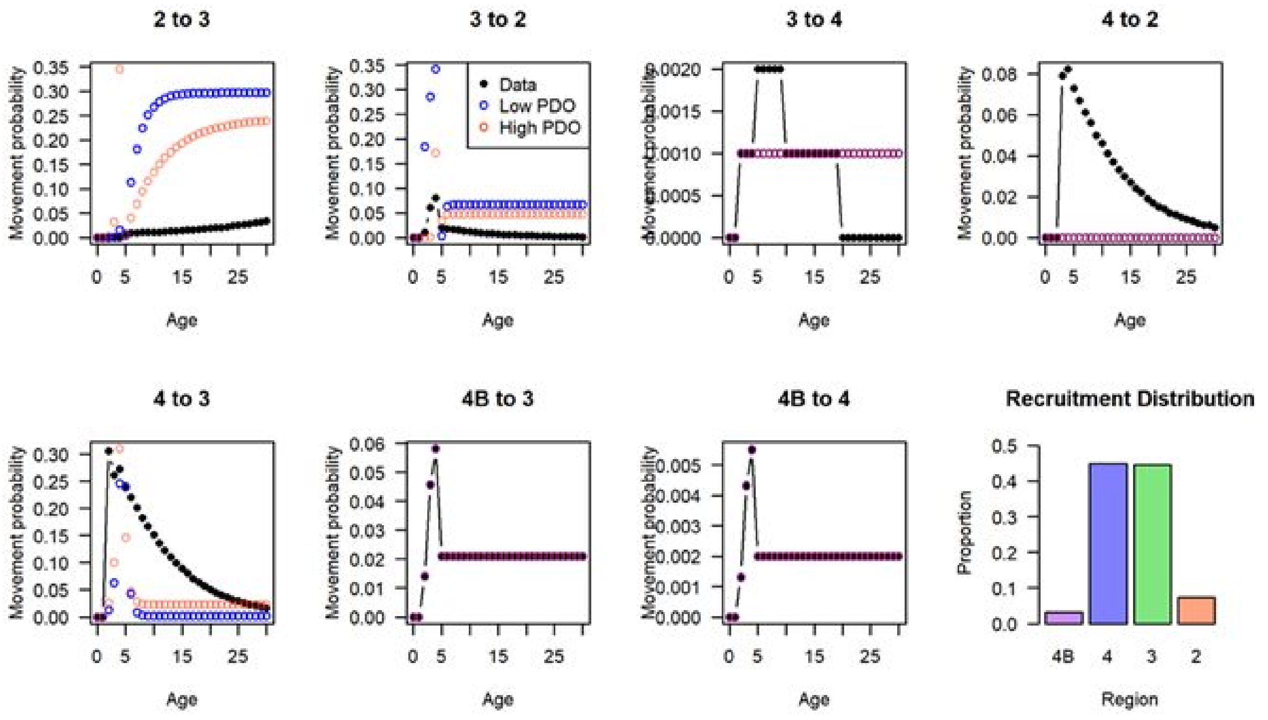

Figure 12: Probabilities of movement-at-age from the data and assumptions (Figure 3) and the conditioned OM (blue and red circles for low and high PDO regimes, respectively). The proportion of recruitment distributed to each Biological Region is shown in the lower right.

The final OM shown here is a reasonable representation of the Pacific halibut population but has some shortcomings. For example, the lack of fit to the 2019 stock distribution in Biological Regions 2 and 3 (Figure 10) and the high predictions of young fish in Biological Region 2 in 2019 (Figure 11). The lack of fit to the proportions-at-age in 2019 are balanced by better fits in previous years (not shown). There are many changes to the model and conditioning process that could be made to potentially improve these fits. For example, movement may be sex-specific, but tagging data are lacking this information.

Overall, the conditioned multi-region model represents the general trends of the Pacific halibut population and is a useful model to simulate the population forward in time and test management strategies.

3.1.1 Uncertainty in the four-region operating model

Uncertainty in population trajectories was captured by adding variability to the parameters of the operating model as specified in Table 3. The correlation matrix estimated from the long AAF model for the R_0, natural mortality (female and male), and recruitment deviations was combined with the correlation matrix for the movement and recruitment distribution parameters as estimated from the conditioning process. The R_0 parameter was estimated in both models and correlations with R_0 were available for all parameters. Otherwise only the correlations for the parameters within a model were available. Parameters were drawn from a multivariate normal distribution to add variability. Correlations and standard deviations for the movement and recruitment distribution parameters were divided by 4 to ensure that the covariance matrix was invertible and to avoid large deviations in movement that may have unknown and undesirable consequences. Hypotheses of movement extremely different than the OM will be investigated through sensitivities and robustness tests.

Fifty trajectories of the OM with parameter variability show a wider range than the 90% credible interval from the ensemble stock assessment (Figure 13). Prior to 1993, the trajectories are in and above the upper portion of the ensemble assessment 90% credible interval, but from 1993 to 2019 the trajectories encompass and extend beyond the credible interval. Therefore, the OM is a reasonable representation of the Pacific halibut population in recent decades and is modelled with variability that will allow for the robust testing of MPs.

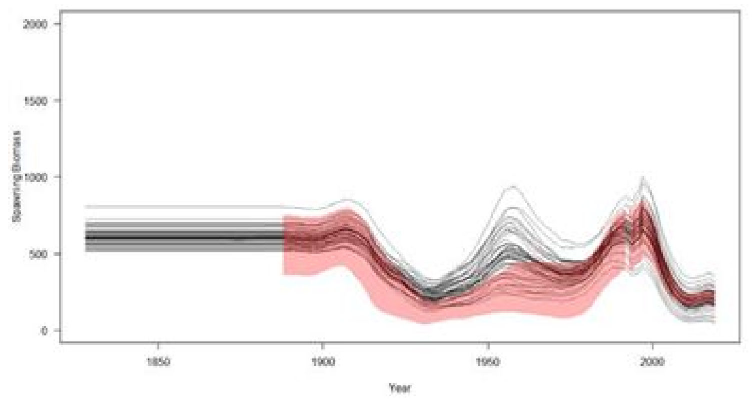

Figure 13: Fifty trajectories of the OM with parameter variability included, shown agains the 90% credible interval of the ensemble stock assessment (two models before 1993 and four models for 1993–2019).

The stock distribution with variability does not show a large departure from the observed stock distribution (Figure 14). The variability is consistent with the observations except at the beginning of the time-series in Biological Region 4 and in 2019 for Biological Regions 2 and 3. The beginning of the time-series in Biological Region 4 was estimated with few data. The recent year may have seen a shift in movement that is not explained by the OM.

Projections with the OM incorporated parameter variability (Table 3) and projection variability (Table 4) produced a wide range of trajectories. Figure 15 shows the median of one-hundred simulations to 2099 without mortality due to fishing along with the interval between the 5th and 95th percentiles. Individual trajectories show that a single trajectory may cover a wide range of that interval in this 80-year period. The variability looks like it has reached its full range after 30 years, although there is an increasing trend near year 2090. This could be due to the small number of simulations and the expected high variability without fishing mortality.

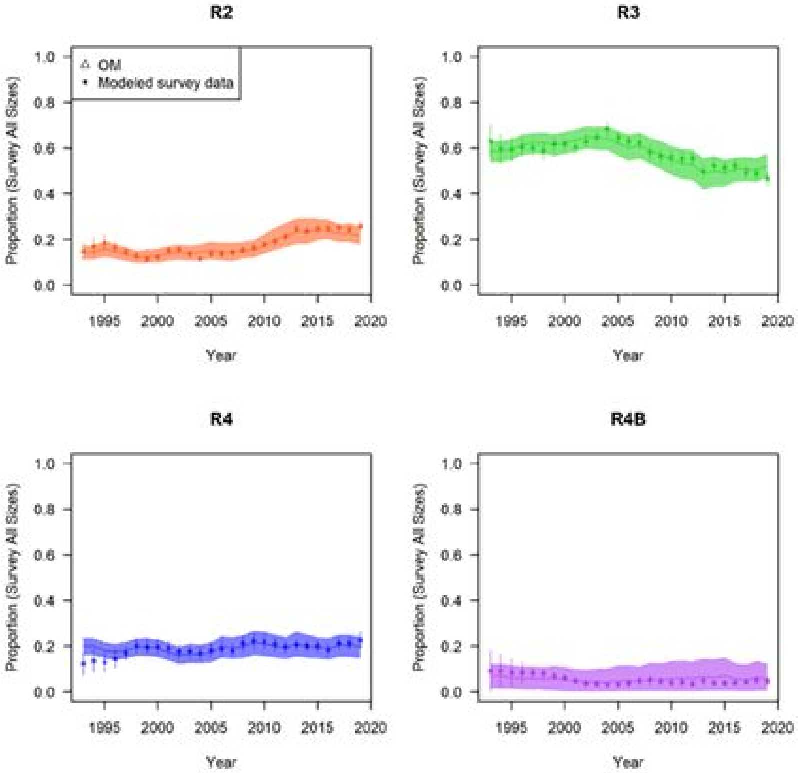

Figure 14: Stock distribution determined from FISS observations (points) and from the OM with variability (shaded areas).

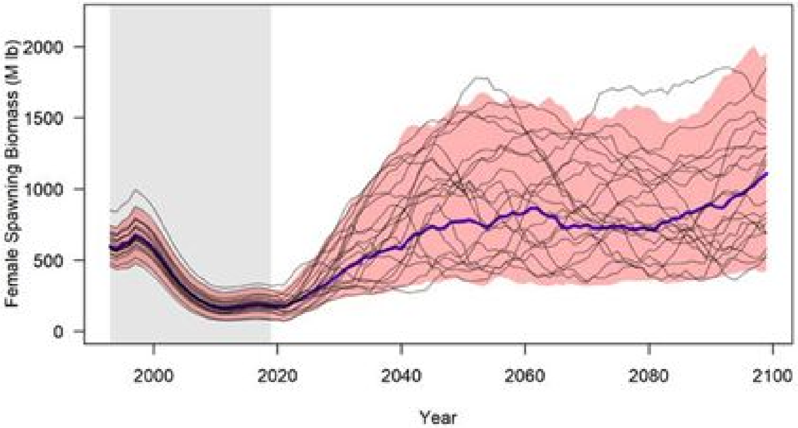

Figure 15: One-hundred simulations for 80 years without fishing mortality. The blue line is the median and the pink shaded area show the interval between the 5th and 95th percentiles. The light shaded grey area between 1993 and 2019 is the historical period, and 2020 has fixed fishing mortality based on the already defined catch limits for 2020. The grey lines are the first 20 individual trajectories.

3.2 Closed-loop simulation results

Simulation results will be made available in a revision of the document.

4 PROGRAM OF WORK

Many important MSE tasks have already been completed; past accomplishments include the following:

1. Familiarization with the MSE process.
2. Defining conservation and fishery goals.
3. Defining objectives and performance metrics for those goals.
4. Developing coast-wide (single-area) and spatial (multiple-area) operating models.
5. Identifying management procedures for the coastwide fishing intensity and distributing the TCEY to IPHC Regulatory Areas.
6. Presentation of results investigating coastwide fishing intensity.

Management Strategy Evaluation is a process that can develop over many years with many iterations. It is also a process that needs monitoring and adjustments to make sure that management procedures are performing adequately. Therefore, the MSE work for Pacific halibut fisheries will be ongoing as new objectives are defined, more complex models are built, and results are updated. This time will include continued consultation with stakeholders and managers via the MSAB meetings, defining and refining goals and objectives, developing alternative operating models, running simulations, and reporting results. Along the way, there will be useful outcomes that may be used to improve existing management and will influence recommendations for future work. Embracing this iterative process, the program of work identifies the tasks to continue to make progress on the investigation of management strategies.

4.1 Five-year program of work

Eight (8) categories have been define in the five-year program of work (Figure 16).

Task 1: Review, update, and further define goals and objectives

Task 2: Develop performance metrics to evaluate objectives

Task 3: Identify realistic management procedures of interest to evaluate

Task 4: Design and code a closed-loop simulation framework

Task 5: Further the development of operating models

Task 6: Run closed-loop simulations and evaluate results

Task 7: Develop tools that will engage stakeholders and facilitate communication

Details of many tasks have not been specified beyond 2021, and the description below focuses on 2020 leading up to the 97th Annual Meeting (AM097) in January 2021.

The first full MSE results incorporating coastwide scale and distribution components of the management procedure (Figure 5) will be presented at the 97th IPHC Annual Meeting (AM097) in January 2021. There are three main tasks to accomplish in 2020: 1) identify management procedures incorporating coastwide and distribution components to simulate, 2) condition a multi-area operating model and prepare a framework for closed-loop simulations, and 3) present results in various ways in order to evaluate the management procedures. These three main tasks are described below and Table 6 identifies the tasks that will be undertaken at each MSAB and SRB meeting in 2020.

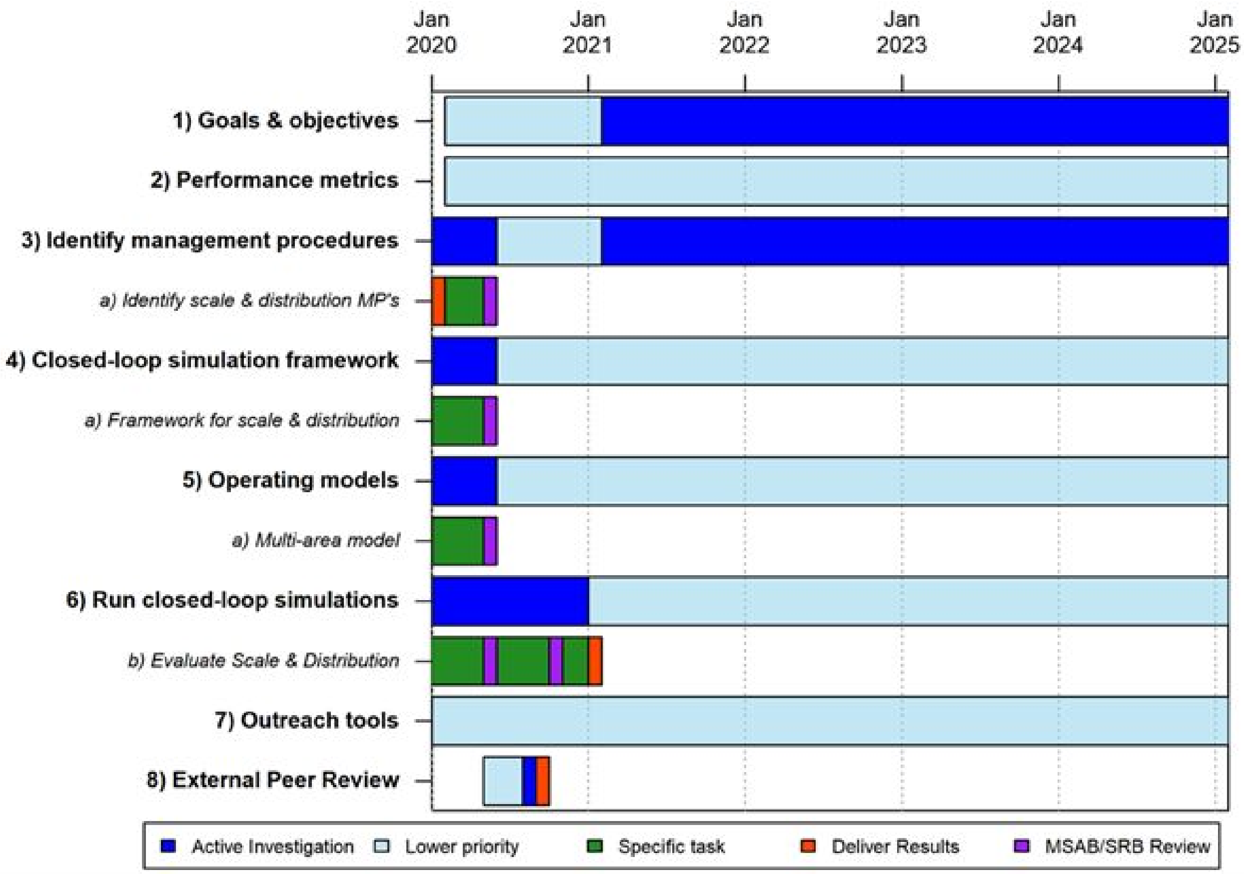

Figure 16: Gantt chart for the five-year work plan. Tasks are listed as rows. Dark blue indicates when the major portion of the main tasks work will be done. Light blue indicates when preliminary or continuing work on the main tasks will be done. Dark green indicates when the work on specific sub-topics will be done. Red areas show when results will be presented to the Commission. Purple areas show when the task will be reviewed by the MSAB and/or the SRB.

Table 6: Tasks to complete in 2020 at the MSAB and SRB meetings.

May 2020 MSAB Meeting (MSAB015)	**Progress**
Review Goals and Objectives (Distribution & Scale)	Completed
Review simulation framework	Completed
Review multi-area model	Completed
Review preliminary results	
Identify MPs (Distribution & Scale)	Completed
June 2020 SRB Meeting (SRB016)	
Review simulation framework	Completed
Review multi-region operating model	Completed
Review preliminary results	
August 2020 MSAB Ad Hoc 03	
Examine preliminary results	Completed
September 2020 SRB Meeting (SRB017)	
Review multi-region operating model	
Review penultimate results	
October 2020 MSAB Meeting (MSAB016)	
Review final results	
Provide recommendations on MPs for scale and distribution	
Annual Meeting 2021	
Presentation of first complete MSE product to the Commission Recommendations on Scale and Distribution MP	

5 RECOMMENDATIONS

That the SRB:

a) **NOTE** paper IPHC-2020-SRB017-09 which provides a description of the IPHC MSE framework, a description of the specifications of the multi-area operating model, results from conditioning the multi-area operating model, and an overview of the implementation of management procedures.

b) **RECOMMEND** the use of the MSE framework to evaluate management procedures incorporating scale and distribution elements.

c) **RECOMMEND** improvements for the MSE framework including data generation, estimation models, multi-region operating models, and methods to simulate processes.

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7 APPENDICES

Appendix I: Primary objectives defined by the Commission for the MSE

Appendix II: Proposed and Recommended Management Procedures from MSAB015

APPENDIX I
PRIMARY OBJECTIVES DEFINED BY THE COMMISSION FOR THE MSE

Table 7: Primary measurable objectives, evaluated over a simulated ten-year period, accepted by the Commission at the 7th Special Session of the Commission (SS07). Objective 1.1 is a biological sustainability (conservation) objective and objectives 2.1, 2.2, and 2.3 are fishery objectives.

GENERAL OBJECTIVE	MEASURABLE OBJECTIVE	MEASURABLE OUTCOME	TIME-FRAME	TOLERANCE	PERFORMANCE METRIC
1.1. KEEP FEMALE SPAWNING BIOMASS ABOVE A LIMIT TO AVOID CRITICAL STOCK SIZES AND CONSERVE SPATIAL POPULATION STRUCTURE	Maintain a female spawning stock biomass above a biomass limit reference point at least 95% of the time	*SB* < Spawning Biomass Limit (SB_{Lim}) SB_{Lim}=20% unfished spawning biomass	Long-term	0.05	$P(SB < SB_{Lim})$
	Maintain a defined minimum proportion of female spawning biomass in each Biological Region	$p_{SB,2} > 5\%$ $p_{SB,3} > 33\%$ $p_{SB,2} > 10\%$ $p_{SB,2} > 2\%$	Long-term	0.05	$P(p_{SB,R} < p_{SB,R,min})$
2.1 MAINTAIN SPAWNING BIOMASS AROUND A LEVEL THAT OPTIMIZES FISHING ACTIVITIES	Maintain the coastwide female spawning biomass above a biomass target reference point at least 50% of the time	*SB*<Spawning Biomass Target (SB_{Targ}) SB_{Targ}=$SB_{36\%}$ unfished spawning biomass	Long-term	0.50	$P(SB < SB_{Targ})$
2.2. LIMIT CATCH VARIABILITY	Limit annual changes in the coastwide TCEY	Annual Change (*AC*) > 15% in any 3 years	Short-term		$P(AC_3 > 15\%)$
		Median coastwide Average Annual Variability (AAV)	Short-term		*Median AAV*
	Limit annual changes in the Regulatory Area TCEY	Annual Change (*AC*) > 15% in any 3 years	Short-term		$P(AC_3 > 15\%)$
		Average AAV by Regulatory Area (AAV_A)	Short-term		*Median* AAV_A
2.3. PROVIDE DIRECTED FISHING YIELD	Optimize average coastwide TCEY	Median coastwide TCEY	Short-term		*Median* $\overline{TCEY}$
	Optimize TCEY among Regulatory Areas	Median $TCEY_A$	Short-term		*Median* $\overline{TCEY_A}$
	Optimize the percentage of the coastwide TCEY among Regulatory Areas	Median $\%TCEY_A$	Short-term		*Median* $\overline{\left(\frac{TCEY_A}{TCEY}\right)}$
	Maintain a minimum TCEY for each Regulatory Area	Minimum $TCEY_A$	Short-term		*Median Min(TCEY)*
	Maintain a percentage of the coastwide TCEY for each Regulatory Area	Minimum $\%TCEY_A$	Short-term		*Median Min(%TCEY)*

APPENDIX II
PROPOSED AND RECOMMENDED MANAGEMENT PROCEDURES FROM MSAB015

Recommended management procedures to be evaluated by the MSAB in 2020 and the priority of investigation. A priority of 1 denotes a focus on producing precise performance metrics. Reproduced from IPHC-2020-MSAB015-R.

Table II.1: Recommended management procedures to be evaluated by the MSAB in 2020 and the priority of investigation. A priority of 1 denotes a focus on producing precise performance metrics. A priority of 2 denotes potentially fewer simulations are desired, if time is constrained.

MP	Coastwide	Regional	IPHC Regulatory Area	Priority
MP 15-A	SPR 30:20		• O32 stock distribution • Proportional relative harvest rates (1.0 for 2-3A, 0.75 for 3B-4) • 1.65 Mlbs floor in 2A[1] • Formula percentage for 2B[2]	1
MP 15-B	SPR 30:20 MaxChange15%		• O32 stock distribution • Proportional relative harvest rates (1.0 for 2-3A, 0.75 for 3B-4) • 1.65 Mlbs floor in 2A[1] • Formula percentage for 2B[2]	1
MP 15-C	SPR 30:20 MaxChange15%	Biological Regions, O32 stock distribution Rel HRs[3]: R2=1, R3=1, R4=0.75, R4B=0.75	• O32 stock distribution • Relative harvest rates not applied • 1.65 Mlbs floor in 2A[1] • Formula percentage for 2B[2]	2
MP 15-D	SPR 30:20 MaxChange15% Max FI (36%)		First • O32 stock distribution • Relative harvest rates (1.0 for 2-3A, 0.75 for 3B-4) Second within buffer (pro-rated if exceeds buffer) • 1.65 Mlbs floor in 2A[1] • Formula percentage for 2B[2]	2
MP 15-E	SPR 30:20 MaxChange15%		• O32 stock distribution • Proportional relative harvest rates (1.0 for 2-3A, 0.75 for 3B-4) • 1.65 Mlbs floor in 2A[1]	2
MP 15-F	SPR 30:20 MaxChange15%	National Shares: 20% to 2B, 80% to other	• O32 stock distribution to areas other than 2B • Relative harvest rates (1.0 for 2-3A, 0.75 for 3B-4)	1
MP 15-G	SPR 30:20 MaxChange15%		• O32 stock distribution • Relative harvest rates (1.0 for 2-3A, 0.75 for 3B-4)	1

MP	Coastwide	Regional	IPHC Regulatory Area	Priority
MP 15-H	SPR 30:20 MaxChange15%		• O32 stock distribution • Relative harvest rates (1 for 2-3, 4A, 4CDE, 0.75 for 4B)	1
MP 15-I	SPR 30:20 MaxChange15%		• All sizes stock distribution • Relative harvest rates (1.0 for 2-3A, 0.75 for 3B-4)	2
MP 15-J	SPR 30:20 MaxChange15%		• O32 stock distribution (5-year moving average) • Relative harvest rates (1.0 for 2-3A, 0.75 for 3B-4)	1
MP 15-K	SPR 30:20 MaxChange15%		• 5-year shares determined from 5-year O32 stock distribution (vary over time but change only every 5th year)	2

[1] paragraph 97b IPHC-2020-AM096-R

[2] paragraph 97c of IPHC-2020-AM096-R

[3] R2 refers to Biological Region 2 (2A, 2B, 2C); R3 refers to Biological Region 3 (3A, 3B); R4 refers to Biological Region 4 (4A, 4CDE), and R4B refers to Biological Region 4B

Technical details of the IPHC MSE framework

PREPARED BY: IPHC SECRETARIAT (A. HICKS, P. CARPI, & S. BERUKOFF; 21 AUGUST 2020)

PURPOSE

To provide technical details of the International Pacific Halibut Commission (IPHC) Management Strategy Evaluation (MSE) framework.

1 INTRODUCTION

This document provides technical details of the International Pacific Halibut Commission (IPHC) Management Strategy Evaluation (MSE) framework. Some sections are incomplete and additional details can be found in IPHC-2020-SRB017-09.

2 RECOMMENDATIONS

That the SRB:

a) **NOTE** paper IPHC-2020-SRB017-10 which provides some technical details of the IPHC MSE framework.

3 APPENDICES

I. Technical details of the IPHC MSE framework

APPENDIX I

Technical Details Of the IPHC MSE Framework

IPHC-2020-SRB017-10

Compiled By

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Piera Carpi
Steve Berukoff

DRAFT
August 20, 2020

International Pacific
Halibut Commission

Contents

Chapter 1

Introduction

This technical document describes the Management Strategy Evaluation (MSE) framework and its elements, details specifications of the framework for the evaluation of scale and distribution management procedures, provides definition of terms used, and defines the technical details of the models and equations used within the framework. This is a working document that will be revised often as development of the MSE framework progresses. Therefore, this document is currently incomplete and will have occasional revisions.

1.1 Management Strategy Evaluation

MSE is a process to evaluate harvest strategies and develop a management procedure that is robust to uncertainty and meets defined objectives, and can be partitioned into four separate components that interact with each other (Figure 1.1). Management Procedures (MPs) are defined, often with input from stakeholders and managers but not necessarily, and evaluated against objectives which are determined with input from stakeholders and managers. Simulations of the various MPs are performed and evaluated against the objectives to identify the best performing MP to apply within a harvest strategy policy.

A harvest strategy policy can be implemented in a number of ways. Many fisheries are managed by applying the chosen management procedure each management cycle and implementing the results as management. Other agencies use the outcomes of the management procedure as a reference from which other considerations (e.g., socio-economic) are taken into account when determining a tactical decision of the management outcomes. This variability around the management procedure is called implementation variability and should be a part of the simulations and evaluation.

The four boxes shown in Figure 1.1 are all important component of an MSE. The objectives are the connection to stakeholders and managers. Performance metrics are derived from well defined objectives that are used in the evaluation. Management procedures are the link to a transparent management process and need to be clearly defined so that they are formulaic and can be written as computer code for the closed-loop simulations. The closed-loop simulations also consist of an operating model which simulates the population and produces the observations needed for the management procedure. Applying the best performing MP is the goal of MSE but is not the

Figure 1.1: An illustration of the closed-loop simulation within the MSE framework consisting of an operating model and a management procedure.

end. The MSE should be updated as additional observations and knowledge is gained from the population, fishery, or management process.

The engine of the MSE framework is the closed-loop simulation with the operating model (OM) and management procedure (Figure 1.2). The OM simulates the dynamics of the population and the fisheries that interact with it. The processes simulated by the OM can be thought of as processes that management does not, or chooses not, to control. For example, natural mortality is not a process that is not managed, and some aspects of the fisheries are not managed (e.g., specific daily decisions). These unmanaged processes result in variability that is normal to the system, referred to as 'natural variability' in this document, and is simulated by the OM.

The MP consists of elements that are managed and may include data collection and monitoring, estimation models, and the harvest rules that determine how the fisheries are managed. MSE can evaluate any of these elements including how changes in monitoring, and different estimation model, or various harvest rules affect the outcomes. This elements may be simple or complex.

The chapters in this document begin with a generalized operating model that can be specified for any fish population. The following chapter presents the specifications of the MSE for Pacific halibut fisheries, and the sections within that chapter follow the three boxes in Figure 1.1 labeled Goals & Objectives, Management Procedure, and Simulation.

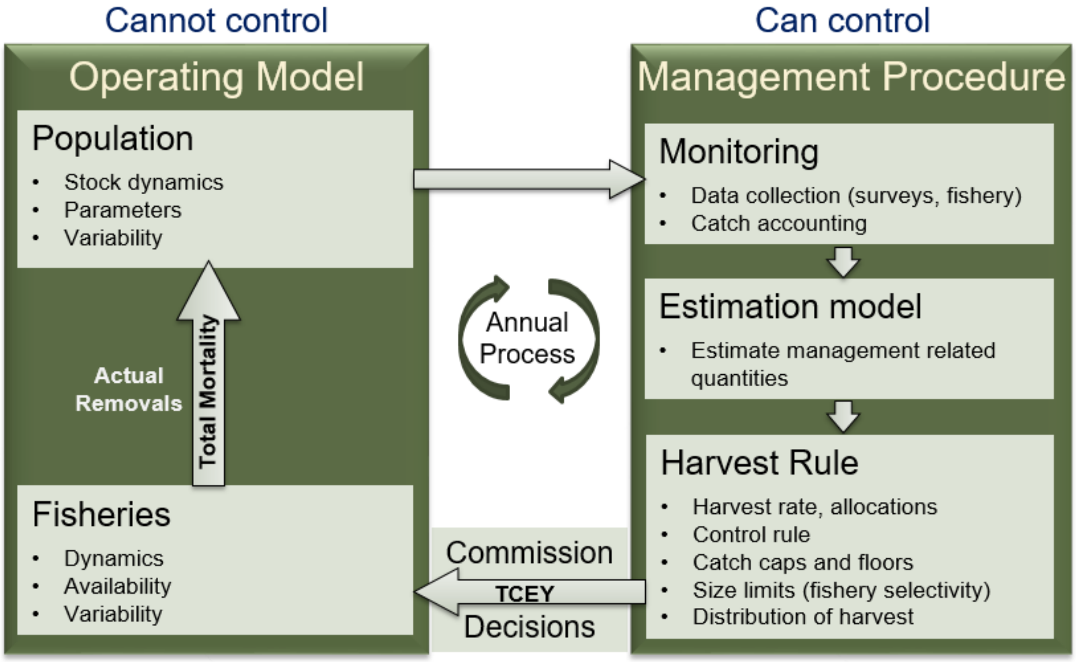


Figure 1.2: An illustration of the closed-loop simulation within the MSE framework consisting of an operating model and a management procedure.

Chapter 2

Operating model

In a management strategy evaluation (MSE), operating models (OM) simulate the population and fishery dynamics. It incorporates life-history processes such as recruitment, growth, migration, maturation, and mortality of the fish population, as well as fishery processes such as selectivity, availability, and catchability. Descriptions of the various processes are provided below along with the mathematical equations used to simulate those processes. Many of the details are drawn from the Hilborn and Walters (1992), Quinn and Deriso (1999), the CASAL manual Bull *et al.* (2012), Stock Synthesis technical details Methot and Wetzel (2013), and the Coleraine manual Hilborn *et al.* (2000).

There is uncertainty in the parameterization of the processes, natural variability in the processes, and multiple hypotheses about the mechanisms of the processes. These three sources of variability are introduced in three different ways.

1. Parameter uncertainty is introduced by conditioning the operating model to data, and determining the distribution of uncertainty for each parameter as well as correlation with other parameters. Parameter values for an individual simulated trajectory are randomly drawn from the multivariate estimated probability distribution. Therefore, each simulated trajectory uses a different set of parameters, thus including variability that represents the uncertainty in the parameters. This is described in Section 2.4.
2. Natural variability is introduced by defining a random process associated with various concepts. For example, recruitment varies naturally and is modelled by including random deviates applied annually to average recruitment. Other processes may have specific patterns such as changes in weight-at-age. This is described in Section 2.5.
3. Structural uncertainty is included by defining multiple hypotheses and implementing them as separate operating models. For example, growth may occur in different ways between models. Or, data may be structured in a different way when conditioning the model. Structural uncertainty captures the variability that can not be captured by the two methods above.

Parameters that will have uncertainty are defined (and those that are fixed are given fixed values), methods to include natural variability are defined, and potential areas of structural uncertainty are noted.

2.1 The state object

The state is the accounting of the population in numbers within an operating model and is contained in a state object with many dimensions. The state represents the intrinsic characteristics of the modeled population: age, maturity, and sex. This state is then evolved on a computational domain parameterized by time and space, which are extrinsic variables. Furthermore, sectors (fisheries and survey) interact with the state. Clarified this way, the state object contains a representation of the stock at a place and time and can be subsetted along any of these axes as needed to determine the state for any combination of these dimensions.

The dimensions are fixed inputs that are defined by the user, thus may be unique to any operating model. The different dimensions, and maximum ranges, are shown in Table 2.1. Maturity state (immature or mature) is not included as a dimension here (specifically for the Pacific halibut operating model) but may be a useful charactersitic to track for some stocks, depending on fishing intensity and the proportion maturing at age. Instead, the mature population is determined using the proportion mature at age, which can be applied to various dimensions of the population state (see Section 2.3).

Table 2.1: Partitions of the state object that are fixed inputs and the likely minimum and maximum input for each partition.

	Dimension		
Variable	Min	Max	Description
Age (a)	1	251	Age classes ranging from 0 to 250. Halibut will likely use 0 to 30 and age always starts at zero. A capital A indicates the maximum age
Sex (s)	1	3	Sex, which includes female, male, and unsexed, in that order, labeled 1, 2, and 3.
Time (t)	0	∞	A minimum and maximum time-step (e.g., year) is input by user. The difference +1 determines the number of time-steps. These are not projected time-steps, but time-steps modelled to condition the OM. A time-step will typically be a year, but specific points in time (e.g., beginning, middle, or end of the year) may be noted in a superscript (see below).
Region (r)	1	∞	Number of spatial regions with migration between
Area within Region (r_l)	1	∞	Number of areas within a region. Migration is not modelled between areas.
Sector (f)	1	∞	Number of fishing-related sectors, which includes fisheries and surveys. Sectors typically will operate at the region level or a finer scale, but there may be a case where a sector operates across regions (which is unlikely for the Pacific halibut operating model).

The state object is the key component of the population dynamics and must contain sufficient information to determine the population dynamics as well as any intermediate calculations, such as fishery catches. In this implementation, there are always six partitions, but some operating models may have a partition with only one element, effectively eliminating that dimension. For example, a single-sex, single-area model with no maturity partition would simply be a matrix of years and ages.

2.2 Notation

Notation of the variables in the operating model uses the concept of defining a quantity of the population (such as numbers or biomass), subscripted by various characteristics (intrinsic and extrinsic) and superscripted by specific concepts (such as spawning or exploitable). The subscripts reflect the intrinsic and extrinsic characteristics of the population by listing the intrinsic characteristics first (age and sex), followed by the extrinsic characteristics (time, region/area, and fishing sector). The possible subscripts are defined in Table 2.1 and are always subscripted in the order presented in those tables. For example, the numbers for age and sex in a year and region is $N_{a,s|y,r}$. When a subscript is not included, it is implied that the quantity is a summation over that index (or the index doesn't apply, as in the case of fishing sector) and ambiguity will be alleviated using the letter associated with the index when necessary (e.g., $N_{s=1|y=1}$ is the number of females in year 1 summed over all ages and regions).

Variables specific to a fishing sector (f) include a subscript for that sector at the end. For example, the catch-at-age for females from sector f in year 1 and region 2 would be notated as $C_{a,1|1,2,f}$. Fishery sectors typically will operate at the region level or a finer scale, but the region subscript is retained for clarity and in case a sector does operate across regions (which is unlikely for the Pacific halibut operating model).

Finally, superscripts are used to notate specific concepts such as spawning biomass, which would be notated as $B^{sp}_{s=1|y=1}$ to represent the spawning biomass for females in year 1 over all regions. Additionally, a superscript that is a number between 0 and 1 indicates the time in the year that the quantity is calculated. For example, $B^{sp,0}$, $B^{sp,0.5}$, $B^{sp,1}$ would be the spawning biomass calculated at the beginning of the year, middle of the year, and end of the year, respectively. Possible superscripts and their definition are shown in Table 2.2.

Table 2.2: Superscripts for variable and their meaning.

Variable	Description
ma	Mature
sp	Spawning. Most often used with B^{sp} to represent spawning biomass.
sr	Selected and retained referring to the fish that are landed by a fishery sector.
n	Numbers. Indicates that a quantity, such as catch, is in numbers (C^n). Note that if a superscript is not used on catch, it is in weight.
$'$	Denotes update made to numbers-at-age after partial timestep is complete, which includes the effect of movement but not mortality.
$''$	Denotes update made to numbers-at-age at the end of the timestep.
Number 0-1	A number between zero and 1 (inclusive) indicates the time within the year. For example, 0 indicates beginning of the year, 0.5 indicates middle of the year, and 1 indicates end of the year.

2.3 Population dynamics

The population dynamics are modelled as an age-structured annual process accounting for changes in the numbers-at-age for each partition within the state (e.g., age and sex).

The sequence of processes from the start of the time-step (typically annual) is

1. *age increment*,
2. *recruitment (based on spawning biomass calculated at end of previous time-step or at the beginning of the current time-step)*,
3. *movement*,
4. *mortality*. The sequence of mortality from all sources is theoretically described below, but does not need to be specifically modelled as such because the mortality calculations will appropriately account for the sequence, as described in Section 2.3.4 and a later Appendix.
    (a) portion of natural mortality,
    (b) fishing mortality for one or more sectors,
    (c) portion of natural mortality,
    (d) fishing mortality for one or more sectors,
    (e) etc., until a full time-step of natural mortality has been applied
5. *spawning*.

The state object ($N_{a,s|t,r}$) is updated at three different points in the annual process, and superscripts note the time point.

N : Beginning of the time-step after age increment and recruitment of age 0.
$N^{'}$: After movement before mortality
$N^{''}$: End of the time-step, after all natural and fishing mortality

At any point in time, the biomass may be desired and can be calculated from numbers-at-age ($N_{a,s|t,r}$) and weight-at-age ($W_{a,s|t,r}$).

$$B_{a,s|t,r} = N_{a,s|t,r} W_{a,s|t,r} \tag{2.1}$$

Various partitions of biomass may be desired. For example, spawning biomass is the weight of spawning fish, and exploitable biomass is the weight of fish available to a specific sector. Biomass can also be calculated at specific points of time in the time-step. These various types of biomass will be defined in the sections below, and will be noted with a superscript. For example, spawning biomass is B_y^{sp}.

This section describes the technical specifications of the general population dynamics and how the historical population can be modelled given inputs such as catch and weight-at-age, as well as parameters that may be fixed or estimated from data. Conditioning the operating model is the process of determining the range of parameters and hypotheses that describe the observations, and is covered in Section 2.4. Projecting the population forward in time is discussed in Section 2.5, and involves defining random and fixed processes such as recruitment and changes in weight-at-age.

2.3.1 Age increment

The numbers-at-age at the beginning of the time-step with an annual time-step is obtained by incrementing the previous time-step's age class to one time-step older and calculating recruitment for age 0.

$$N_{a,s|t,r} = \begin{array}{ll} R_{s|t,r} & a = 0 \\ N_{a-1,s|t-1,r} & 1 \leq a < A \\ N_{a-1,s|t-1,r} + N_{A,s|t-1,r} & a = A \end{array} \tag{2.2}$$

2.3.2 Recruitment

Recruitment is a function of the spawning biomass calculated from the end of the previous time-step after all of the processes (movement and mortality) have occurred. See Section 2.3.6 for a description of spawning biomass.

$$R_{s|t,r} \quad = \quad p^R_{y,r} \times p^R_s \times f(B^{sp,1}_{s=1|t-1}) \times e^{(\varepsilon_{y,r} - b_y \frac{\sigma^2_R}{2})} \times e^{I_y \delta} \tag{2.3}$$

where $p_{y,r}$ is the proportion recruiting to region r in time-step t, p_s is the proportion of sex s (typically 0.50), $f(B^{sp,1}_{s=1|t-1})$ is the equilibrium stock-recruit relationship using the end of the time-step spawning biomass (superscripts) for females from the previous time-step (subscripts), e^{ϵ} is the annual deviation in recruitment for time-step t, b is a bias-correction multiplier, and $e^{I_y * \delta}$ is an overall adjustment for recruitment regime shift.

Density-dependent Recruitment

Density-dependence in the spawner-recruit relationship is modelled using a Beverton-Holt formulation.

$$f(B^{sp,1}_{s=1|t-1}) = \frac{B^{sp,1}_{s=1|t-1}}{a + bB^{sp,1}_{s=1|t-1}} \tag{2.4}$$

where the parameters a and b are determined from steepness (h), unfished equilibrium recruitment (R_0), and unfished equilibrium female spawning biomass (B^{sp}_0).

$$a \quad = \quad \frac{(1-h)B^{sp}_0}{4hR_0} \tag{2.5}$$

$$b \quad = \quad \frac{5h-1}{4hR_0} \tag{2.6}$$

Steepness (h) is a parameter noting the percentage of unfished equilibrium recruitment (R_0) that occurs when the female spawning biomass is 20% of unfished equilibrium female spawning biomass

(B_0^{sp}). This can be shown using equations 2.4 and 2.5, and assuming that female spawning biomass is $\frac{1}{5}^{th}$ of unfished equilibrium female spawning biomass.

$$\begin{aligned} & \frac{{}^1\!/_5 B_0^{sp}}{\frac{(1-h)B_0^{sp}}{4hR_0} + \frac{5h-1}{4hR_0}({}^1\!/_5 B_0^{sp})} \\ = & \frac{{}^1\!/_5}{\frac{1-h+{}^1\!/_5 5h-{}^1\!/_5}{4hR_0}} \\ = & \frac{{}^4\!/_5 hR_0}{{}^4\!/_5} \\ = & hR_0 \end{aligned}$$

The same method can be used to show that B0 results in R0. An example Beverton-Holt stock-recruit curve with a steepness of 0.70 is shown in Figure 2.1.

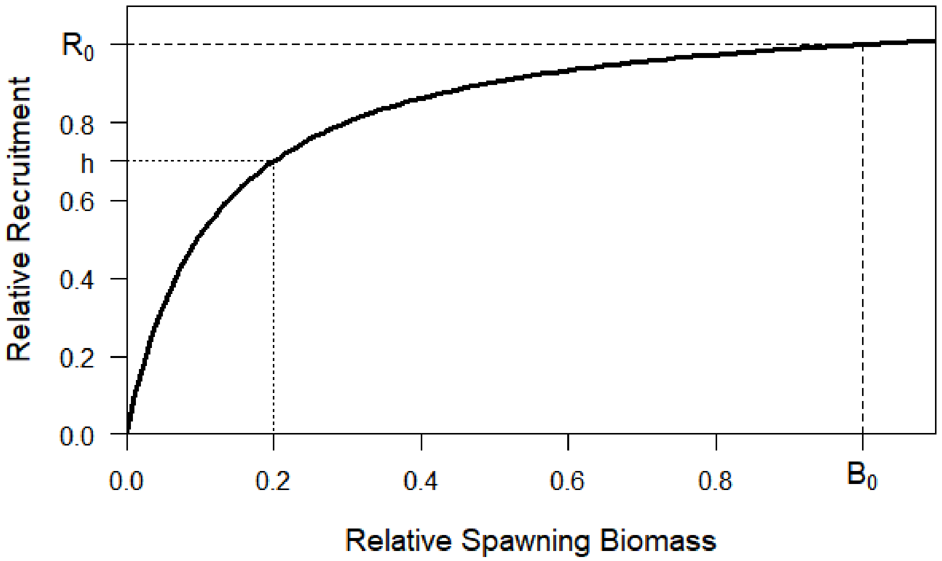


Figure 2.1: An example Beverton-Holt stock-recruit curve with a steepness (h) of 0.70.

The parameter for steepness is typically fixed because accurate estimation requires data informative of recruitment at low biomass levels and variability in recruitment often reduces the information content. The parameter R_0 is often estimated, and B_0^{sp} can be calculated from R_0 and other life history parameters. Given those three parameters, a and b can be calculated.

Recruitment Deviation

Recruitment varies around the stock-recruit curve, which is defined as mean recruitment. The distribution of recruitment is assumed to be lognormal and is parameterized using a Gaussian distributed deviate with an exponentiated mean of one and a variance notated as σ_R^2.

$$\varepsilon_{y,r}\ N(\mu = 0, \sigma_R^2) \tag{2.7}$$

The arithmetic mean of the lognormal distribution is $e^{\mu+\sigma_R^2/2}$, and because R_0 is unfished equilibrium mean recruitment, a bias correction must be applied when simulating log deviates from a normal distribution with a mean/median equal to zero. As shown in equation 2.3, $e^{(\varepsilon_{y,r}-\sigma_R^2/2)}$ is used where the bias correction is $-\sigma_R^2/2$. This ensures that unfished equilibrium recruitment is, on average, $R0$ (e.g., the mean of the biased corrected exponentiated deviate is equal to 1). Figure 2.2 shows an example simulation without fishing when bias correcting and not bias correcting, and (Methot and Taylor 2011) present an analytical proof why bias correction is necessary.

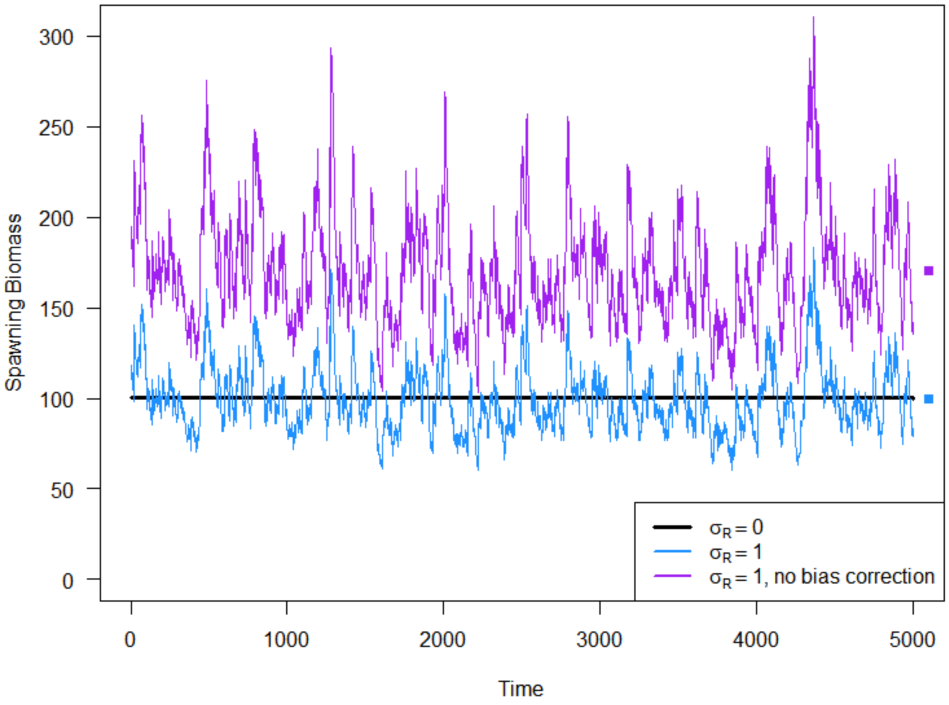


Figure 2.2: An example simulated projection of spawning biomass with no fishing mortality from an age-structured model with $\sigma_R = 1$ and bias-corrected recruitment deviates (blue line) and recruitment deviates not bias-corrected (purple line). A simulated trajectory with $\sigma_R = 0$ is shown by the flat black line, and the means of each simulated trajectory are shown by the appropriate colored square to the right.

Full bias-correction is necessary when simulating the fish population because the full lognormal distribution is used to simulate deviates, as shown in Figure 2.2. However, during estimation, information is reducing the uncertainty (i.e, distribution) around a deviation, and pulling it away from a value of zero. Therefore, a deviate without any information during estimation will be zero and not need bias correction, but a deviate that is fully informed (i.e., known exactly as in a simulation) will need full bias correction. In most estimation models, deviates are not often fully informed and a partial bias-correction is necessary. (Methot and Taylor 2011) provide a much more detailed discussion of this phenomenon. The parameter b_y is included in equation 2.3 to allow for bias-correction if needed during estimation.

The recruitment process is a coastwide process with age-0 recruits distributed to regions. Therefore, the deviates may be region-specific, but it may be more appropriate to use a single coastwide deviate for each year and simulate region-specific variability across time-steps with the parameters representing the proportion recruiting to each region ($p^R_{y,r}$). Using region-specific deviates and proportion of recruits may be confounding.

Recruitment Distribution

Recruitment of age-0 fish to the population is determined from spawning biomass, and depending on the settlement process for a fish species and ocean dynamics, an age-0 fish may recruit a considerable distance from where spawning occurred. Furthermore, fish may migrate to spawning regions that are far from regions they occupied when not spawning. Therefore, the recruitment process is modelled assuming a coastwide spawning population (e.g., fish may spawn in regions where they are not present during the time of fishing) producing age-0 fish (recruits) throughout specified regions. The proportion of recruits in each region in each year is represented with the parameter $p^R_{y,r}$ as shown in equation 2.3, and $r-1$ parameters need to be specified for each time-step because the r^{th} parameter is one minus the sum of the specified parameters (ie., $\sum_r p^R_{y,r} = 1$).

Recruitment Link to an Environmental Variable

Recruitment is modelled (equation 2.3) using a stock-recruit relationship (equation 2.4) that produces an average level of recruitment given current spawning biomass. Changes in the environment may change that average level of spawning biomass and is modelled using an environmental index (I_y) in equation 2.3 with the function $e^{I_y * \delta}$. The parameter δ is a covariate determining how the average recruitment is affected by the environmental index.

2.3.3 Movement

In its most simple form, movement (also called migration) is the proportion of individuals that move from region j to region k (individuals can only move among regions and movement among areas within regions is not explicitly modelled). The probability that the individual stays in its current region is equal to one minus the sum of the probabilities of moving out of the current region. Movement is specific to the partitions age, sex, time-step, and region.

One of the most common ways to model movement is using a transition matrix. Let $\Psi_{j\to k}$ be the instantaneous movement from region j to region k expressed as the proportion of the population in region j moving to region k. The diagonal of the transition matrix will be the proportion that stay in region j and the off-diagonals of $\Psi_{j\to k}$ will represent the proportions that move out of region j. The row of the matrix corresponds to j (from) and k corresponds to the column of the matrix (to). Each row of the transition matrix should sum to 1. Each dimension of the transition matrix will be equal to the number of regions. For example, let there be n regions ($R = 1...n$), then the transition matrix for each age, sex, and time-step will look like:

$$\begin{bmatrix} \Psi_{R=1} & \Psi_{1\to 2} & \cdots & \Psi_{1\to n} \\ \Psi_{2\to 1} & \Psi_{R=2} & \cdots & \Psi_{2\to n} \\ \vdots & \vdots & \ddots & \vdots \\ \Psi_{n\to 1} & \Psi_{n\to 2} & \cdots & \Psi_{R=n} \end{bmatrix}$$

The numbers-at-age in region j after movement, for a given age, sex, and time-step, is determined from the following equation.

$$\begin{aligned}
N'_{a,s,|t,r=j} &= N_{|r=j} - N_{|r=j}\sum_{k\neq j}\Psi_{a,s|t,j\to k} + \sum_{k\neq j} N_{|r=k}\Psi_{a,s|t,k\to j} \\
&= N_{|r=j}\left(1-\sum_{k\neq j}\Psi_{a,s|t,j\to k}\right) + \sum_{k\neq j} N_{|r=k}\Psi_{a,s|t,k\to j} \\
&= N_{|r=j}\Psi_{a,s|t,j\to j} + \sum_{k\neq j} N_{|r=k}\Psi_{a,s|t,k\to j} \\
&= \sum_{k\in r} N_{|r=k}\Psi_{a,s|t,k\to j} \qquad (2.8)
\end{aligned}$$

Movement parameters

There are two options for the construction of the transition matrix:

1. entered as simple proportions in an array by time-step, age, sex, and region of origin, or
2. parameterize the proportions-at-age as a function of age and modify the parameters of the function for each time-step and sex.

A parameterized approach is implemented using functions called *constant* (Equation 2.9), *exponential* (Equation 2.10), or *double exponential* (Equation 2.11). Additionally, specific values for defined ages can be entered *Values* (Equation **??**)

$$\Psi_{a,s|t,k\to j} = \begin{cases} 0 & a \leq \psi_0 \\ \psi_c & a > \psi_0 \end{cases} \qquad (2.9)$$

where, ψ_0 is the oldest age with a movement probability of zero before the first non-zero movement probability, and ψ_c is a constant proportion for all ages greater than ψ_0.

$$\Psi_{a,s|t,k\to j} = \begin{cases} 0 & a \leq \psi_0 \\ \frac{e^{\psi}_{\lambda}(a-\psi_0+1)}{max(\Psi_{a,s|t,k\to j})} \times (\psi_{max} - \psi_{min}) & a > \psi_0 \end{cases} \qquad (2.10)$$

where, ψ_0 is the oldest age with a movement probability of zero before the first non-zero movement probability, ψ_λ is the slope parameter of the exponential function, ψ_{min} is the minimum non-zero probability, and psi_{max} is the maximum probability.

$$\Psi_{a,s|t,k\to j} = \begin{cases} 0 & a \leq \psi_0 \\ \frac{e^{\psi_{\lambda_L}(a-\psi_0)-1}}{max(\Psi_{a,s|t,k\to j})}\psi_{max_L} & \psi_0 < a \leq \psi_{peak_L} \\ (\psi_{max_R} - \psi_a)e^{-\psi\lambda_R(a-\psi_0+1)} + \psi_a & a > \psi_{peak_L} \end{cases} \qquad (2.11)$$

where, ψ_0 is the oldest age with a movement probability of zero before the first non-zero movement probability, ψ_{λ_L} is the slope parameter of the exponential function for the left side of the function, ψ_{λ_R} is the slope parameter of the exponential function for the right side of the function, ψ_{max_L} is the maximum non-zero probability on the left side of the curve, , ψ_{max_R} is the maximum non-zero probability on the right side of the curve, ψ_{peak_L} is the age associated with the peak of the left curve.

$$\Psi_{a,s|t,k\rightarrow j} = \begin{cases} 0 & a \leq \psi_0 \\ \psi_{v_a} & a > \psi_0 \end{cases} \tag{2.12}$$

Overall, the followng are the possible parameters in the four functions described by equations 2.9 to 2.12 that may be specific to a sex, time, and region.

1. ψ_0: The oldest age with a movement probability of zero before the first non-zero movement probability. Therefore, all ages from age 0 to age ψ_0 do not move out the region they are in.
2. ψ_c: The constant non-zero probability of movement.
3. ψ_λ: The 'slope' of the exponential function in either the exponential function or associated with the left (λ_L) or right (λ_R) side of the double exponential.
4. ψ_{min}: The minimum non-zero probability of movement-at-age in the exponential function.
5. ψ_{max}: The maximum probability of the movement-at-age in the exponential function or for the left (max_L) or right (max_R) side of the double exponential function.
6. ψ_{peak_L}: The age at which the peak of the left ($peak_L$) side of the double exponential occurs. This is the transition between the left and right sides of the double exponential function. This parameter is an integer and the peak of the right side is one greater than ψ_{peak_L}.
7. ψ_a: The asymptote of the right side of the double exponential function.
8. ψ_{v_a}: Specific probability-at-age. Subsequent values after the last entered age are set to the last entered age.

2.3.4 Mortality

These operating models contain two types of mortality: natural mortality and fishing mortality. These are described below with definitions and mathematical equations. Total mortality, the summation of natural and fishing mortality, is noted as Z and is often modelled using a differential equation describing the instantanous change with respect to a short period of time.

$$\frac{dN}{dt} = -Z \times N$$

Expanding to a single annual time step, the numbers in the next time-step, if mortality was the only process, are

$$N_{y+1} = N_y e^{-Z} \tag{2.13}$$

However, fishing mortality is often assumed to occur at a specific point in time.

$$N_{y+1} = N_y e^{-M} (1 - U_y) \tag{2.14}$$

where U_y is an annual exploitation rate. This formulation makes the calculations simpler, faster, and easier to interpret. These equations are general mortality equations, and the specific equations related to natural and fishing mortality for the operating models are described below. We follow the FAO definition (`http://www.fao.org/3/a0212e/a0212e12.htm}`)and call the fishing mortality process in Equation 2.13 instantaneous and that in Equation 2.14 finite.

Natural Mortality

Natural mortality represents mortality from all sources other than fishing (e.g., natural causes, predation, and emigration out of the area being modelled) and may reflect some processes that are not specifically accounted for in the model. Many fisheries models assume that natural mortality is constant over time, which will likely capture the general trend in abundance, but natural mortality likely varies from time-step to time-step. Therefore, the operating model allows for natural mortality that is age, sex, time-step, and region specific, but will likely assume a single value for natural mortality for each sex.

Fishing Mortality

Fishing mortality can be modelled using the Baranov catch equation (an instantaneous formulation as with natural mortality), but it is simpler, faster, and more interpretable to model fishing mortality as a finite exploitation rate (also called Pope's approximation). This assumes that fishing occurs at a specific point in time, which will be an important assumption to consider when the fishery operates year round and at high mortality rates. For most applications, especially Pacific halibut with relatively low fishing mortality rates and a defined season, the exploitation rate is a useful approximation.

$$U_{|t,r,f} = \frac{C_{|t,r,f}}{B^{sr,p_f}_{|t,r,f}} \tag{2.15}$$

where $C_{|t,r,f}$ is the catch in time-step t and region r for sector f, and $B^{sr}_{|t,r,f}$ is the selected-and-retained biomass for that fishery. The time-point is the proportion of the time-step, p_f, at which the fishery occurs, and is commonly defined as 0.5. The fishing sectors typically operate at a scale finer than region, but region is used in the equations for fishing mortality because a single Pacific halibut may be available to any of the sectors in a region throughout an annual time step. Therefore, sectors are tracked at the region level, but may represent fishing in a particular area within a region (through selectivity and fishery timing, p_f). If a sector operates at a greater scale than region, that sector should be divided into region-specific sectors. In other words, a sector only operates within a region. Therefore, the region and sector subscripts are redundant, but retained.

Selectivity represents the probability that a fish of a particular age will be caught by the sector. This is a combination of gear selection (e.g., the size of the hook or the width of mesh in a net) and availability (are fish of that age in the area being fished). We do not separate these components and instead model them as a single probability. The selected proportions at age generally increase from young ages to older ages, but may also decline at the oldest ages. This is referred to as dome-shaped selectivity and may occur because older fish move out of the fishing area and become less available to the fishery, older fish may be able to avoid or escape the fishing gear, etc. Selectivity in this model is forced to asymptote at one (and not greater) for at least one age. Therefore, the exploitation rate refers to the proportion of a fully selected age-class of fish removed from the population.

The proportion selected at age can be entered specifically for each age, modelled using a logistic formulation to asymptote at one (equation 2.16),

$$S_{a,s|t,r,f} = \frac{\zeta_{max,s|t,r,f}}{1 + 19^{(\zeta_{a50,s|t,r,f} - age)/(\zeta_{a95,s|t,r,f} - \zeta_{a50,s|t,r,f})}} \tag{2.16}$$

or modelled using a double-normal function to allow for dome-shaped selectivity (equation 2.17).

$$S_{a,s|t,r,f} = \begin{cases} \zeta_{max,s|t,r,f} \dfrac{e^{-(a-\zeta_{peak,s|t,r,f})^2}}{2\zeta_{\sigma_L,s|t,r,f}} & age < \zeta_{peak,s|t,r,f} \\ \mathrm{Max}\left[\zeta_{max,s|t,r,f} \dfrac{e^{-(a-\zeta_{peak,s|t,r,f})^2}}{2\zeta_{\sigma_R,s|t,r,f}},\ \zeta_{final,s|t,r,f}\right] & age \geq \zeta_{peak,s|t,r,f} \end{cases} \tag{2.17}$$

Parameters are described below. Examples of these two parameterizations are shown in Figure 2.3. Additional parameterizations may be introduced in the future. An option for all selectivity parameterizations is to define the age at which selectivity is zero for that age and all lower ages. This parameter is $\zeta_{zero,s|t,r,f}$.

There are three parameters in the logistic function for selectivity.

1. $\zeta_{a50,s|t,r}$: The age at which the probability of selection is 50% for sex s, at time t, for sector f.
2. $\zeta_{a95,s|t,r}$: The age at which the probability of selection is 95% for sex s, at time t, for sector f.
3. $\zeta_{max,s|t,r}$: The maximum probability of selection (asymptote) for sex s, at time t, for sector f.

There are five parameters in the double normal function for selectivity.

1. $\zeta_{peak,s|t,r}$: The age at which the probability of selection is at its maximum for sex s, at time t, for sector f. This is the division between the left and right sides of the function.
2. $\zeta_{\sigma_L,s|t,r}$: The standard deviation of the normal distribution for ages younger than the peak age ($\zeta_{peak,s|t,r}$). This side of the selection curve is referred to as the left side or ascending limb.

3. $\zeta_{\sigma_R,s|t,r}$: The standard deviation of the normal distribution for ages older than the peak age ($\zeta_{peak,s|t,r}$). This side of the selection curve is referred to as the right side or descending limb. To create an asymptotic selectivity ogive with the double normal this parameter would be fixed at a sufficiently large value.

4. $\zeta_{max,s|t,r}$: The probability at the age associated with the peak. This must be set at 1.0 for one of the sexes, but may be less than 1.0 for the other sex.

5. $\zeta_{final,s|t,r}$: The lowest value of the function on the right side of the function. The probability for ages that would be calculated less than this value are fixed at this value.

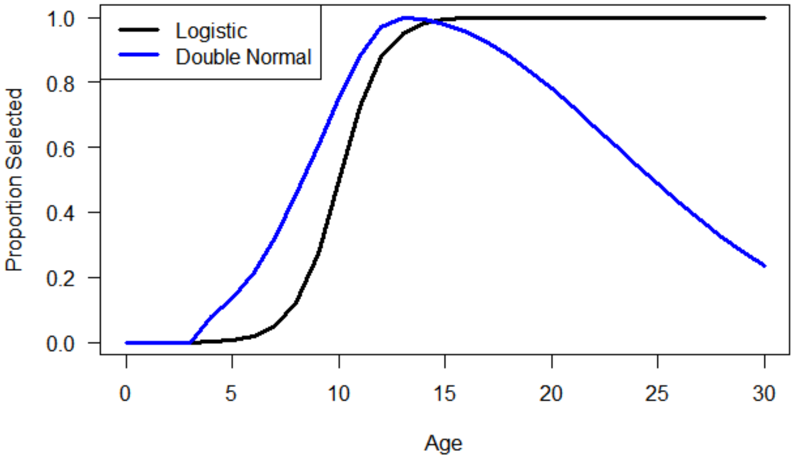


Figure 2.3: Examples of the logistic and double-normal parameterizations for selectivity.

The availability of fish to a sector changes from year to year and changes may be made to gear for efficiency or to meet changes in regulation. Therefore, selectivity likely varies over time, hence the time subscript on the parameters and selectivity-at-age. Time-varying selectivity-at-age can be implemented by adjusting the parameters across time according to the methods described in section 2.3.9.

Specific terms are used to refer to fishery related quantities. Landings are the fish that are landed and quantified. These include commercial landings of O32 Pacific halibut at processing plants and Pacific halibut kept in the recreational fishery. Captured fish refers to fish that are captured by fishing gear, of which some may subsequently survive if released. Some sources may refer to that as catch, but **the term catch in this document is synonymous with landings**. Of the captured fish that are subsequently released, some may die; this is called discard mortality. The sum of catch (i.e., landings) and discard mortality is the total fishing mortality. To model total fishing mortality an exploitation rate, selectivity curve, and retention curve are needed.

Retention-at-age represents the probability that a captured fish is retained. This curve typically increases from lower probabilities at younger ages and nearing one at older ages, but often does not reach exactly one at its peak to represent the occasional discarding or loss of older/larger fish in that fishery. Low retention of young fish may represnet a minimum size limit or high-grading for larger/older fish. Low retentions of older fish may represent a maximum size limit or high-grading for smaller/younger fish. It is important to use retention because it can be used to calculate the proportion of fish-at-age that are released and may suffer discard mortality.

Retention is parameterized using the same options as selectivity (direct input by age, logistic, or double-normal) The retention parameters are

1. $\eta_{a50,s|t,r}$: The age at which the probability of retention is 50% for sex s, at time t, for sector f.
2. $\eta_{a95,s|t,r}$: The age at which the probability of retention is 95% for sex s, at time t, for sector f.
3. $\eta_{max,s|t,r}$: The asymptote or maximum probability of retention at any age (ranges from 0 to 1).

There are five parameters in the double normal function for selectivity and one optional parameter.

1. $\eta_{peak,s|t,r}$: (Required) The age at which the probability of retention is at its maximum for sex s, at time t, for sector f.
2. $\eta_{\sigma_L,s|t,r}$: (Required) The standard deviation of the normal distribution for ages younger than the peak age ($\eta_{peak,s|t,r}$). This side of the retention curve is referred to as the left side or ascending limb.
3. $\eta_{\sigma_R,s|t,r}$: (Required) The standard deviation of the normal distribution for ages older than the peak age ($\eta_{peak,s|t,r}$). This side of the retention curve is referred to as the right side or descending limb. To create an asymptotic retention ogive with the double normal this parameter would be fixed at a sufficiently large value.
4. $\eta_{max,s|t,r}$: The asymptote or maximum probability of retention at any age (ranges from 0 to 1).
5. $\eta_{final,s|t,r}$: The lowest value of the function on the right side of the function. The probability for ages that would be calculated less than this value are fixed at this value.

The logistic function for retention is

$$R_{a,s|t,r,f} = \frac{\eta_{max,s|t,r}}{1+19^{(\eta_{a50,s|t,r,f}-age)/(\eta_{a50,s|t,r,f}-\eta_{a95,s|t,r,f})}} \tag{2.18}$$

and the double-normal function for retention is

$$R_{a,s|t,r,f} = \begin{cases} \eta_{max,s|t,r,f}\dfrac{e^{-(a-\eta_{peak,s|t,r,f})^2}}{2\eta_{\sigma_L,s|t,r,f}} & age < \eta_{peak,s|t,r,f} \\ \text{Max}\left[\eta_{max,s|t,r,f}\dfrac{e^{-(a-\eta_{peak,s|t,r,f})^2}}{2\eta_{\sigma_R,s|t,r,f}},\ \eta_{final,s|t,r,f}\right] & age \geq \eta_{peak,s|t,r,f} \end{cases} \tag{2.19}$$

It is important to not confuse retention with selectivity. For fisheries that retain all fish, the retention curve would be one across all ages because selectivity accounts for the sector not catching younger fish. The resulting product of retention and selectivity is called the keep curve and represents the probabilities-at-age of fish that are captured and retained, thus kept and landed. Figure 2.4 shows examples of selectivity and retention curves, and the resulting keep curve.

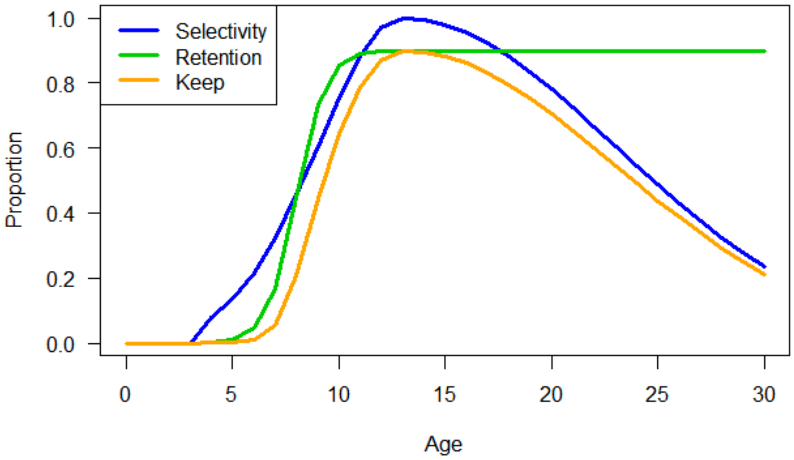


Figure 2.4: Examples of the double-normal parameterization for selectivity, a logistic parameterization for retention, and the resulting keep curve.

The sectors are assumed to operate at a very specific point of time defined as the proportion of the time-step (p_f). Some sectors will operate before others and will affect the abundance available later in the time-step. Therefore, the sequential operation of the sectors is accounted for by applying the probability that a fish survives sectors that occurred previously (catch and discard mortality). This necessitates determining only those sectors that occurred before the sector of interest.

Catch at age and sex in numbers (C^n) or weight (C) for a sector in an area can be determined from the numbers-at-age (N_a), natural mortality rate (M), exploitation rate (U_f), selectivity (S), proportion that are subsequently retained (R), mean weight-at-age (W), and the mortality from fisheries that occurred before the sector of interest. Appendix B presents details of this method as well as a method that does not take the sequence into account.

We notate the numbers-at-age and the biomass-at-age at a particular point in time in a time-step as $N^p_{a,s|t,r}$ and $B^p_{a,s|t,r}$, respectively, where the superscript indicates the proportion of the time-step. Given this notation, the catch for a particular sector is

$$\begin{aligned} C^n_{a,s|t,r,f} &= N^p_{a,s|t,r} U_{|t,r,f} S_{a,s|t,r,f} R_{a,s|t,r,f} \\ C_{a,s|t,r,f} &= N^p_{a,s|t,r} W_{a,s,|t,r,f} U_{|t,r,f} S_{a,s|t,r,f} R_{a,s|t,r,f} \end{aligned}$$

and the total catch for a sector is

$$C^n_{|t,r,f} = \sum_{a=0}^{A} \sum_{s} C^n_{a,s|t,r,f} \tag{2.20}$$

$$C_{|t,r,f} = \sum_{a=0}^{A} \sum_{s} C_{a,s|t,r,f} = U_{|t,r,f} B^{sr,p}_{|t,r,f} \tag{2.21}$$

where $B^{sr,p}_{|t,r,f}$ is the selected and retained biomass for sector f, and will be discussed later.

Discarded fish-at-age (fish caught but not retained) that suffer mortality after release (discard mortality) are an additional source of fishing mortality not accounted for in the retained catch. Discard mortality is calculated as

$$\begin{aligned}
D^n_{a,s|t,r,f} &= N^p_{a,s|t,r} U_{|t,r,f} S_{a,s|t,r,f} \left(1 - R_{a,s|t,r,f}\right) d_{a,s|t,r,f} \\
D_{a,s|t,r,f} &= N^p_{a,s|t,r} W_{a,s,|t,r,f} U_{|t,r,f} S_{a,s|t,r,f} \left(1 - R_{a,s|t,r,f}\right) d_{a,s|t,r,f}
\end{aligned}$$

where $d_{a,s|t,r,f}$ is the discard mortality rate (DMR) and $(1 - R_{y,a,s,f})\, d_{y,a,s,r,f}$ is the proportion of selected fish that are released and do not survive. The summation of catch ($C_{|t,r,f}$) and discarded fish that die ($D_{|t,r,f}$) is the total mortality for sector f.

$$TM_{|t,r,f} = C_{|t,r,f} + D_{|t,r,f} \tag{2.22}$$

When modelling multiple fisheries occurring at different times, the calculation of N^p incorporates the mortality from fisheries that occurred previous to the sector of interest. The code may divide a time-step into sub-time-steps, but a more efficient method can be done using the probability that a fish survives an earlier sector in that time-step. The reader is referred to Appendix B for the details. The catch for a sector is

$$\begin{aligned}
C^n_{a,s|t,r,f} = {} & N_{a,s|t,r} e^{-p_f M_{a,s|t,r}} \times \\
& \prod_{i \in p_j < p_f} \left\{1 - U_{|t,r,i} S_{a,s|t,r,i} \left[R_{a,s|t,r,i} + (1 - R_{a,s|t,r,i}) d_{a,s|t,r,i}\right]\right\} \times \\
& U_{|t,r,f} S_{a,s|t,r,f} R_{a,s|t,r,f}
\end{aligned} \tag{2.23}$$

$$C_{a,s|t,r,f} = C^n_{a,s|t,r,f} W_{a,s|t,r} \tag{2.24}$$

where

$$N^p_{a,s|t,r} = N_{a,s|t,r} e^{-p_f M_{a,s|t,r}} \prod_{i \in p_j < p_f} \left\{1 - U_{|t,r,i} S_{a,s|t,r,i} \left[R_{a,s|t,r,i} + (1 - R_{a,s|t,r,i}) d_{a,s|t,r,i}\right]\right\}$$

and incorporates the product of the probabilities-at-age of surviving fisheries that occurred prior to the sector of interest (f). The total predicted catch for a sector in a region is shown in equation B.3.

Discarded fish-at-age (fish caught but not retained) that suffer mortality after release (discard mortality) is calculated in a similar manner.

$$\begin{aligned}
D^n_{a,s|t,r,f} = {} & N_{a,s|t,r} e^{-p_f M_{a,s|t,r}} \times \\
& \prod_{i \in p_j < p_f} \left\{1 - U_{|t,r,i} S_{a,s|t,r,i} \left[R_{a,s|t,r,i} + (1 - R_{a,s|t,r,i}) d_{a,s|t,r,i}\right]\right\} \times \\
& U_{|t,r,f} S_{a,s|t,r,f} \left(1 - R_{a,s|t,r,f}\right) d_{a,s|t,r,f}
\end{aligned} \tag{2.25}$$

$$D_{a,s|t,r,f} = D^n_{a,s|t,r,f} W_{a,s|t,r,f} \tag{2.26}$$

where $d_{a,s|t,r,f}$ is the discard mortality rate (DMR) and $(1 - R_{y,a,s,f})\, d_{y,a,s,r,f}$ is the proportion of selected fish that are released and do not survive. The summation of catch ($C_{|t,r,f}$) and discarded fish that die ($D_{|t,r,f}$) is the total mortality for sector f (equation 2.22) and can be written as

$$
\begin{aligned}
TM^{n}_{|t,r,f} &= \sum_{a=0}^{A}\sum_{s} N_{a,s|t,r} e^{-p_f M_{a,s|t,r}} \times \\
&\quad \prod_{i \in p_j < p_f} \left\{1 - U_{|t,r,i} S_{a,s|t,r,i} \left[R_{a,s|t,r,i} + (1 - R_{a,s|t,r,i}) d_{a,s|t,r,i}\right]\right\} \times \\
&\quad S_{a,s|t,r,f} \left[R_{a,s|t,r,f} + \left(1 - R_{a,s|t,r,f}\right) d_{a,s|t,r,f}\right]
\end{aligned} \tag{2.27}
$$

$$
\begin{aligned}
TM_{t,r,f} &= \sum_{a=0}^{A}\sum_{s} N_{a,s|t,r} e^{-p_f M_{a,s|t,r}} \times \\
&\quad \prod_{i \in p_j < p_f} \left\{1 - U_{|t,r,i} S_{a,s|t,r,i} \left[R_{a,s|t,r,i} + (1 - R_{a,s|t,r,i}) d_{a,s|t,r,i}\right]\right\} \times \\
&\quad S_{a,s|t,r,f} \left[R_{a,s|t,r,f} + \left(1 - R_{a,s|t,r,f}\right) d_{a,s|t,r,f}\right] W_{a,s|t,r,f}
\end{aligned} \tag{2.28}
$$

The selected-and-retained biomass for sector f in the population is simply the catch divided by the exploitation rate, but catch is an input and selected-at-retained biomass must be calculated from selectivity (S), proportion retained (R), and mean weight-at-age (W) to determine the exploitation rate U_f (equation B.11).

$$
\begin{aligned}
B^{sr,p}_{|t,r,f} &= \frac{C_{a,s|t,r,f}}{U_{|t,r,f}} \\
&= \sum_{a=0}^{A}\sum_{s} N_{a,s|t,r} e^{-p_f M_{a,s|t,r}} \times \\
&\quad \prod_{i \in p_j < p_f} \left\{1 - U_{|t,r,i} S_{a,s|t,r,i} \left[R_{a,s|t,r,i} + (1 - R_{a,s|t,r,i}) d_{a,s|t,r,i}\right]\right\} \times \\
&\quad S_{a,s|t,r,f} R_{a,s|t,r,f} W_{a,s|t,r,f}
\end{aligned} \tag{2.29}
$$

Therefore, natural and fishing mortality can be accounted for simultaneously, and the numbers-at-age in the next time-step, accounting for all mortality, are

$$
N^{''}_{a,s|t,r} = N^{'}_{a,s|t,r} e^{-M_{a,s|t,r}} \prod_{f} \left\{1 - U_{|t,r,i} S_{a,s|t,r,i} \left[R_{a,s|t,r,i} + (1 - R_{a,s|t,r,i}) d_{a,s|t,r,i}\right]\right\} \tag{2.30}
$$

See Appendix B for details.

The exploitation rate is defined to be between zero and one, but it is possible that the explotation rate may exceed one if the calculated exploitable biomass is less than the fixed input catch for a sector. If the exploitation rate for a specific sector exceeds 1, a negative population size may occur. Therefore, a maximum exploitation rate (U_{max}) must be specified, which is realistically less than one. If the exploitation rate for a sector exceeds the defined maximum, the exploitation rate for that sector should be set to the defined maximum. When this adjustment occurs, the predicted catch will be different than the input catch, and a penalty should be applied since catches are considered observed inputs (not data with error). This penalty will be discussed in a later section on conditioning.

2.3.5 Maturity

Maturity and spawning may be separated into two separate states with maturity being a part of the state object, and the numbers of mature fish specifically tracked as part of the state. However, this operating model does not partition maturity in the state, but instead simply determines the numbers of mature fish from mature proportions-at-age (called the maturity curve).

$$N^{ma}_{a,s|t,r} = N^{''}_{a,s|t,r}\Omega_{a,s|t,r} \tag{2.31}$$

Maturity functional forms and parameters

The maturity curve (Ω) may be an empirical vector of proportions input by the user from externally estimated data. Alternatively, the vector or proportions may be determined from a functional form, such as a logistic equation, with appropriate parameters defined.

$$\Omega_{a,s|t,r} = \frac{\omega_{max,s|t,r}}{1 + 19^{(\omega_{a50,s|t,r} - age)/(\omega_{a95,s|t,r} - \omega_{a50,s|t,r})}} \tag{2.32}$$

There are three parameters in this asymmetric logistic function.

1. $\omega_{max,s|t,r}$: The asymptote or maximum proportion mature at any age (ranges from 0 to 1).
2. $\omega_{a50,s|t,r}$: The age at which the proportion mature equals 50% of the asymptote for sex s, at time t, and in region r.
3. $\omega_{a95,s|t,r}$: The age at which the proportion mature is 95% of the asymptote for sex s, at time t, and in region r. Must be greater than $\omega_{a50,s|t,r}$.

2.3.6 Spawning biomass

The number of spawning individuals is the number that are mature at age times the proportion spawning at age. This allows for the accounting of individuals that are mature (able to produce gametes) but are not actively spawning in that time-step (e.g., skip spawning), and those that are mature and actively spawning in that time-step.

$$N^{sp}_{a,s|t,r} = N^{ma}_{a,s|t,r}\Phi_{a,s|t,r} \tag{2.33}$$

The spawning biomass (B^{sp}) is calculated as follows.

$$B^{sp}_{|t,r} = \sum_{a=0}^{A}\sum_{s} N^{sp}_{a,s|t,r}W^{1}_{a,s|t,r} \tag{2.34}$$

where $W^{1}_{a,s|t,r}$ is the weight-at-age for that age, sex, time-step, and region at the end of the time-step.

Most sex-specific stock assessments account for only the female spawning biomass, which would simply be

$$B^{sp}_{s=1|t,r} = \sum_{a=0}^{A} N^{sp}_{a,s=1|t,r} W^{1}_{a,s=1|t,r} \tag{2.35}$$

Spawning proportion parameters

The proportions spawning (Φ) is a vector of proportions-at-age input by the user from externally estimated data. Typically, this vector contains a value of 1 for all ages because there is currently a paucity of information for many fish stocks.

2.3.7 Size-at-age

Growth is not modelled specifically (e.g, length-at-age), but weight-at-age is used to calculate biomass-at-age from numbers-at-age. Mean weight-at-age, sex, and region for a particular time-step and sector ($W_{a,s|t,r,f}$, which will simply be referred to as weight-at-age regardless of the various partitions), is input by the user. Sector-specific weight-at-age are used because selectivity may operate on the larger fish of a certain age, resulting in a larger weight-at-age than in the population.

Projecting variability in weight-at-age is discussed in Section 2.5.

2.3.8 Initial population

The initial population is the partitioned population numbers at the start of the first modelled time-step, and is based on unfished equilibrium recruitment (R_0) with three potential adjustments.

1. An overall adjustment ($e^{\delta_{|I}}$) that changes R_0 (i.e., the overall scale of recruitment) and could mimic a different regime that influenced the initial population.
2. Cohort (a) specific adjustments to account for recruitment variability ($\varepsilon_{a|I}$).
3. Adjustments by age to account for an average level of fishing that occurred before the initial time-step: $\prod_f \left\{1 - U_{|t,r,f} S_{a,s|t,r,f} \left[R_{a,s|t,r,f} + (1 - R_{a,s|t,r,f}) d_{a,s|t,r,f}\right]\right\}$.

Calculating the initial equilibrium population size is not a simple calculation when region is in the partition and initial recruitment deviations are used. It is easiest to build up the population sequentially by each cohort that makes up the initial population using the sequence of processes described in Section 2.3: recruitment, movement, and mortality. This will be time-consuming, but only has to be done while an operating model is being conditioned.

The numbers at age 0 for the cohort that is age a in the initial time-step (I) for each sex and region is

$$N_{0,s|I-a,r} = p_s\, p_{a|I,r}\, e^{\delta_{|I}} R_0\, e^{\left(\varepsilon_{a|I}-\frac{\sigma_R^2}{2}\right)} \prod_f \left\{1 - U_{|I,r,f} S_{0,s|I,r,f}\left[R_{0,s|I,r,f} + (1-R_{0,s|I,r,f}) d_{0,s|I,r,f}\right]\right\} \tag{2.36}$$

where p_s is the proportion of sex s at birth ($\sum_s p_s = 1$) and $p_{a|I,r}$ is the proportion of cohort a recruiting to region r in the initial time-step ($\sum_r p_{|I,a,r} = 1$). It is assumed that there is a single selectivity curve for the initial time period that applies equally to all cohorts and a constant exploitation rate for all cohorts over their life-span before the initial time-step.

Equation 2.36 calculates the number for each cohort when they were age 0 prior to the initial time-step. To calculate the numbers-at-age in the initial time-step, the annual process for each cohort is iterated up to the age that each cohort would be in the initial time-step. For example, to calculate the cohort that is age 3 in the initial population, Equation 2.36 would first determine the number of that cohort that were born into the population three time-steps prior. Then, the population dynamics would apply to that cohort for three iterations (0 to 1, 1 to 2, and 2 to 3) to determine the numbers in that cohort at age 3 in the initial time-step. Therefore, the annual process for the cohort that is age a in the initial time-step is iterated from $i = a \ldots 1$ in the following equations. It begins by incrementing the annual process.

$$N_{a-i+1,s|I-i+1,r} = N_{a-i,s|I-i,r} \tag{2.37}$$

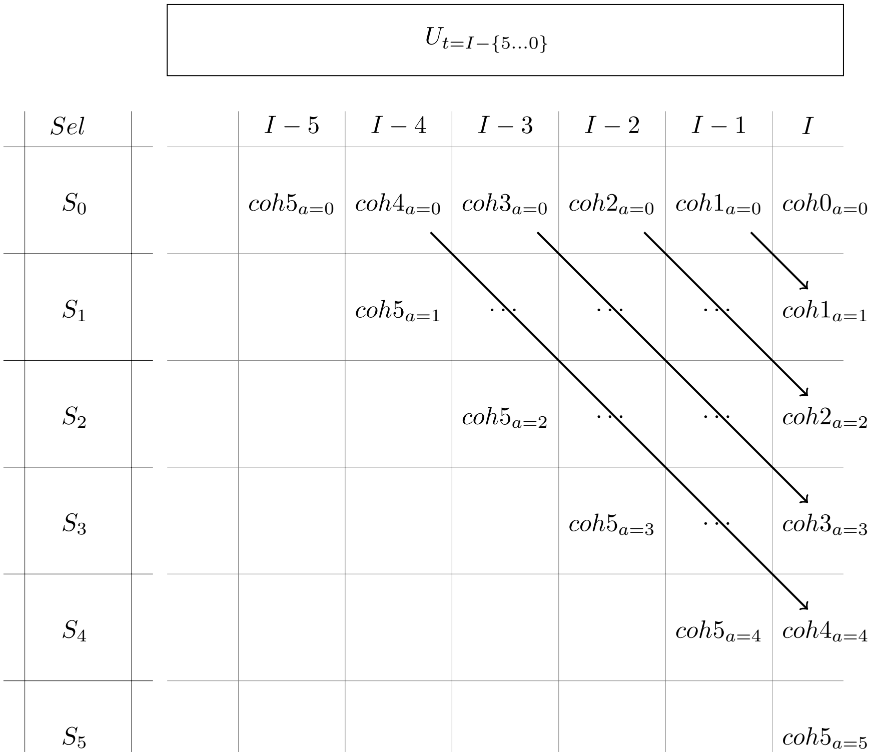
Then, movement from region j to k is applied. The subscripts for age, sex, and time-step are dropped for clarity in the derivation below, but are noted in the final equation. Also note that the movement-at-age, Psi, does not change in time-steps prior to the initial time-step.

$$\begin{aligned}
N'_{a-i+1,s|I-i+1,j} &= N_{|j} - N_{|j}\sum_{k\neq j}\Psi_{|j\to k} + \sum_{k\neq j} N_{|k}\Psi_{|k\to j} \\
&= N_{|j}\left(1 - \sum_{k\neq j}\Psi_{|j\to k}\right) + \sum_{k\neq j} N_{|k}\Psi_{|k\to j} \\
&= N_{|j}\Psi_{|j\to j} + \sum_{k\neq j} N_{|k}\Psi_{|k\to j} \\
&= \sum_{k\in r} N_{a-i+1,s|I-i+1,k}\Psi_{a-i+1,s|I,k\to j} \qquad (2.38)
\end{aligned}$$

Finally, natural and fishing mortality is applied. Subscripts for age, sex, and time-step are dropped for clarity, but are the same as in the left side of the equation unless indicated (e.g., M, U, S, R, and d).

$$N''_{a-i+1,s|I-i+1,r} = N'_{|r} e^{\left(-M_{|I,r}\right)} \prod_f \left\{1 - U_{|I,r,f} S_{|I,r,f}\left[R_{|I,r,f} + (1-R_{|I,r,f}) d_{|I,r,f}\right]\right\} \tag{2.39}$$

Graphically, the process will look like:



$U_{t=I-\{5...0\}}$

Sel		$I-5$	$I-4$	$I-3$	$I-2$	$I-1$	I
S_0		$coh5_{a=0}$	$coh4_{a=0}$	$coh3_{a=0}$	$coh2_{a=0}$	$coh1_{a=0}$	$coh0_{a=0}$
S_1			$coh5_{a=1}$	$\cdots$	$\cdots$	$\cdots$	$coh1_{a=1}$
S_2				$coh5_{a=2}$	$\cdots$	$\cdots$	$coh2_{a=2}$
S_3					$coh5_{a=3}$	$\cdots$	$coh3_{a=3}$
S_4						$coh5_{a=4}$	$coh4_{a=4}$
S_5							$coh5_{a=5}$

Table 2.3

	Years before Initial						
	$\dots$	I-5	I-4	I-3	I-2	I-1	I
Cohort							$coh0_{a=0}$
						$coh1_{a=0}$	$coh1_{a=1}$
					$coh2_{a=0}$	$coh2_{a=1}$	$coh2_{a=2}$
				$coh3_{a=0}$	$coh3_{a=1}$	$coh3_{a=2}$	$coh3_{a=3}$
			$coh4_{a=0}$	$coh4_{a=1}$	$coh4_{a=2}$	$coh4_{a=3}$	$coh4_{a=4}$
		$coh5_{a=0}$	$coh5_{a=1}$	$coh5_{a=2}$	$coh5_{a=3}$	$coh5_{a=4}$	$coh5_{a=5}$
	$\dots$	$\dots$	$\dots$	$\dots$	$\dots$	$\dots$	$\dots$

Summary of initial population numbers

To summarize how the initial numbers in the partitions are completed, psuedo code is provided below.

1. Determine the inital number of age zero ($i = 0$) fish for the cohort ("*coh*" in the schematic representation above) of age a from Equation 2.36, where $a = 0, 1, 2, \dots, nA$. The n is a multiplier on the plus group age A to simulate beyond the plus group to ensure the dynamics of the plus group are correct.

2. Loop over $a = 1, 2, \ldots, nA$. For each a,
    (a) loop over $i = a, a-1, \ldots, 2, 1$ applying Equations 2.37, 2.38, and 2.39 to build up the initial numbers for each cohort at age a.
3. sum numbers over $a = A, A+1, \ldots, nA$ to create the plus group (A).

A value of 3 is typically used for n, but it depends on the plus group age and the time willing to spend iterating over ages.

Calculation of other initial population values

Initial spawning biomass is calculated after the initial numbers-at-age are completed.

$$B^{sp}_{|I,r} = \sum_{a=0}^{A}\sum_{s} N^{''}_{a,s|I,r}\Omega_{a,s|I,r}\Phi_{a,s|I,r}W^{1}_{y,a,s,r} \tag{2.40}$$

Population Dynamics

The sequence

1. *age increment*,
2. *spawning (or may occur at end)*,
3. *recruitment*,
4. *movement*,
5. *mortality*, and
6. *spawning (or may occur at beginning)*.

The notation

N : Beginning of the time-step after age increment and recruitment.
$N^{'}$: After movement before mortality
$N^{''}$: End of the time-step, after natural and fishing mortality

The equations

$$N_{y,a,s,r,m} = \begin{array}{ll} R_{s|t,r} & a = 0 \\ N_{a-1,s|t-1,r} & 1 \leq a < A \\ N_{a-1,s|t-1,r} + N_{a,s|t-1,r} & a = A \end{array}$$

$$N^{'}_{a,s|t,r} = \sum_{k \in r} N_{a,s|t,k}\Psi_{a,s|t,k \to r}$$

$$N^{''}_{a,s|t,r} = N^{'}_{a,s|t,r}e^{-M_{a,s|t,r}}\prod_{f}\left\{1 - U_{|I,r,f}S_{|I,r,f}\left[R_{|I,r,f} + (1 - R_{|I,r,f})d_{|I,r,f}\right]\right\}$$

2.3.9 Parameter evolution through time

A description of deviations applied to parameters.

2.4 Conditioning the Operating Models

2.4.1 Observations and Data

The current assessment used eight categories of observations and data in the modelling and fitting process (IPHC-2020-SA-01, https://iphc.int/uploads/pdf/sa/2020/iphc-2020-sa-01.pdf). A detailed description of the various data used in the stock assessment and related data sets are provided in IPHC-2020-SA-02 (https://iphc.int/uploads/pdf/sa/2020/iphc-2020-sa-02.pdf). Below is a description of the categories of data/observations and what may be available for use in conditioning the multi-area operating model, including data that may not currently be used in the stock assessment.

Fishing mortality

The mortality of Pacific halibut due to fishing (i.e., landings and discard mortality) are not treated as data in the stock assessment because they are entered as fixed, known values without error (empirical observations). Fishing mortality is a very important driver of the population dynamics.

Sectors

FISS Indices

These data are an annual relative index of abundance or biomass. They represent changes in abundance or biomass from year to year, but do not represent the absolute scale. Fishery-Independent Setline Survey (FISS) numbers-per-unit-effort (NPUE), survey weight-per-unit-effort (WPUE), and fishery catch-per-unit-effort in weight (CPUE) are available for Pacific halibut. The survey index in numbers-per-unit-effort (NPUE) is available coastwide, by Biological Region, or by IPHC Regulatory Area.

FISS Age Compositions

These data are the numbers-at-age of Pacific halibut (commonly in proportions) in the survey catches and fishery catches. Survey observations are available for each sex and two years of separate sex data are currently available for fishery landings (2017 and 2018). Differences in sex ratios inform differences in selectivity, availability, and potentially movement between areas.

Fishery CPUE

These data are an annual relative index of abundance or biomass. They represent changes in abundance or biomass from year to year, but do not represent the absolute scale. Fishery-Independent Setline Survey (FISS) numbers-per-unit-effort (NPUE), survey weight-per-unit-effort (WPUE), and fishery catch-per-unit-effort in weight (CPUE) are available for Pacific halibut.

Fishery Age Compositions

These data are the numbers-at-age of Pacific halibut (commonly in proportions) in the survey catches and fishery catches. Survey observations are available for each sex and two years of separate sex data are currently available for fishery landings (2017 and 2018). Differences in sex ratios inform differences in selectivity, availability, and potentially movement between areas.

Weight-at-age

These data are the weight-at-age of Pacific halibut observed from various sources and are commonly summarized as the average weight-at-age. They are entered as empirical data in the stock assessment and are not involved in the fitting process.

Maturity-at-age

There are limited data on maturity-at-age for Pacific halibut and a single ogive representing the probability of being mature at each age is used to calculate fecundity and entered as empirical data.

Environmental Observations

The Pacific halibut stock assessment uses an index linked to average recruitment (high or low) that is developed from the Pacific Decadal Oscillation (PDO).

Additional environmental observatiosn may be useful to condition the multi-area operating model. These may be ocean temperatures or prey abundance, for example.

Other Surveys

There are many other surveys that catch Pacific halibut, including NMFS trawl and longline surveys. These data may inform abundances of various cohorts in specific areas.

Lengths

Length data are not used in the age-structured stock assessment model but more samples are available coastwide than age data. They may be useful to investigate differences between areas.

Stock distribution

The stock distribution estimated from FISS data are available by IPHC Regulatory Area and by Biological Region. Changes in this distribution over time may indicate differences in fishing pressure between areas and may also inform movement.

Tag returns

Tagging data are useful to inform movement, migration, and mortality. There are many years of tag releases and returns for Pacific halibut, which are mostly informative of movement between specific areas. The synthesis of this information over amny years can provide an insight into the movement of Pacific halibut.

2.4.2 Predictions from the stock assessment

The stock assessment integrates various data sources to predict population quantities as well as uncertainty in those quantities. Four inidividual models are combined in an ensemble to account for structural and parameter uncertainty. Two of the individual models incorporate a short time-series starting in 1993, thus only predictions from 1993 onward can be supplied by the ensemble.

2.5 Projecting the Operating Models

2.5.1 Recruitment

See IPHC-2018-MSAB012-07. Discuss regimes, PDO, and recruitment variability.

2.5.2 Fishing mortality

Based on the management procedure. Mimic catch sharing plans by IPHC Regulatory Area to determine allocation across sectors. Selectivity deviations for commercial fishery and survey.

2.5.3 Movement

Annual variability in movement yet to be determined.

2.5.4 Weight-at-age

Projected values of weight-at-age are modelled using a random walk to introduce inter-annual variability. Done by region with some synchrony.

2.6 Reference Points

Unfished, equilibrium spawning biomass at the start of the year was found using weight-at-age, maturity-at-age, natural mortality, and unfished, equilibrium recruitment (R_0).

$$B_0 = R_0 \left[\sum_{a=1}^{A-1} e^{-M(a-1)} \overline{w}_a m_a + \frac{e^{-M(A-1)} \overline{w}_A m_A}{1 - e^{-M}} \right] \tag{2.41}$$

Unfished equilibrium spawning biomass (i.e., B_0) requires the definition of many parameters (e.g., weight-at-age) that are likely time-varying, thus the spawning biomass will fluctuate without fishing. Therefore, dynamic calculations of unfished equilibrium spawning biomass are calculated using information from recent years. This is a measure of the stock size if fishing had not occurred and is useful to calculate a stock status that is reflective of the effect of fishing and not the environment.

Dynamic unfished quantities are calculated by simulating a 'shadow' state alongside the fished state. All parameters (including deviations) are the same, except that the 'shadow' state does not have any fishing mortality. The additional processing time is minimal because the 'shadow' state is entirely processed in memory with almost negligible additional reading or writing to disk and the fishing processes are not called, which are typically a large part of the processing time.

The calculation of Total Mortality based on SPR...

Chapter 3

Specifications for the Pacific halibut MSE framework

The Management Strategy Evaluation for Pacific halibut is currently being used to investigate management procedures to set the coastwide mortality limit (coastwide scale) and determine catch limits for each IPHC Regulatory Area (distribution of mortality limits, Figure 3.1). This requires a multi-area operating model with fleets represented within IPHC Regulatory Areas. The specifications for this MSE are provided below.

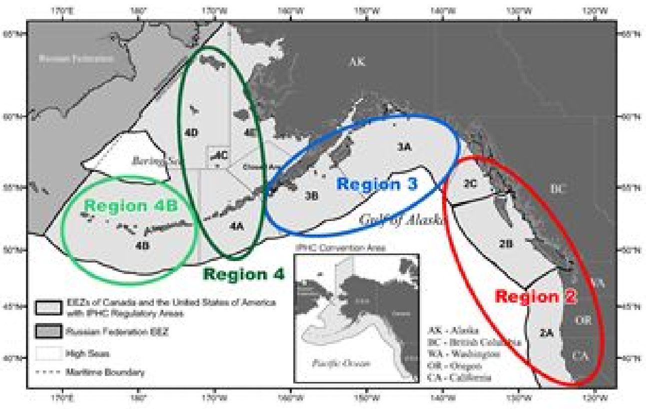


Figure 3.1: IPHC Regulatory Areas (grey shaded areas) and Biological Regions (colored circles).

There are many parameters that make up the Operating Model including population parameters and fishery parameters. Some of the parameters are simply a set parameter that drives the population, and are called input parameters. Derived parameters are calculated from parameters, inputs, and outputs. An example is that natural mortality (M) is an input parameter that in combination with other parameters results in the spawning biomass (a derived parameter). Parameters are described below.

3.1 Management Procedures

3.1.1 Data Generation

The OM provides outputs that can be used to generate data from the Pacific halibut stock. In particular, for each year in the simulation the model provides numbers-at-age in the stock by sex and region, numbers-at-age in the catch by sex, region and fishery sector, numbers-at-age available to each fishery at a specific point in time, selectivity-at-age by fishery sector, and weight-at-age by sex, region and fishery sector. From these outputs it would be possible to obtain all the inputs currently used in the stock assessment. To maintain consistency between the various elements needed by the Estimation Model (EM) and with the way data are collected in reality, all quantities are first generated at an IPHC Regulatory Area level and then aggregated to a coastwide level.

Coastwide total mortality The total mortality (TM) for a fishery is set equal to the TCEY resulting from the application of the harvest control rule, but may be modified in the OM to account for implementation error. Therefore, the coastwide total mortality required by the assessment is obtained by summing the total mortality from each fishery.

Proportion at age in the catch and in the survey. Proportion-at-age in the catch by fishery sector are derived from the numbers-at-age available to each fishery sector at a specific point in time times the selectivity-at-age for each specific fishery sector. From this exploitable abundance-at-age the proportions-at-age are calculated.

$$pNAA_{a,s|t,r} = \frac{(N_{a,s|t,r} \times S_{a,s|t,f})}{\sum_{a=0}^{A} N_{a,s|t,r}} \tag{3.1}$$

where $N_{a,s|t,r}$ are the numbers-at-age in the population available to a specific fishery sector f, $S_{a,s|t,f}$ is the selectivity by age and sex for each year and fishery sector f. Observation error is implemented by means of a Dirichlet distribution, using a sample size (3.1.1) as scale parameter. The generated proportion-at-age by fishery sector are then multiplied by the fishery sector total mortality in number, to calculate catch-at-age in numbers per each fishery sector. These catch-at-age are aggregated to a coastwide level, and the proportions-at-age by sector are re-calculated to be used in the EM.

Sample size The number of fish aged for each fishery (sample size) is used as the scale parameter for the Dirchlet distribution. The total coastwide number of fish aged in a specific year is also an input of the estimation model. Two options are suggested for the calculation of the sample size:

1. the sample size by Biological Region is generated from the sample size by Biological Region used in the long coastwide assessment model: in particular, the sample size is randomly drawn from the sample size available historically for each fishery sector.

2. the sample size by Biological Region is generated directly using a fixed proportion of the total mortality by fishery sector or total abundance by Biological Region:
   - sample size for the directed commercial, non-directed commercial discard mortality, recreational and subsistence sectors: for each sector, the sample size is calculated using a fixed proportion of the total mortality by Biological Region and sector.
   - sample size for survey and directed commercial discard mortality sectors: for each sector, the sample size is calculated using a fixed proportion of the available numbers-at-age by region.

   The proportion chosen could be an average derived from observations on the historical data.

Survey NPUE and commercial WPUE. The Fishery Independent Setline Survey (FISS) NPUE ($I_{t,r}^{sur}$) and the commercial WPUE ($I_{t,r}^{comm}$) are needed for the EM at a coastwide level, and for the MP at a Biological Region or IPHC Regulatory Area level. The OM produce the numbers-at-age available to the survey and the numbers-at-age available to the directed commercial sectors: from these values, the exploitable abundance and biomass are calculated at a Biological Region level. These are then multiplied by the catchability for each specific Biological Region.

$$I_{t,r}^{sur} = q_{t,r}^{sur} \sum_{a=0}^{A} N_{a,s|t,r} \times S_{a,s|t,f} \tag{3.2}$$

$$I_{t,r}^{comm} = q_{t,r}^{comm} \times \sum_{a=0}^{A} N_{a,s|t,r} \times S_{a,s|t,f} \times W_{a,s|t,f} \tag{3.3}$$

Some of the harvest control rules require the provision of the over 32 inches (O32) stock distribution at biological region and regulatory area level. In this case, the numbers-at-age are multiplied by the probability of each age to be 32 inches or bigger (see section **??**):

$$I_{t,r}^{sur} = q_{t,r}^{sur} \sum_{a=0}^{A} N_{a,s|t,r,f} \times O32prob_{a,s} \times S_{a,s|t,f} \tag{3.4}$$

(3.5)

Regional q is specified as a relative q by region (i.e. Biological Region 3 will have $q = 1$, and the other regional q will be relative to this one) whose weighted mean (where the weight is the survey bottom area and the commercial catch for the NPUE and WPUE respectively) will equal the coastwide q. The proportion of each regional q relative to q in Biological Region 3 was arbitrarily fixed to the average of the last 20 years (Fig 3.2)

To derive the indices at the IPHC Regulatory Area level, as required by some of the MPs, the exploitable abundance and biomass are partitioned to each IPHC Regulatory Area using an average of the historical stock distribution from the modelled FISS survey (Fig 3.3). The catchability is assumed to be equal for each IPHC Regulatory Area in a Biological Region.

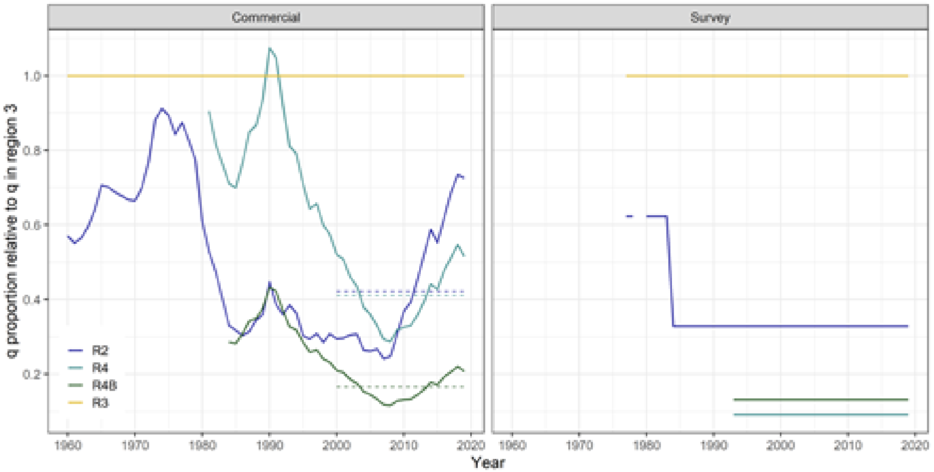


Figure 3.2: Proportion of each regional q relative to Biological Region 3 for the commercial WPUE (left) and the survey NPUE (right). The average of the years 2000 to 2019 is shown as a dotted line.

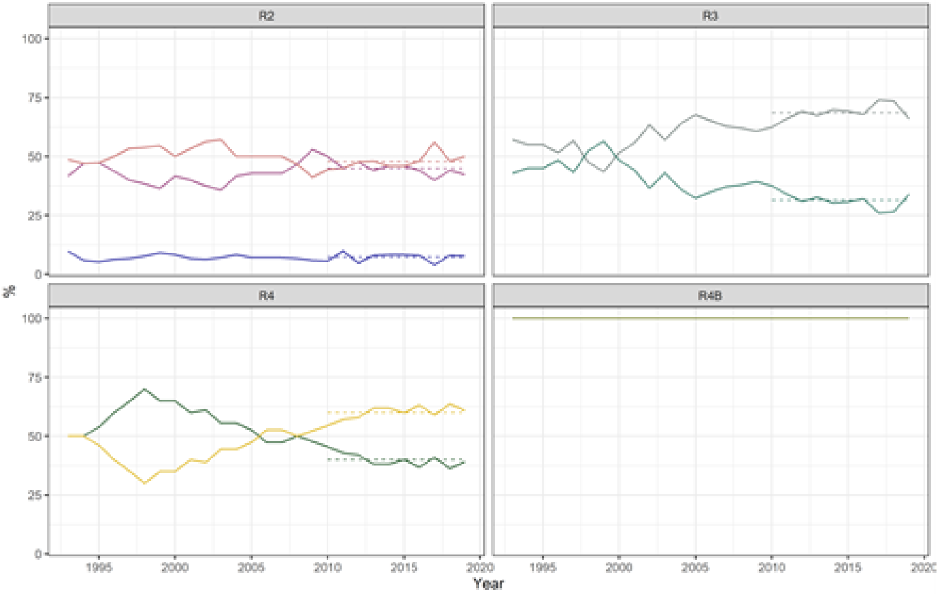


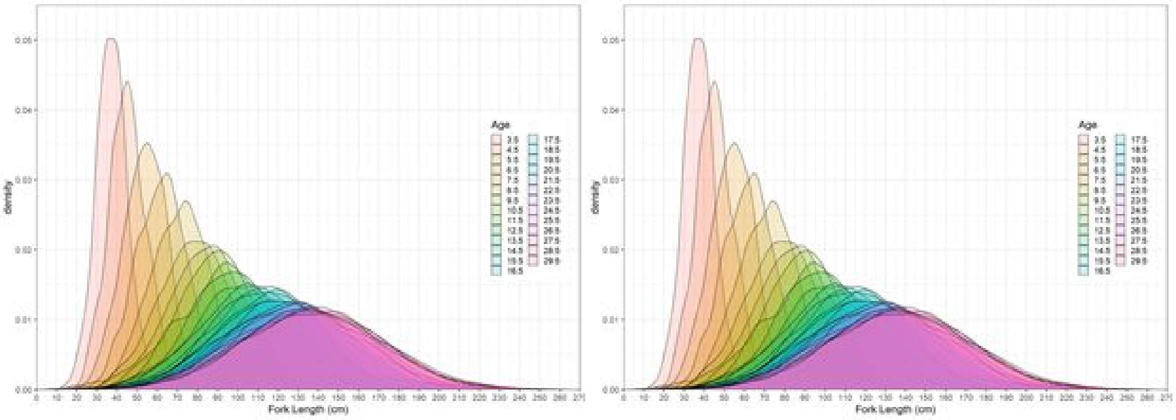
Figure 3.3: Proportion of stock distribution in each IPHC Regulatory Area by Biological Region from the modelled FISS survey. The 10 year average is shown as a dotted line.

In the base case the catchability coefficient is time invariant. Alternative scenarios will test a time variant catchability parameter modeled as a random walk of the coastwide q or of the regional q as a function of the abundance in each Biological Region.

The coastwide NPUE and WPUE will be calculated as the weighted average of the indices for each Biological Region. The weights are the survey bottom area and the commercial catch for the NPUE and WPUE, respectively.

3.1.2 Modelling length-at-age

Fish have different lengths within age groups and this variability was modelled using probability distributions. The data used to inform the model are the length-at-age distribution resulting from the long coastwide SS model used in the ensemble for Pacific halibut (section `Biology_at_age_in_endyr_with_CV` of the report file). One-thousand randomly generated values with mean equal to the average length-at-age-and standard deviation of length-at-age were drawn from a normal distribution for males and females separately (Figure 3.4).



(a) Females **(b)** Males

Figure 3.4: Length distribution at ages 3 to 25 for females and males of Pacific halibut

For each age group, the proportion of fish within each lenght bin l for age a and gender s is equal to:

$$\Phi_{s,a,l} = \begin{cases} \Phi\frac{L'_m in-\widetilde{L}_{s,a}}{\sigma_{s,a}} & l = 1 \\ \Phi\frac{L'_{l+1}-\widetilde{L}_{s,a}}{\sigma_{s,a}} - \Phi\frac{L'_l-\widetilde{L}_{s,a}}{\sigma_{s,a}} & 1 < l < A_l \\ 1 - \Phi\frac{L'_m ax-\widetilde{L}_{s,a}}{\sigma_{s,a}} & l = A_l \end{cases} \tag{3.6}$$

where Φ is the standard normal cumulative density function, L'_l is the lower limit of the smallest bin, L'_l is the lower limit of the length bin l, $L'_m ax$ is the lower limit of the largest bin.

The proportion of fish in each age class above 32 inches are then summed up (Fig 3.5).

3.1.3 Estimation Model

The estimation model chosen for Pacific halibut uses two stock synthesis (v. 3.30.13) models mimicking the short coastwide and long coastwide models in the stock assessment. This approach

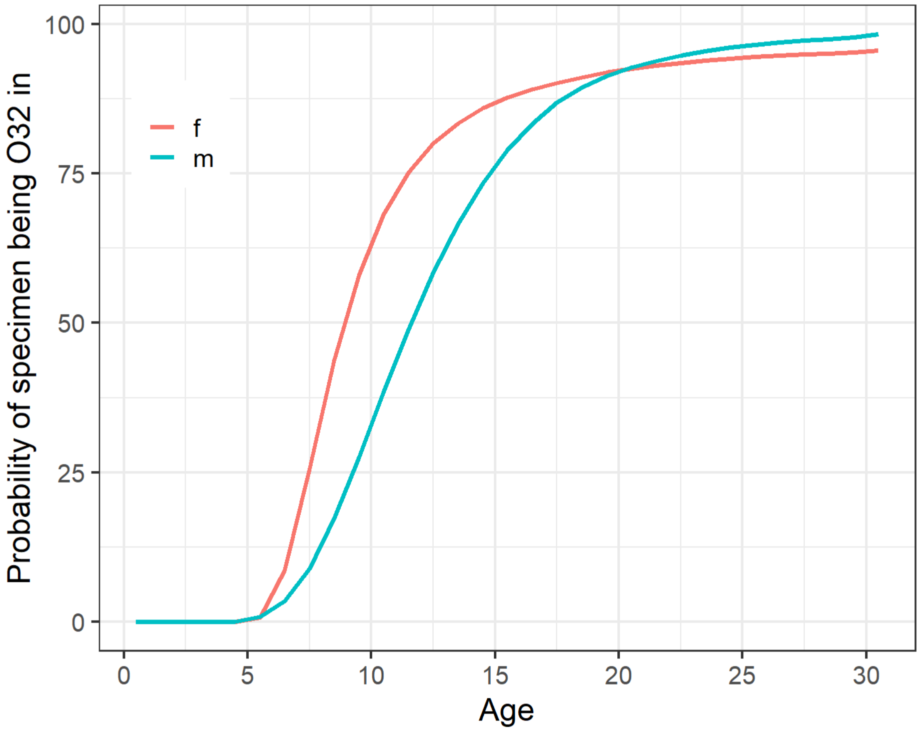


Figure 3.5: Proportion of fish above 32 inches by sex

aims at capturing the correlated error and potential biases in the estimated management quantities. The two stock synthesis models are averaged to represent a simplified version of the stock assessment ensemble currently used for Pacific halibut. The coastwide models (long and short coastwide) were chosen from the four currently used in the stock assessment ensemble and were streamlined to increase efficiency and to reduce the time of the MSE simulations, yet retain the complexity and uncertainty captured by the full stock assessment ensemble. The short and long coastwide models represent the uncertainty in natural mortality rates (estimated in the long time-series but fixed for females in the short time-series), the environmental effect on recruitment (estimated only in the long time-series), as well as other structural and parameter assumptions.

The streamlining of the coastwide models consisted of:

- Reducing the amount of data included (e.g. fewer years with age composition, long coastwide model starting from 1935, etc.)
- Using the optimized version of stock Synthesis (SS 3.30.13)
- Fixing annual deviations in selectivity parameters for the historical time series, and estimate only the deviations for the most recent 10 years.
- Using the ss.par file from the original assessment model for the starting parameters values

To speed up the estimation time, the hessian is not estimated, the estimation of parameters start after the last phase (so all parameters are estimated at the same time), and screen outputs are reduced to a minimum.

See IPHC-2020-SRB-08 for more description.

3.1.4 Harvest Rule

The harvest rule is the defined procedure that uses outputs from data generation and the estimation models to determine mortality limits for each fishery. Currently, this uses a fishing mortality rate based on SPR, a control rule to reduce the fishing intensity below specified stock sizes, and a distribution procedure to distribute the coastwide TCEY to each IPHC Regulatory Areas and then to each fishery. Different specifications of the harvest rule are the main focus for investigation of management procedures for Pacific halibut.

3.2 Population structure

To simulate the distribution of mortality and determine how management procedures meet objectives specific to IPHC Regulatory Areas and fisheries, the operating model will have to include multiple regions with migration between them. Biological Regions (Figure 3.1) have been defined based on current knowledge of movement as well as biological understanding. A Biological Region is larger than an IPHC Regulatory Area (Figure 3.1), but fisheries operate at the level of the IPHC Regulatory Area or finer. Movement will not be specifically modelled between areas within a region, but movement will always be modelled between regions. Even though the computer program for the operating model allows flexibility to define any arrangement of regions and areas, with movement modelled between Biological Regions, it would be moot to model movement within a Biological Region on an annual time-step because it is assumed that a fish may be anywhere within the region within a year. The modelling of fisheries in separate areas is described below. Additionally, the detailed understanding of movement within a Biological Region is not well understood and would be difficult to parameterize.

3.2.1 Input population parameters

3.2.2 Derived population parameters

3.3 Structure of the fisheries

The annual mortality limits determined for various fishery sectors occur at the level of IPHC Regulatory Areas (Figure 3.1). However, some fisheries for Pacific halibut may operate at a finer scale than an IPHC Regulatory Area. The best definition of fishery areas was determined from the objectives defined for the MSE, input from stakeholders, as well as the availability of knowledge to parameterize the fisheries for simulation, which is likely at the IPHC Regulatory Area level. This can be done when modelling the population at larger Biological Regions by defining separate sectors within a region, and using separate selectivity curves and exploitation rates to account for the availability of Pacific halibut to a particular sector (see Section **??**). This assumes that each fishery within a Biological Region operates on the same pool of fish, but each fishery encounters those fish differently.

See IPHC-2020-SRB016-08 for a description of the fisheries included in the OM.

3.3.1 Fishery parameters

Parameters for each fishery were determined from the 2019 long AAF assessment model. Selectivity for the directed commercial and survey fisheries were made asymptotic because movement should account for at least some of the differences in availability between Biological Regions.

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Appendix A

Parameters and notation

Table A.1: Dimension and partition notation in the operating models (used as subscripts).

Parameter	**Description**
y	Year.
a	Age. A capital A indicates the maximum age.
s	Sex, which includes female, male, and unsexed, in that order, labeled 1, 2, and 3.
r	Region with movement occurring between regions.
r_l	Area within region. Movement is not modelled between areas.
im	Immature state of the maturity partition.
ma	Mature state of the maturity partition.
sp	Spawning state calculated from the maturity partition. Note that this is not a specific partition in the state object.
f	Fishery sector.
I	Initial, meaning the starting time-step.

Table A.2: Parameters in the operating models.

Parameter	**Description**
Population dynamics parameters	
$N_{y,a,s,r,m}$	Numbers for year, age, sex, region, and maturity
B_0	Unfished equilibrium biomass
R_0	Unfished equilibrium recruitment
$B_{y,a,s,r,m}$	Biomass at the beginning of year y (and possibly other partitions as noted)
$B^M_{y,a,s,r,m}$	Mature biomass at the beginning of year y
$B^S_{y,a,s,r,m}$	Spawning biomass at the beginning of year y
$B^R_{y,r,f}$	Biomass selected and retained by sector f in year y
$M_{y,a,s,r}$	Natural mortality
$W_{y,a,s,r}$	Mean weight-at-age in year y (and possibly other partitions)
Ω	Proportion of mature individual at age, or the proportion transitioning from immature to mature at age, depending on partioning maturity in the state object.
Φ	Proportion of spawning individuals at age
$\Psi_{j \to k}$	Movement rate from area j to area k
ρ_1	Parameter for Type II functional response of movement from area 1 to area 2
ρ_2	Parameter for Type II functional response of movement from area 1 to area 2
p_s	Proportion of females at birth.
$p_{y,r}$	Proportion of recruitment in region r in year y. Sums to one over regions.
p_f	Proportion of natural mortality that occurs before exploitation from sector f occurs.

Table A.2 continued.

Parameter	**Description**
Fishing mortality related parameters	
$C_{y,a,s,r,f}$	Catch (in weight) for year, age, sex, region, and sector. Catch summed over age and sex ($C_{y,r,f}$) is typically an input to the model.
$C^N_{y,a,s,r,f}$	Catch (in numbers) for year, region, and sector.
$U_{y,r,f}$	Exploitation rate for sector f
$S_{a,f}$	Selectivity-at-age for sector f
$R_{a,f}$	Proportion retained-at-age for sector f
Survey parameters	
Z_j	Survey index for year j
q	Survey catchability
τ_j	Error in year j for the survey series
$\sigma^2_{\tau_j}$	Total variability of the survey in year j
CPUE parameters	
$U_{u,i}$	CPUE for year i
α	Multiplier in relationship between CPUE and abundance for the CPUE series
β	Nonlinearity parameter in relationship between CPUE and abundance
ν_i	Error in year i for CPUE series
$\sigma^2_{\nu_i}$	Total variability of the CPUE series in year i

Appendix B

Fishing mortality using exploitation rates: two approaches

This appendix presents two methods to determine catch and exploitation rates when modelling the fisheries with an exploitation rate (finite or Pope's approximation) instead of the instantaneous formulation (i.e. Baranov equation). The benefit of using an exploitation rate is that the code does not have to iterate to find the fishing mortality rate (i.e., there is not closed-form solution for the Baranov formulation). This will speed up the simulation time.

These equations have been simplified to show the concept. For example, retention and discard mortality are not considered, and sex and region subscripts have been ommitted. The subscripts remaining are a for age, t for time-step, and f for fleet/fishery. Superscripts are used to indicate specific about the quantity, such as n for numbers and sr for selected-retained (i.e., exploitable by a particular fleet), as well as the timing within the time-step (e.g., 0.25 would be one-quarter of the natural mortality in that time-step occurred).

B.1 Fisheries are independent and do not effect each other

To make things simpler, in a sense, we may make the assumption that the fisheries are independent of each other or they occur at exactly the same time. That means that the sequential nature of the fisheries does not have to be tracked, making the equations and accounting simpler. However, an additional complication is introduced in making sure that the total exploitation rate (sum over all fisheries) does not exceed a defined maximum (or a value of one).

Fishing mortality is parameterized with an exploitation rate and is assumed to occur at a specific point in time after a proportion of the mortality ($p_{|f}$) has occurred. The proportion may be equal for all fleets, and if not then it is assumed that the removals from a fleet operating before other fleets does not affect the biomass available to subsequent fleets (may be OK with small exploitation rates).

Catch at age and sex in numbers (C^n) or weight (C) for a sector in an area can be determined from the exploitation rate (U), selectivity (S), and mean weight-at-age (W). Note that retention is not listed to simplify the examples shown here.

$$C^n_{a|t,f} = U_{|t,f} N_{a|t} S_{a|t,f} e^{-p_f M_{a|t}} \tag{B.1}$$

$$C_{a|t,f} = U_{|t,f} N_{a|t} S_{a|t,f} W_{a|t,f} e^{-p_f M_{a|t}} \tag{B.2}$$

and the total predicted catch for a sector in a region is

$$C^n_{|t,f} = \sum_{a=0}^{A} C^n_{a|t,f} \tag{B.3}$$

$$C_{|t,f} = \sum_{a=0}^{A} C_{a|t,f} = U_{|t,f} B^{sr,p}_{|t,f} \tag{B.4}$$

Natural and fishing mortality can be accounted for simultaneously, and the numbers-at-age in the next time-step, after all mortality, can be simply determined with a single equation. Let's assume there are two fleets with the mortality from fleet 1 occurring after three fifths of the natural mortality ($p_{|1} = 0.6$) and the mortality from fleet 2 occurring after one-quarter of the natural mortality ($p_{|2} = 0.25$). The catch (in numbers) for each fleet is

$$C^n_{a|t,f=1} = N_{a|t} U_{|t,f=1} S_{a|t,f=1} e^{-0.6 M_a} \tag{B.5}$$

$$C^n_{a|t,f=2} = N_{a|t} U_{|t,f=2} S_{a|t,f=2} e^{-0.25 M_a} \tag{B.6}$$

The numbers-at-age in the next year, accounting for fishing mortality by removing the catch at the appropriate time, is

$$N_{a|t+1} = \left[\left[N_{t,a}e^{-0.25M_a} - C^N_{a|f=2}\right] e^{-(0.6-0.25)M_a} - C^N_{a|f=1}\right] e^{-(1-0.6)M_a} \tag{B.7}$$

Converting the catch (C^n) to exploitation rates using equation B.5 and simplifying produces the equation for N in the next time-step.

$$\begin{aligned} N_{a|t+1} &= \left[\left[N_{t,a}e^{-0.25M_a} - N_{a|t}U_{|t,f=2}S_{a|t,f=2}e^{-0.25M_a}\right] e^{-(0.6-0.25)M_a} - \right.\\ &\quad \left. N_{a|t}U_{|t,f=1}S_{a|t,f=1}e^{-0.6M_a}\right] e^{-(1-0.6)M_a} \\ &= \left[N_{t,a}e^{-0.25M_a}e^{-0.35M_a}(1 - U_{|t,f=2}S_{a|t,f=2}) - N_{a|t}U_{|t,f=1}S_{a|t,f=1}e^{-0.6M_a}\right] e^{-0.4M_a} \\ &= \left[N_{t,a}e^{-0.6M_a}(1 - U_{|t,f=2}S_{a|t,f=2}) - N_{a|t}U_{|t,f=1}S_{a|t,f=1}e^{-0.6M_a}\right] e^{-0.4M_a} \\ &= \left[N_{t,a}e^{-0.6M_a}(1 - U_{|t,f=2}S_{a|t,f=2} - U_{|t,f=1}S_{a|t,f=1})\right] e^{-0.4M_a} \\ &= N_{t,a}e^{-M_a}(1 - \sum_f U_{|t,f}S_{a|t,f}) \end{aligned} \tag{B.8}$$

This can be generalized to any set of $p_{|f}$ as long as the proportions are sorted from smallest to largest in the derivation. The sequential nature of the fleets does not need to be accounted for in the calculations.

However, a potential problem is that the sum of the exploitation rates in equation B.14 may exceed a value of one (or some defined maximum), which is theoretically impossible. Therefore, a maximum exploitation rate (U_{max}) must be specified, which is realistically less than one. To determine if the overall exploitation rate is greater than U_{max}, the partition-specific exploitation rates (e.g., age, sex, region, and fleet) for a time-step are summed across fleets within a region, and the maximum rate within a region over the partions are determined. This is called U^{maxObs}_y.

$$U^{maxObs}_{|t} = max_a\left(\sum_f S_{a|t,f}U_{|t,f}\right) \tag{B.9}$$

If $U^{maxObs}_y > U_{max}$, then

$$U_{|t,f} = \frac{U_{max}}{U^{maxObs}_{|t}}\frac{C_{|t,f}}{B^{sr,p}_{|t,f}} \tag{B.10}$$

which is simply an adjustment to the original exploitation rate ($U_{|t,f}$). When this adjustment occurs, the predicted catch will be different than the input catch, and a penalty should be applied since catches are considered observed inputs (not data with error).

Catch is an input and biomass is calculated as part of the modelling process, so the exploitation rate is calculated as the ratio between catch and exploitable biomass for a particular fleet.

$$U_{|t,f} \quad = \quad \frac{C_{|t,f}}{B^{sr,p}_{|t,f}} \tag{B.11}$$

where $C_{|t,r,f}$ is the catch in time-step t and region r for sector f, and $B^{sr}_{|t,r,f}$ is the selected-and-retained (exploitable) biomass for that fishery.

The exploitable biomass is calculated from the numbers-at-age (N), selectivity (S), and mean weight-at-age (W).

$$B^{sr,p}_{|t,f} \quad = \quad \sum_{a=0}^{A} N_{a|t} S_{a|t,f} W_{a|t,f} e^{-p_{|f} M_{a|t}} \tag{B.12}$$

B.2 Fisheries are sequential and earlier fisheries effect later ones

The more appropriate way to model the fisheries, but more complex in terms of accounting, is to account for the decline in the population from fisheries occuring before later fisheries. For example, as above, let's assume there are two fleets with the mortality from fleet 1 occurring after three fifths of the natural mortality ($p_{|1} = 0.6$) and the mortality from fleet 2 occurring after one-quarter of the natural mortality ($p_{|2} = 0.25$). The "pulse" fishing activity of fleet 2 causes a reduction in the population by the time fleet 1 operates its fishery, and the catch (in numbers) for each fleet would be calculated as follows.

$$\begin{aligned}
C^{n}_{a|t,f=2} &= N_{a|t} e^{-p_2 M_{a|t}} U_{|t,2} S_{a|t,2} \\
C^{n}_{a|t,f=1} &= \left(N_{a|t} e^{-p_2 M_{a|t}} - C^{n}_{a|t,f=2} \right) U_{|t,1} S_{a|t,1} e^{-(p_1 - p_2) M_{a|t}} \\
&= \left(N_{a|t} e^{-p_2 M_{a|t}} - U_{|t,2} S_{a|t,2} e^{-p_2 M_{a|t}} N_{a|t} \right) U_{|t,1} S_{a|t,1} e^{-(p_1 - p_2) M_{a|t}} \\
&= N_{a|t} e^{-p_2 M_{a|t}} \left(1 - U_{|t,2} S_{a|t,2} \right) U_{|t,1} S_{a|t,1} e^{-(p_1 - p_2) M_{a|t}} \\
&= N_{a|t} e^{-p_1 M_{a|t}} \left(1 - U_{|t,2} S_{a|t,2} \right) U_{|t,1} S_{a|t,1}
\end{aligned}$$

Generally,

$$C^{n}_{a|t,f} \quad = \quad U_{|t,f} S_{a|t,f} e^{-p_f M_{a|t}} N_{a|t} \prod_{f' \in p_{j \neq f} < p_f} \left(1 - U_j S_{a|t,f'} \right) \tag{B.13}$$

where $(1 - U_j S_{a|t,f'})$ is the probability of surviving a fishery that occurs before the fishery for fleet f. This requires some additional logic to determine which fisheries have occurred before the fishery of interest to properly account for that preceeding mortality.

The numbers-at-age in the next time-step can be derived in a similar manner as above, except using the newly defined catch equations.

$$N_{a|t+1} = \left[\left[N_{t,a} e^{-0.25M_a} - C^N_{a|f=2}\right] e^{-(0.6-0.25)M_a} - C^N_{a|f=1}\right] e^{-(1-0.6)M_a} \tag{B.14}$$

Converting the catch (C^N) to exploitation rates using equation B.13 and simplifying produces the equation for N in the next time-step.

$$\begin{aligned}
N_{a|t+1} &= \Big[\left[N_{a|t} e^{-0.25M_a} - N_{a|t} U_{|t,f=2} S_{a|t,f=2} e^{-0.25M_a}\right] e^{-(0.6-0.25)M_a} - \\
&\qquad N_{a|t} U_{|t,f=1} S_{a|t,f=1} e^{-0.6M_a} (1 - U_{|t,f=2} S_{a|t,f=2})\Big] e^{-(1-0.6)M_a} \\
&= \left[N_{a|t} e^{-0.6M_a} (1 - U_{|t,f=2} S_{a|t,f=2}) - N_{a|t} U_{|t,f=1} S_{a|t,f=1} e^{-0.6M_a} (1 - U_{|t,f=2} S_{a|t,f=2})\right] e^{-0.4M_a} \\
&= \left[N_{a|t} e^{-0.6M_a} (1 - U_{|t,f=2} S_{a|t,f=2})(1 - U_{|t,f=1} S_{a|t,f=1})\right] e^{-0.4M_a} \\
&= N_{a|t} e^{-M_a} \prod_f (1 - U_{|t,f} S_{a|t,f}) \qquad \text{(B.15)}
\end{aligned}$$

This is simply the numbers-at-age in the current time-step times the survival from natural causes times the survival from each fishery. With this formulation, adjusting for a maximum exploitation rate is not necessary, other than ensuring that each fleet-specific exploitation rate does not exceed a value of one (or a defined maximum).

Catch is an input and biomass is calculated as part of the modelling process, so the exploitation rate is calculated as the ratio between catch and exploitable biomass for a particular fleet, as shown in B.11.

The exploitable biomass is calculated from the numbers-at-age (N), selectivity (S), and mean weight-at-age (W), and accounts for the decrease in abundance due to fisheries that occurred previously.

$$
\begin{aligned}
B^{sr,p}_{|t,f=2} &= \sum_{a=0}^{A} N_{a|t} S_{a|t,2} W_{a|t,2} e^{-p_{|2} M_{a|t}} && \text{(B.16)} \\
B^{sr,p}_{|t,f=1} &= \sum_{a=0}^{A} \left(N_{a|t} e^{-p_{|2} M_{a|t}} - C^{n}_{a|t,2} \right) S_{a|t,1} W_{a|t,1} e^{-(p_{|1} - p_{|2}) M_{a|t}} && \text{(B.17)} \\
&= \sum_{a=0}^{A} \left(N_{a|t} e^{-p_{|2} M_{a|t}} - U_{|t,2} S_{a|t,2} e^{-p_{2} M_{a|t}} N_{a|t} \right) S_{a|t,1} W_{a|t,1} e^{-(p_{|1} - p_{|2}) M_{a|t}} && \text{(B.18)} \\
&= \sum_{a=0}^{A} N_{a|t} e^{-p_{|2} M_{a|t}} \left(1 - U_{|t,2} S_{a|t,2} \right) S_{a|t,1} W_{a|t,1} e^{-(p_{|1} - p_{|2}) M_{a|t}} && \text{(B.19)} \\
&= \sum_{a=0}^{A} N_{a|t} e^{-p_{|1} M_{a|t}} \left(1 - U_{|t,2} S_{a|t,2} \right) S_{a|t,1} W_{a|t,1} && \text{(B.20)} \\
& && \text{(B.21)}
\end{aligned}
$$

which is the same result if using the equation $C = U \times B$.

B.3 Comparison

It can be shown that these two assumptions produce the exact same results when only one fishery is considered. When two or more fisheries occur at exactly the same time, the catch is exactly the same (i.e., one fishery does not occur before another, thus they operate on the same biomass), but the equation for N_{t+1} is slightly different between the two formulations. Say that two fisheries operate $\frac{3}{5}^{ths}$ of the way through the time-step, each with an exploitation rate of 0.5. If they operated independently and each took half of the exploitable biomass, then all of the exploitable biomass would be removed since the sum of the two exploitation rates is 1. The real issue comes in when the sum of the exploitation rates is greater than 1, which is theoretically impossible.

Using the above two fishieries occurring at exactly the same time, let's assume that the exploitation rates were 0.3 and 0.4, which is still quite high for a marine commercial fishery. That is a combined exploitation rate 0.7 (assuming selectivity equals 1) and the equations for abundance in the next year (equations B.14 and B.15) are

$$
\begin{aligned}
\text{Independent fisheries} &= N_{a|t} e^{-M_a} [1 - (0.3 + 0.4)] = N_{a|t} e^{-M_a} (0.3) \\
\text{Sequential fisheries} &= N_{a|t} e^{-M_a} (1 - 0.3)(1 - 0.4) = N_{a|t} e^{-M_a} (0.42)
\end{aligned}
$$

Therefore, the number-at-age is 1.4 times greater for the sequential fishery compared to the independent fisheries. This occurs because of the product of the two exploitation rates is added back in, when expanded.

$$\begin{aligned}\text{Independent fisheries} &= [1-(U_1+U_2)] = (1-U_1-U_2)\\ \text{Sequential fisheries} &= (1-U_1)(1-U_2) = (1-U_1-U_2+U_1U_2)\end{aligned}$$

This is especially useful when the exploitation rate is high because it never allows the exploitation rate to exceed one. For example, when U=1 (the theoretcial maximum) the independent fisheries equation results in a multiplier of -1, while the sequential fisheries equation results in a multiplier of 0. When exploitation rates are 0.2 for two fisheries, the difference between the two methods is small (i.e., $0.2 \times 0.2 = 0.04$ and 1.07 times greater for the sequential fisheries). Additionally, exploitation rates in the sequential method are more interpretable as exploitation rates and do not need adjustments to make them remain below the theoretical maximum of one. Figure B.1 shows that are small exploitation rates, the difference in survival between the two methods is small.

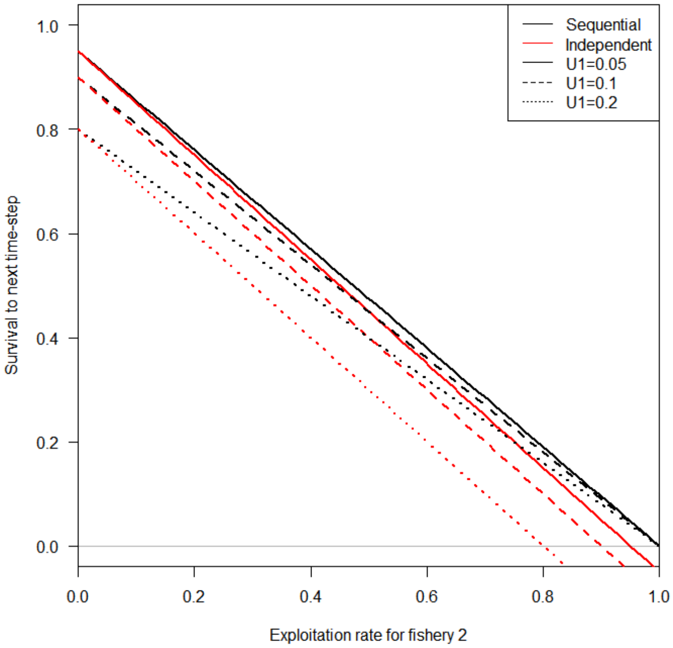

Figure B.1: A comparison of survival to the next-time step for the sequential (black) and independent (red) methods assuming exploitation rates (U) of 0.05, 0.1, and 0.2 for fishery 1, and a range of exploitation rates for fishery 2.

It is unlikely that two fisheries operate independently when exploitation rates are high and it may be more prudent to treat them in a sequential nature, calculating the exploitation rates for each from the sequential exploitable biomass (or splitting them up into many catch events and switching back and forth between the two, which is overly complicated). We propose to use the equations under the sequential fisheries, and when two or more fisheries operate at the exact same time, the fishery operates in a sequence in order of the size of their catch for that time-step (smallest to largest).

B.4 A more complex example with three fisheries and discard mortality

It is worth working through the concept of sequential fisheries when three fisheries occur and each has discard mortality. Let's assume there are three fleets with the mortality from fleet 1 occurring after one-fifth of the time-step ($p_{|1} = 0.2$), the mortality from fleet 2 occurring after two-fifths of the time-step ($p_{|2} = 0.4$), and the mortality from fleet 3 occurring after four-fifths of the time-step ($p_{|2} = 0.8$). The total mortality (in numbers) includes catch and discard mortality for each fleet and would be calculated as follows (with the current time-step subscript (t) removed for simplicity).

$$\begin{aligned}
TM^n_{a|f=1} &= C^n_{a|1} + D^n_{a|1} \\
&= N_a e^{-p_1 M_a} U_{|1} S_{a|1} R_{a|1} + N_a e^{-p_1 M_a} U_{|1} S_{a|1} (1 - R_{a|1}) d_{a|1} \\
&= N_a e^{-p_1 M_a} U_{|1} S_{a|1} \left[R_{a|1} + (1 - R_{a|1}) d_{a|1}\right] \\
TM^n_{a|f=2} &= \left(N_a e^{-p_1 M_a} - TM^n_{a|1}\right) U_2 S_{a|2} \left[R_{a|2} + (1 - R_{a|2}) d_{a|2}\right] e^{-(p_2 - p_1) M_a} \\
&= N_a e^{-p_2 M_a} U_2 S_{a|2} \left[R_{a|2} + (1 - R_{a|2}) d_{a|2}\right] \left[1 - U_1 S_{a|1} \left[R_{a|1} + (1 - R_{a|1}) d_{a|1}\right]\right] \\
TM^n_{a|f=3} &= \left[\left(N_a e^{-p_1 M_a} - TM^n_{a|1}\right) e^{-(p_2 - p_1)} - TM^n_{a|2}\right] U_3 S_{a|3} \left[R_{a|3} + (1 - R_{a|3}) d_{a|3}\right] e^{-(p_3 - p_2) M_a} \\
&= N_a e^{-p_3 M_a} U_3 S_{a|3} \left[R_{a|3} + (1 - R_{a|3}) d_{a|3}\right] \prod_{i=1}^{2} \left\{1 - U_i S_{a|i} \left[R_{a|i} + (1 - R_{a|i}) d_{a|i}\right]\right\}
\end{aligned}$$

Generally,

$$\begin{aligned} TM^{n}_{a|f} &= N_a e^{-p_f M_a} U_f S_{a|f} \left[R_{a|f} + (1 - R_{a|f}) d_{a|f} \right] \times \\ & \prod_{i \in p_j < p_f} \left\{ 1 - U_i S_{a|i} \left[R_{a|i} + (1 - R_{a|i}) d_{a|i} \right] \right\} \end{aligned} \tag{B.22}$$

where j is over all fleets. In essence, the total mortality is determined from the numbers-at-age that survived naturally to that point and survived the probability of fishing mortality (retained or discarded and died) from all fleets up to that point in the time-step.