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

PREPARED BY: IPHC SECRETARIAT (R. WEBSTER; 20 DECEMBER 2019)

PURPOSE

To provide the Commission with a summary of the results of the 2019 space-time modelling of Pacific halibut survey data (which includes data from other fishery-independent surveys), as well as results of the IPHC fishery-independent setline survey (FISS) expansions in IPHC Regulatory Areas 3A and 3B, and modelling results from fixed and snap gear comparison in Regulatory 2C. Also presented are methods for rationalising the FISS following completion of the final set of expansions in 2019.

BACKGROUND/INTRODUCTION

The IPHC has completed a series of FISS expansions, beginning with a 2011 pilot in IPHC Regulatory Area 2A, and continuing from 2014-19 as follows:

- 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 purpose of the expansion program has been to fill in the often large gaps in the annually-fished FISS to build a complete picture of Pacific halibut density throughout its range, and thereby reduce bias and improve precision in density indices and other quantities computed from the FISS data.

With the expansions completed in 2019, the intention is to use our improved understanding of the Pacific halibut distribution to re-design the annual FISS. As a result, it is likely that stations that were previously fished annually may require less frequent fishing, and it may be efficient to annually fish some expansion stations that have been surveyed just once to date. This report proposes criteria and methods for evaluating such a FISS rationalisation, and uses Regulatory Area 4B as an example to demonstrate the application of our proposed approach. We envision the rationalisation as an ongoing process: as new data become available each year and relative costs change with time, future designs choices will be re-evaluated and modified to adapt to changing data needs.

Snap gear is increasingly used in the commercial fishery, and allowing vessels using snap gear to participate in the FISS (previously fixed-gear only) increases the number of available vessels. Using a study design that fished each FISS station in Regulatory 2C twice, once with each gear type, provided data for comparing snap and fixed gears, including examining the effect of gear type on weight and numbers per unit effort indices through space-time modelling.

Space-time modelling results for 2019

Revisions to the data inputs for space-time modelling of survey data include: the addition of expansion stations in Regulatory Areas 3A and 3B; the use of direct individual weight measurements of FISS Pacific halibut in computing 2019 station-level WPUE; the application of revised effectiveness criteria for whale depredation for FISS sets; the inclusion of snap-gear data in Regulatory Area 2C modelling; and the inclusion of FISS stations within the area of overlap of US and Canadian maritime claims in Dixon entrance in the estimation of WPUE and NPUE indices in both Regulatory Areas.

Figures 1-2 show time series estimates of O32 WPUE (most comparable to fishery catch-rates) and all sizes NPUE over the 1993-2019 period included in the 2019 space-time modelling. Declines of 4-5% were estimated in all three indices from 2018-19, largely driven by 8-10% declines in Biological Region 3. Equivalent figures for Regulatory Areas are in Appendix A.

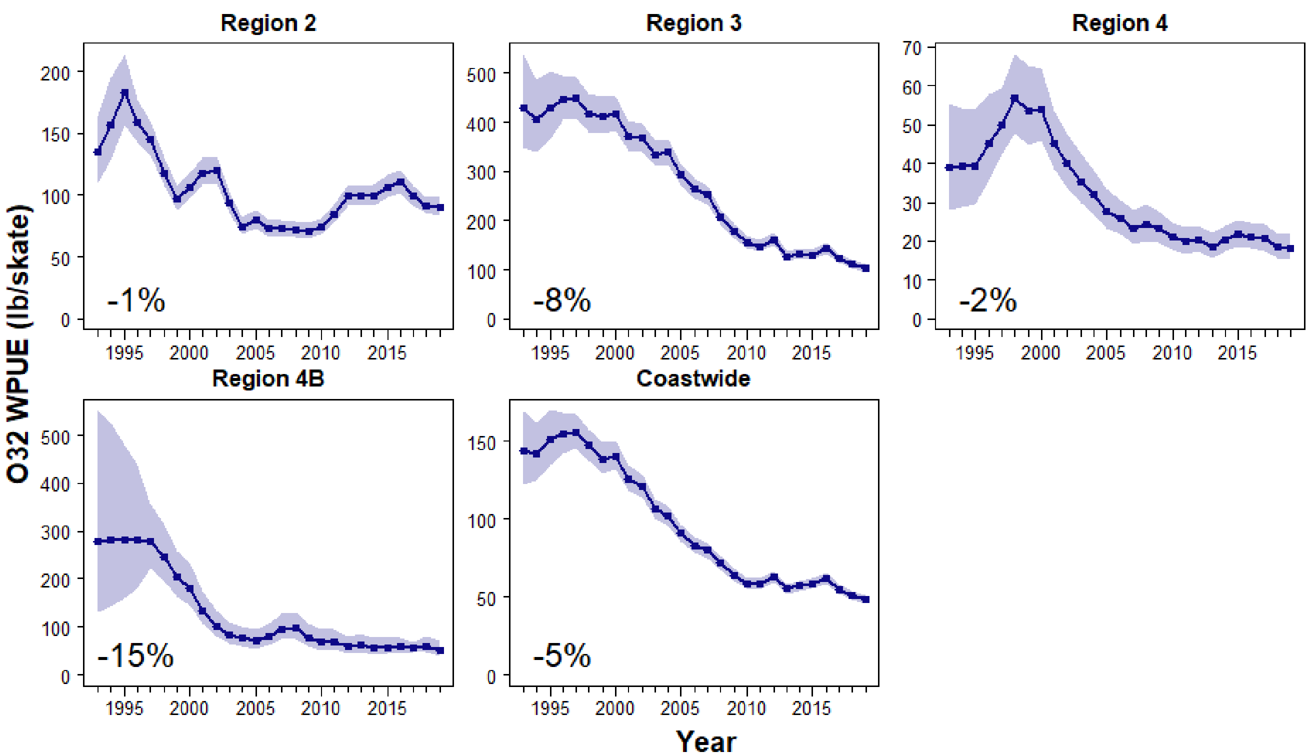

Figure 1. Space-time model output for O32 WPUE for 1993-2019 for Biological Regions. Filled circles denote the posterior means of O32 WPUE for each year. Shaded regions show posterior 95% credible intervals, which provide a measure of uncertainty: the wider the shaded interval, the greater the uncertainty in the estimate. Numeric values in the lower left-hand corners are estimates of the change in mean O32 WPUE from 2018 to 2019.

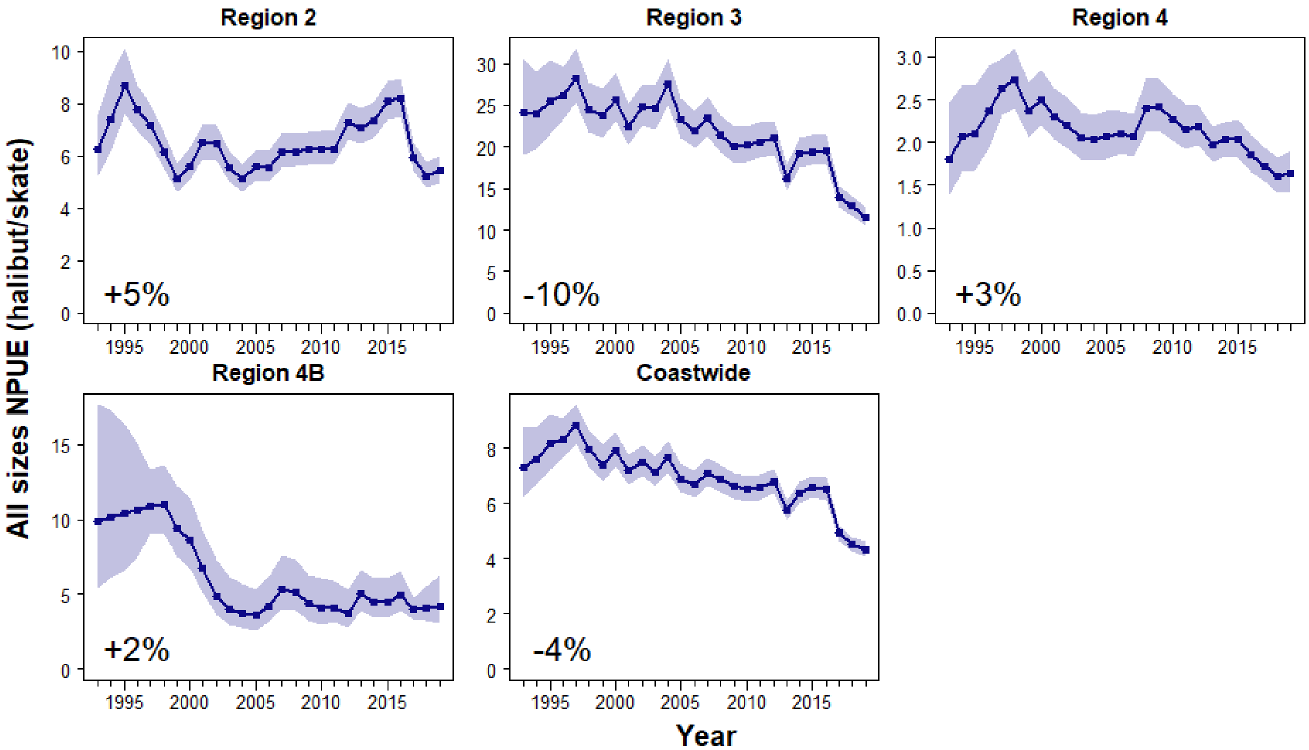

Figure 2. Space-time model output for all sizes NPUE for 1993-2019 for Biological Regions. Filled circles denote the posterior means of all sizes NPUE for each year. Shaded regions show posterior 95% credible intervals, which provide a measure of uncertainty: the wider the shaded interval, the greater the uncertainty in the estimate. Numeric values in the lower left-hand corners are estimates of the change in mean all sizes NPUE from 2018 to 2019.

In Regulatory Area 2C, data from both fixed and snap gears were used in the modelling. Parameters allowing for different catch rates of the two gears were included in the models, and estimates of WPUE and NPUE series were based on model predictions assuming fixed gear to ensure consistency with other Regulatory Areas. Comparisons of estimates based on data with and without the snap gear data show no meaningful effect of including the snap gear data on either means or uncertainty (Appendix B). Note that these figures do not imply there were no gear differences in catch rates, since we have standardized for gear type by predicting at fixed gear only. Indeed, parameter estimates of gear type differences showed some evidence that snap gear catch rates were lower on average (Table 1), with estimated catch rate ratios of 0.86 for all three indices modelled in 2019 (i.e., we estimate snap gear had 86% of the catch of fixed gear on average). Posterior 95% credible intervals all had an upper limit of 1.00, i.e., no difference in catch rate, so evidence for a difference in gear types was not strong. Although there is no impediment to using these data in generating estimates of indices, with the calibration estimated within the space-time model, the results imply the need to collect additional data comparing fixed and snap gears in order to better understand the relative efficiency of the gears and potential variability over time and space.

Table 1. Posterior estimates of the ratio of snap to fixed gear catch rates for O32 and all sizes WPUE, and all sizes NPUE, from space-time modelling of data from Regulatory Area 2C in 2019.

Variable	**Ratio of snap to fixed catch rate**	
	Posterior mean	**95% credible interval**
O32 WPUE	0.86	0.74 – 1.00
All sizes WPUE	0.86	0.75 – 1.00
All sizes NPUE	0.86	0.75 – 1.00

The 2019 FISS expansions in Regulatory Areas 3A and 3B led to improvements in precision and reductions in bias (Appendix C). This was particularly true for Regulatory Area 3A, where the addition of expansion stations to previously very poorly-predicted locations in places like Cook Inlet and Prince William Sound greatly reduced uncertainty (Figures C.1 and C.2).

Methods for FISS rationalisation

The primary purpose of the annual FISS is to sample Pacific halibut to provide data for the stock assessment and estimates of stock distribution. The priority of a rationalised FISS is therefore to maintain or enhance data quality (precision and bias) by establishing minimum 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 2.

Table 2. 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

The historical sampling, combined with FISS expansions from 2014-2019, established a full sampling frame of 1890 stations from California to the Bering Sea shelf edge on a 10 nmi grid from depths of 10 – 400 ftm (Figure 3). Future annual FISS designs will comprise a selection of stations from this frame. Examples of such designs include completely randomized sampling within each Regulatory Area (Figure 4), and randomized cluster sampling (Figure 5). In the latter case, clusters of stations are selected that comprise (where possible) 3-4 stations to make an operationally efficient fishing day, and thus this design is an example of one that includes a consideration of logistics and cost.

We propose precision targets that the designs should meet in order to maintain data quality for the stock assessment and stock distribution estimation. For designs such as those in Figures 4 and 5, the randomization ensures that resulting estimates (eg, WPUE, NPUE indices) are unbiased. Other designs under consideration require an evaluation of the potential for bias, as discussed below.

From a scientific perspective, more information is always better; however, sampling the full grid (Figure 4) 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 Regulatory Areas where Pacific halibut are concentrated in a subset of the available habitat, such a design can be inefficient. We therefore evaluate another type of 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.

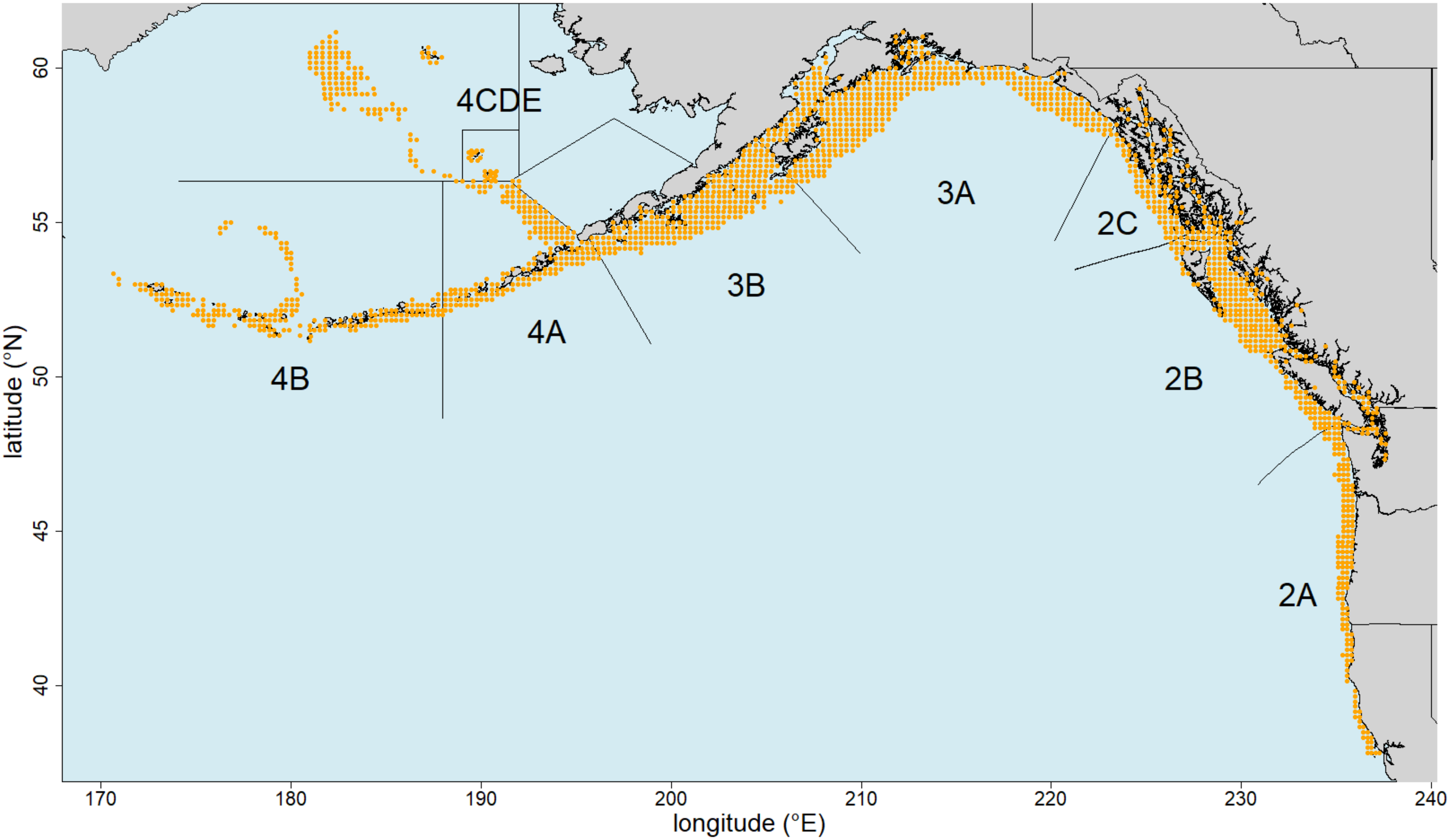

Figure 3. Map of the full FISS sampling frame to be used from 2020 onwards. Each orange circle represents a FISS station.

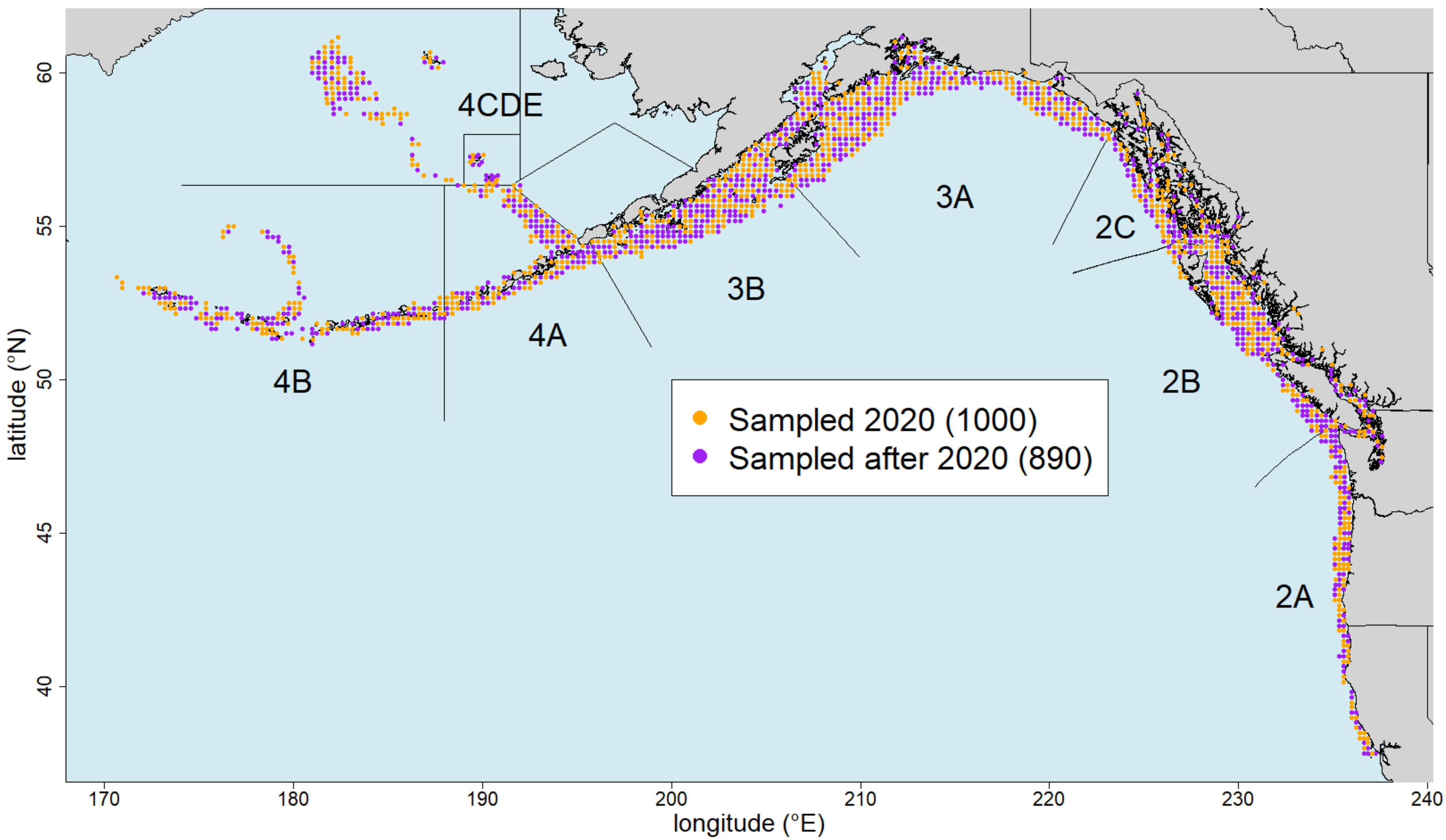

Figure 4. Map of a hypothetical randomized sampling design for 2020 with a target coastwide sample size of 1000 stations.

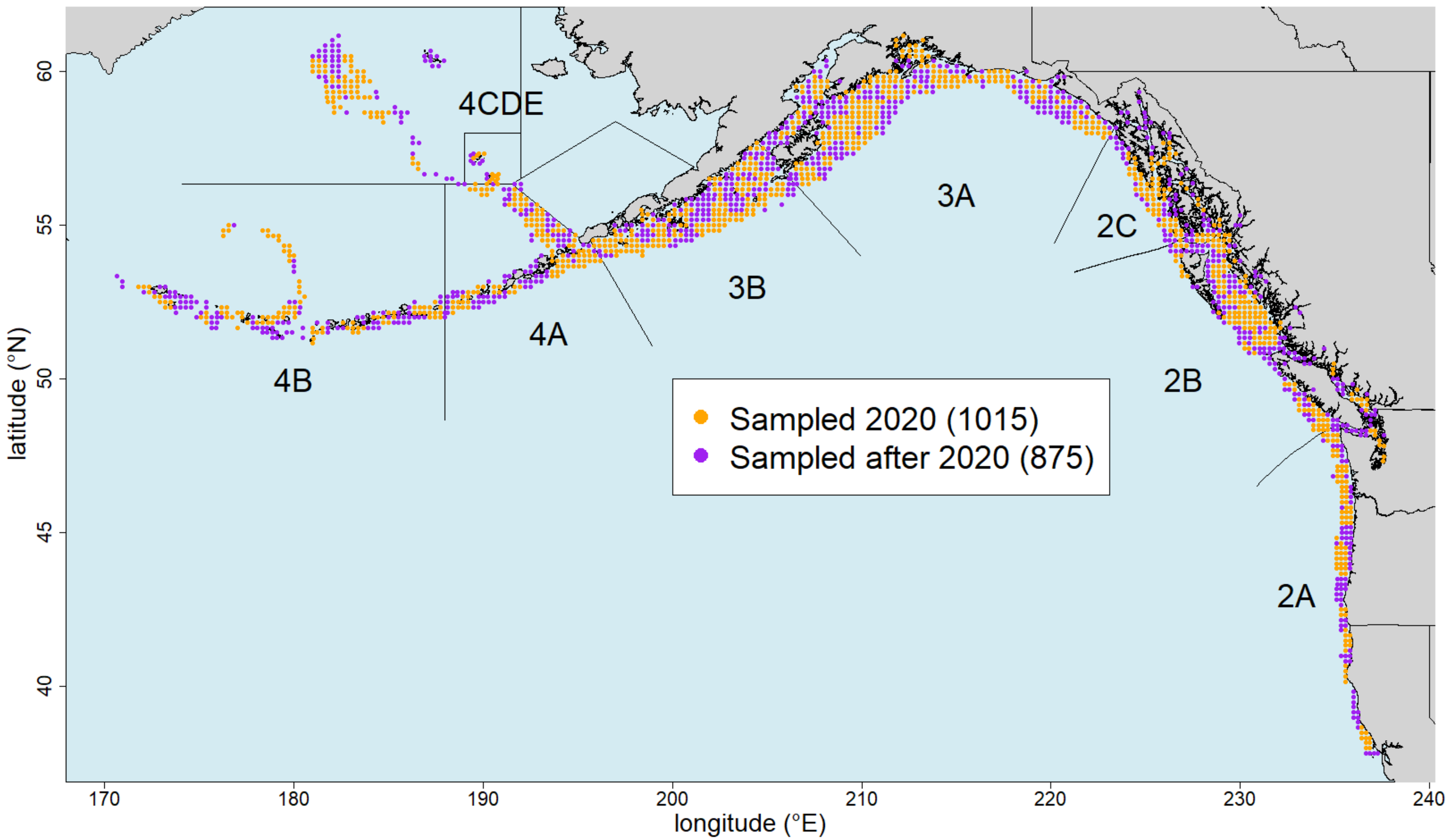

Figure 5. Map of a hypothetical randomized cluster sampling design for 2020 with a target coastwide sample size of approximately 1000 stations.

Precision targets

Previously, 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 has been achieved in all areas from 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).

Table 2. Range of coefficients of variation for O32 and all sizes WPUE from 2011-18 by Regulatory Area.

Reg Area	O32 WPUE (2011-19)				All sizes WPUE (2011-18)			
	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.

Considering Biological Regions, CVs for WPUE in Region 2 and Region 3 were at or below 5% in all years from 2011 (Table 3). Region 4 CVs for WPUE were below 10%, while the smallest region, Region 4B, has some years with CVs above 15% as noted previously. For all sizes NPUE (Table 4), CVs were above 10% in all Regions except Region 4B. Based on this information, constraining the FISS design to produce CVs of 10% or less for Regions 2-4 and 15% for Region 4B should allow for some reduced FISS effort in the former regions, while maintaining low uncertainty in Region 4B.

Table 3. Range of coefficients of variation for O32 and all sizes WPUE from 2011-19 by Biological Region.

Region	WPUE (2011-19)				All sizes WPUE (2011-19)			
	Lowest CV (%)	Year	Highest CV (%)	Year	Lowest CV (%)	Year	Highest CV (%)	Year
2	4	2018*	4	2012	4	2018*	4	2012
3	4	2019*	4	2011	4	2018	5	2011
4	8	2014*	9	2019	5	2014*	9	2019
4B	10	2017*	16	2012	10	2017*	16	2012

* Year of FISS expansion in at least part of the Region.

Table 4. Range of coefficients of variation for all sizes NPUE from 2011-19 by Biological Region.

Region	All sizes NPUE (2011-19)			
	Lowest CV (%)	Year	Highest CV (%)	Year
2	4	2018*	5	2011
3	4	2018*	5	2011
4	5	2014*	8	2019
4B	9	2017*	20	2019

* Year of FISS expansion in at least part of the Region.

Finally, the CV of coastwide, all sizes NPUE (used in the stock assessment) is estimated to be from 3-9% for all years of estimation from 1993 to 2019 (3-4% for 2011-19). This suggests a target of 10% for the CV of this index will ensure that uncertainty is maintained at a low level for this key stock assessment input.

In summary, in order to maintain the quality of the estimates used for the assessment, and for estimating stock distribution, we propose that a rationalised FISS should be designed to meet the following precision targets:

- CVs below 15% for O32 and all sizes WPUE for all Regulatory Areas
- CVs below 10% for O32 WPUE, all sizes WPUE, and all sizes NPUE for Regions 2, 3 and 4
- CVs below 15% for O32 WPUE, all sizes WPUE, and all sizes NPUE for Region 4B
- CVs below 10% for the coastwide, all sizes NPUE index

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, when 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, when trends in the unsurveyed portion of a management unit (Regulatory Area or Region) differ from 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) should be surveyed in order to reduce the likelihood of appreciable bias. For this, we propose 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 keep down the chance of its percentage changing by more than 10% between successive surveys of the subarea, we reduce the potential for appreciable bias in the Regulatory Area or Region’s indices as a whole.

Analytical methods

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

- Where a randomized design is not used, identify 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 is not considered worthwhile, as we expect further evaluation undertaken following collection of data during the one to three-year time period to influence design choice to subsequent years.

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 informative.

In considering potential FISS designs, we distinguish between the core area of the stock, where densities are relatively high (Regulatory Areas 2B, 2C, 3A and 3B) from the margins of the stock (Regulatory Areas 2A, 4A, 4B and 4CDE), which contains subareas of higher density, along with large regions of lower density. A fully randomized design for the latter can be an inefficient way of conducting the sampling, and we propose an alternative that may make more effective use of resources to achieve the scientific goals of the FISS.

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 2):

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 3) 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 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 shows 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.

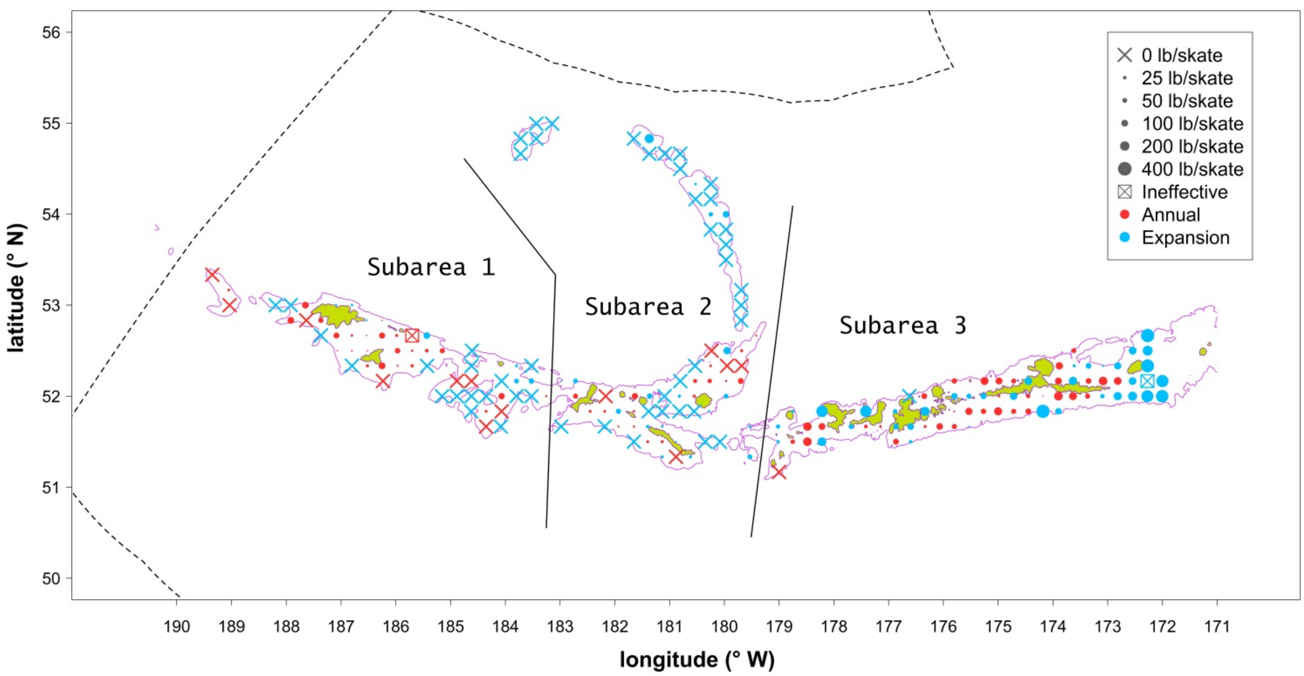

Figure 2. Map of the 2017 FISS expansion design in IPHC Regulatory Area 4B showing the subareas used in the analysis.

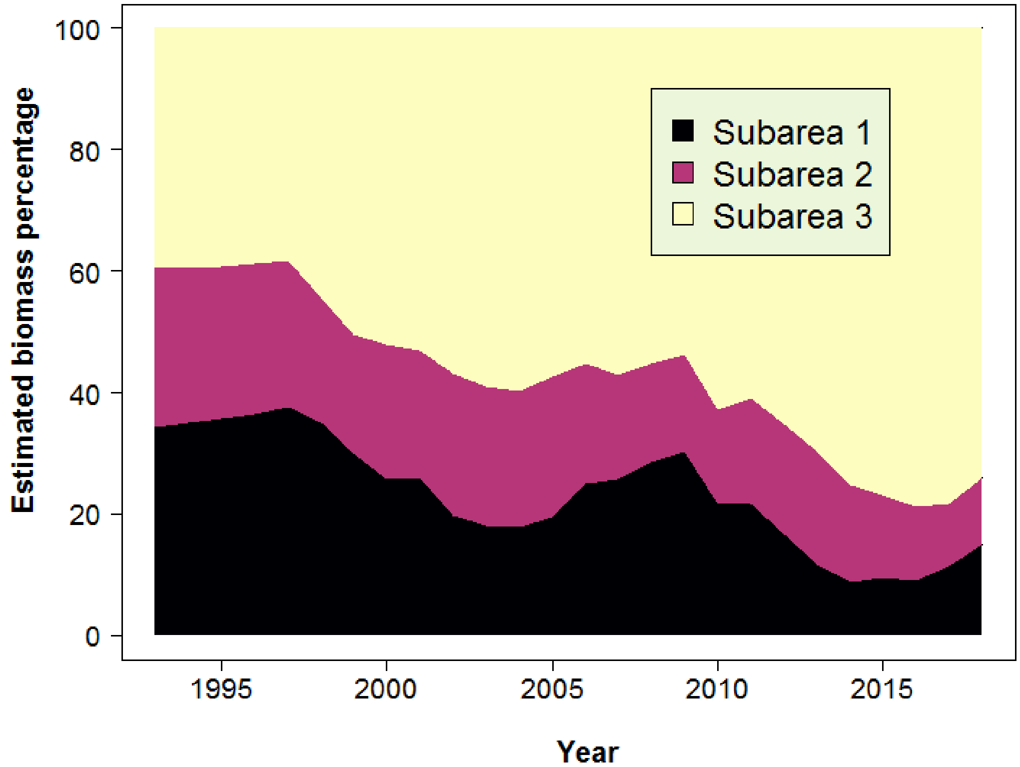

Figure 3. Estimated Regulatory Area 4B biomass % by subarea and year.

IPHC Regulatory Area 4A

Like Regulatory Area 4B, we have divided Regulatory Area 4A into geographic subareas (Figure 4) 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 5). 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)

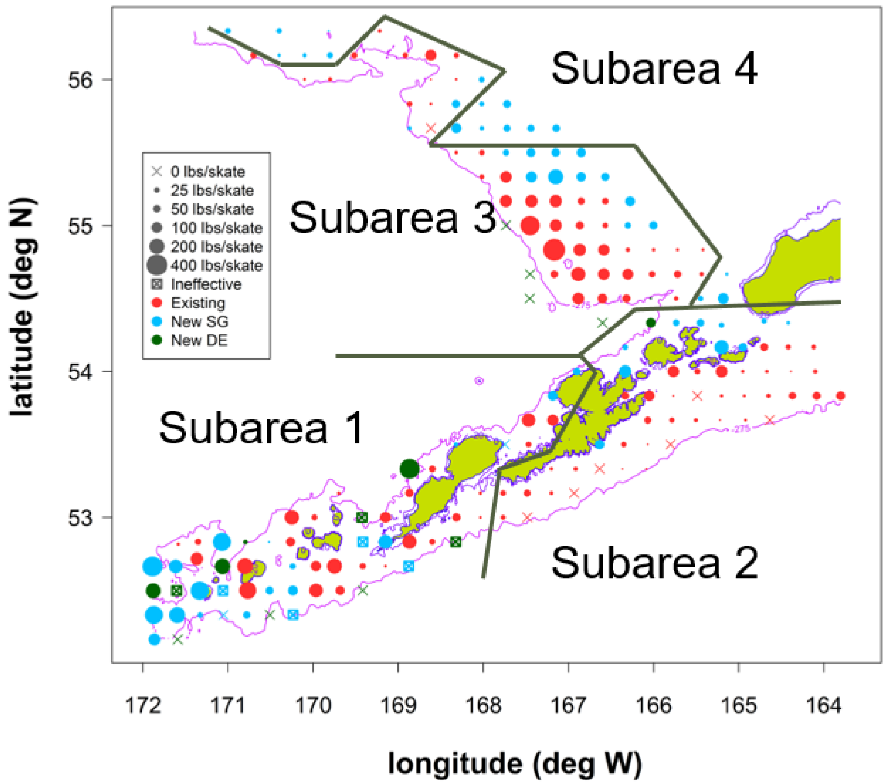

Figure 4. Map of the 2014 FISS expansion design in IPHC Regulatory Area 4A showing the subareas used in the analysis.

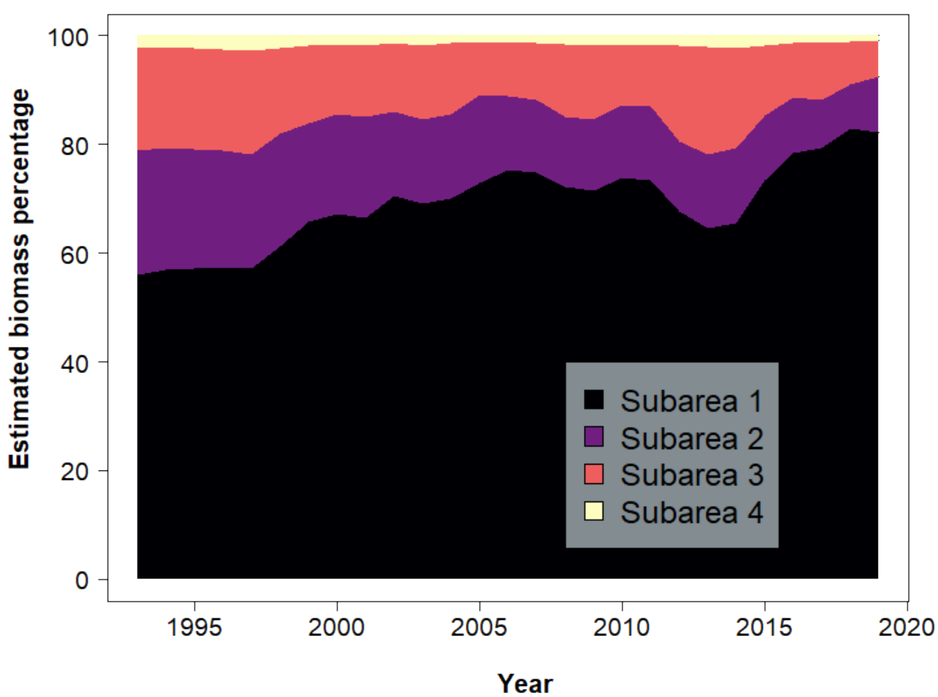

Figure 5. Estimated Regulatory Area 4A biomass % by subarea and year.

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 Regulatory Area 2A, we again proposed subareas based on density and geography, but there 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 6). 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 7), 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 bias due to the stability of the biomass distribution among subareas.

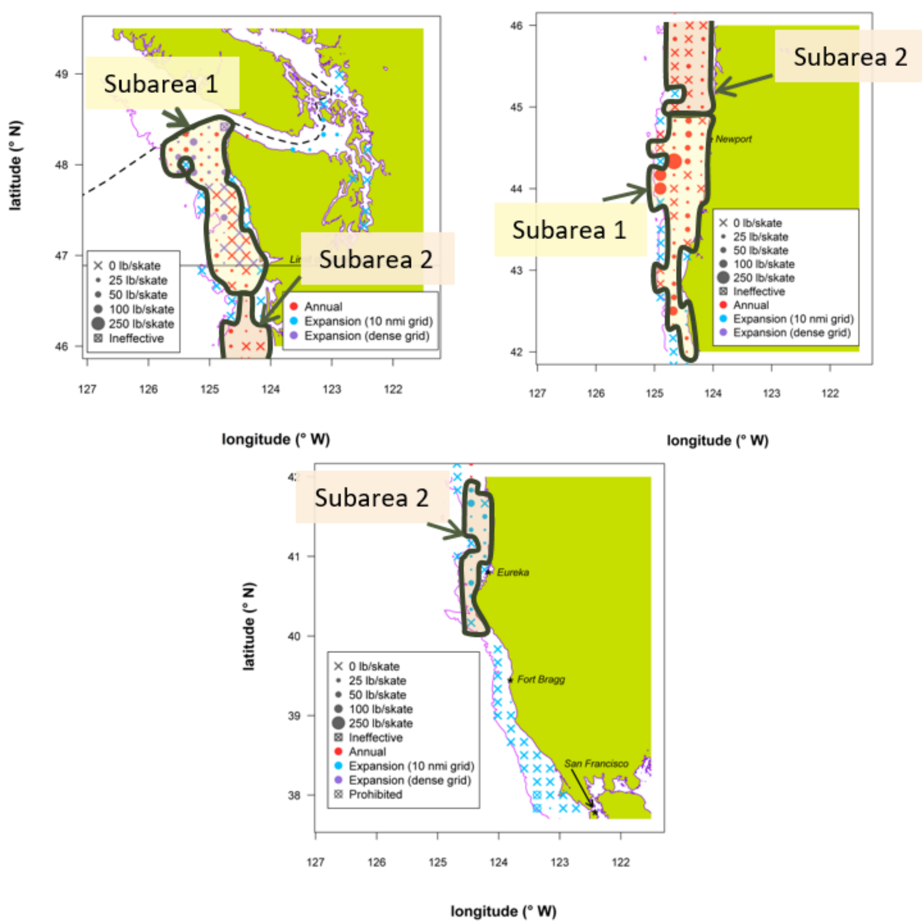

Figure 6. Map of the 2017 FISS expansion design in IPHC Regulatory Area 2A showing the subareas used in the analysis. Subarea 3 is unlabeled but is comprised of the stations outside of Subareas 1 and 2.

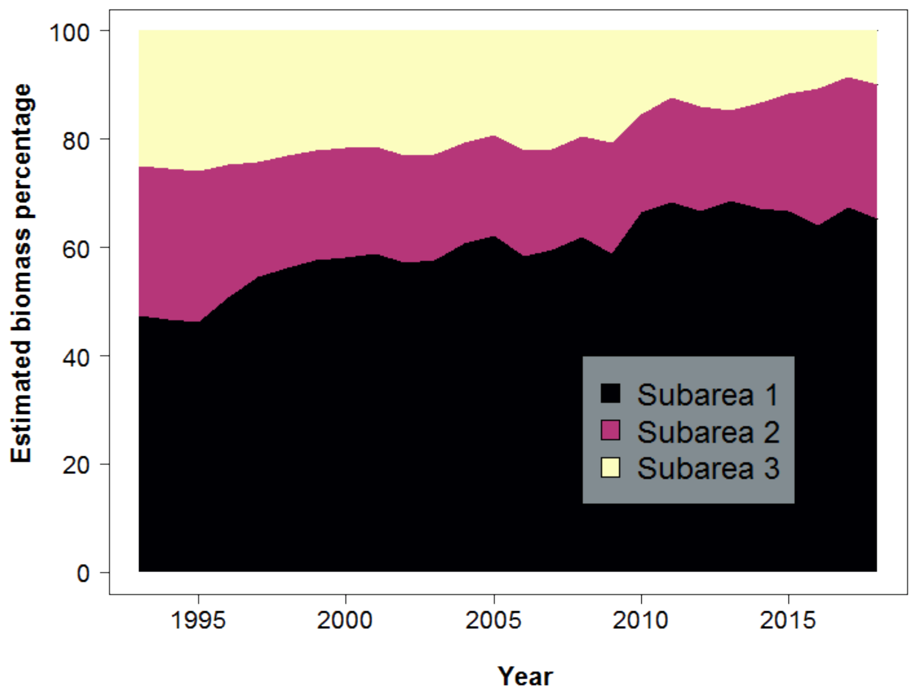

Figure 7. Estimated Regulatory Area 2A biomass % by subarea and year.

Other Regulatory Areas

Regulatory Areas 2B, 2C, 3A and 3B represent the core of the Pacific halibut stock, with generally high relative density throughout. It was therefore more difficult to identify subareas based on density, geographic regions, or biological differences. Instead, IPHC FISS regions were considered as subareas, and sampling priorities were based on the density and temporal variability of these. Specifically, we considered designs in which two FISS region per year were omitted from the six regions in Regulatory 2B, the eight regions in Regulatory 3A and the five regions in Regulatory 3B, and where two of the three FISS regions in Regulatory 2C were fished. Those regions with either the highest densities in recent years, or (in the case of Regulatory Area 3B), with densities that varied greatly over short time periods, were prioritized for annual sampling, while other FISS regions can be sampled on a rotating basis. As described above, the proposed designs for each Regulatory Area in 2020 were evaluated to ensure that precision and bias criteria were met.

Proposals for 2020-2022

The full proposal for 2020-22 based on a subarea design is shown in Figures 8-10. This represents a design that will meet the data quality criteria for analytical purposes, and comprises approximately 1150 stations, fewer than in recent years.

An alternative design is presented in Figures 11-13. This design uses efficient subarea sampling in Regulatory Areas 2A, 4A and 4B, but incorporates a randomized design in Regulatory Areas 2B, 2C, 3A and 3B (except for the near-zero catch rate inside waters around Vancouver Island), with a sampling rate chosen to keep the sample size close to 1000 stations in an average year. Advantages of this design over the full subarea proposal in Figures 8-10 include maintaining spatially comprehensive biological and environmental sampling in the core Regulatory Areas, unbiased estimation of WPUE and NPUE indices in those areas, and expected greater precision with fewer stations. The disadvantages are possible increased cost and more challenging logistics in fishing the sparser design.

Each proposal includes fishing the full 10 nmi grid along the Regulatory Area 4CDE edge in 2020-22 (last fished in 2016). While it may be possible to reduce FISS sampling and still meet precision/bias targets, we note 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 will be re-evaluated following the results of the 2020 FISS.

For proposals that do not sample all stations in the design, additional stations can be included if there are specific needs beyond precision and bias criteria, such as for sampling efficiency, cost recovery, biological sampling, environmental monitoring, and IPHC policy decisions.

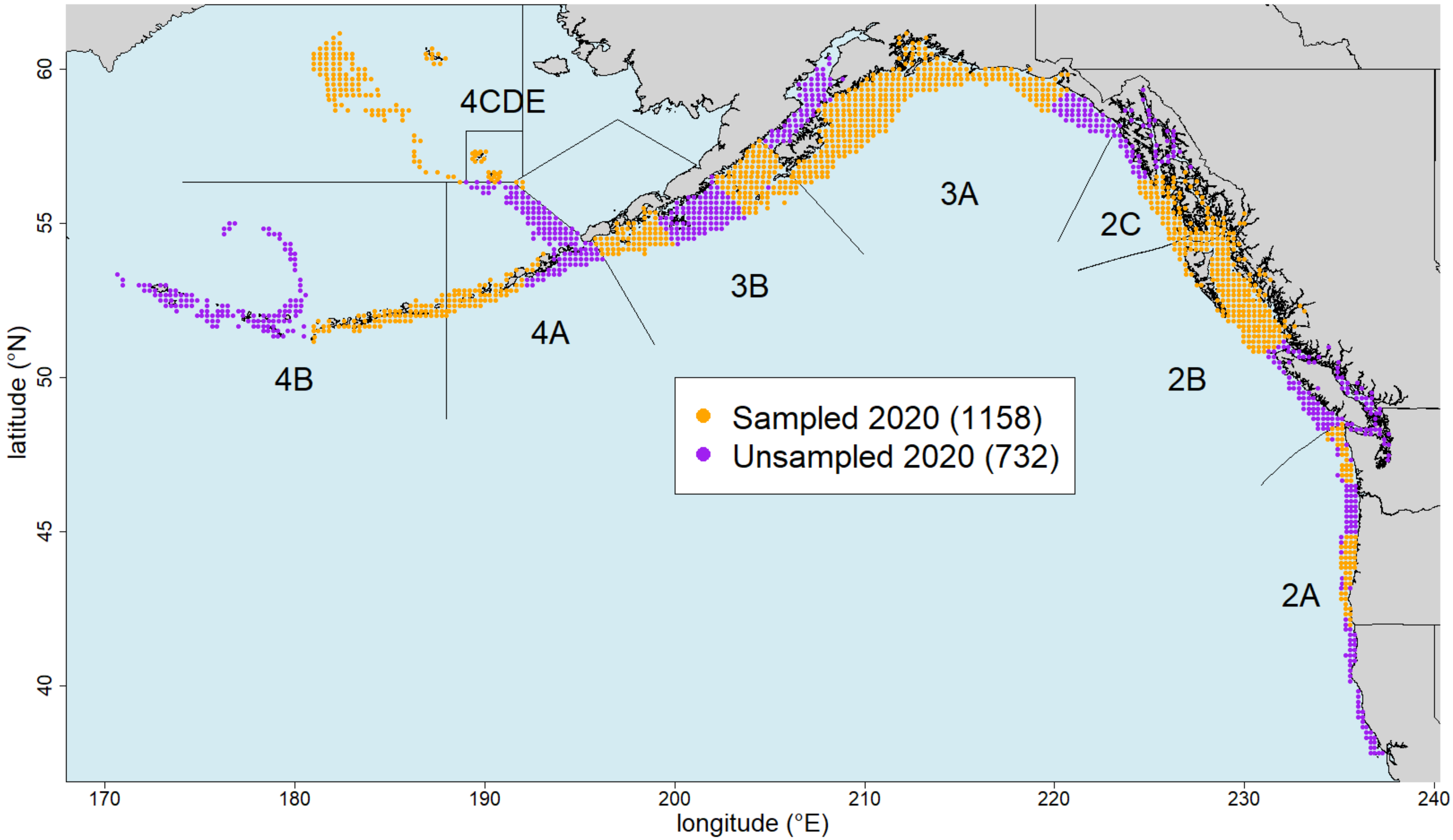

Figure 8. Proposed minimum FISS design in 2020 (orange circles) based on subareas. Purple circles are optional for meeting data quality criteria.

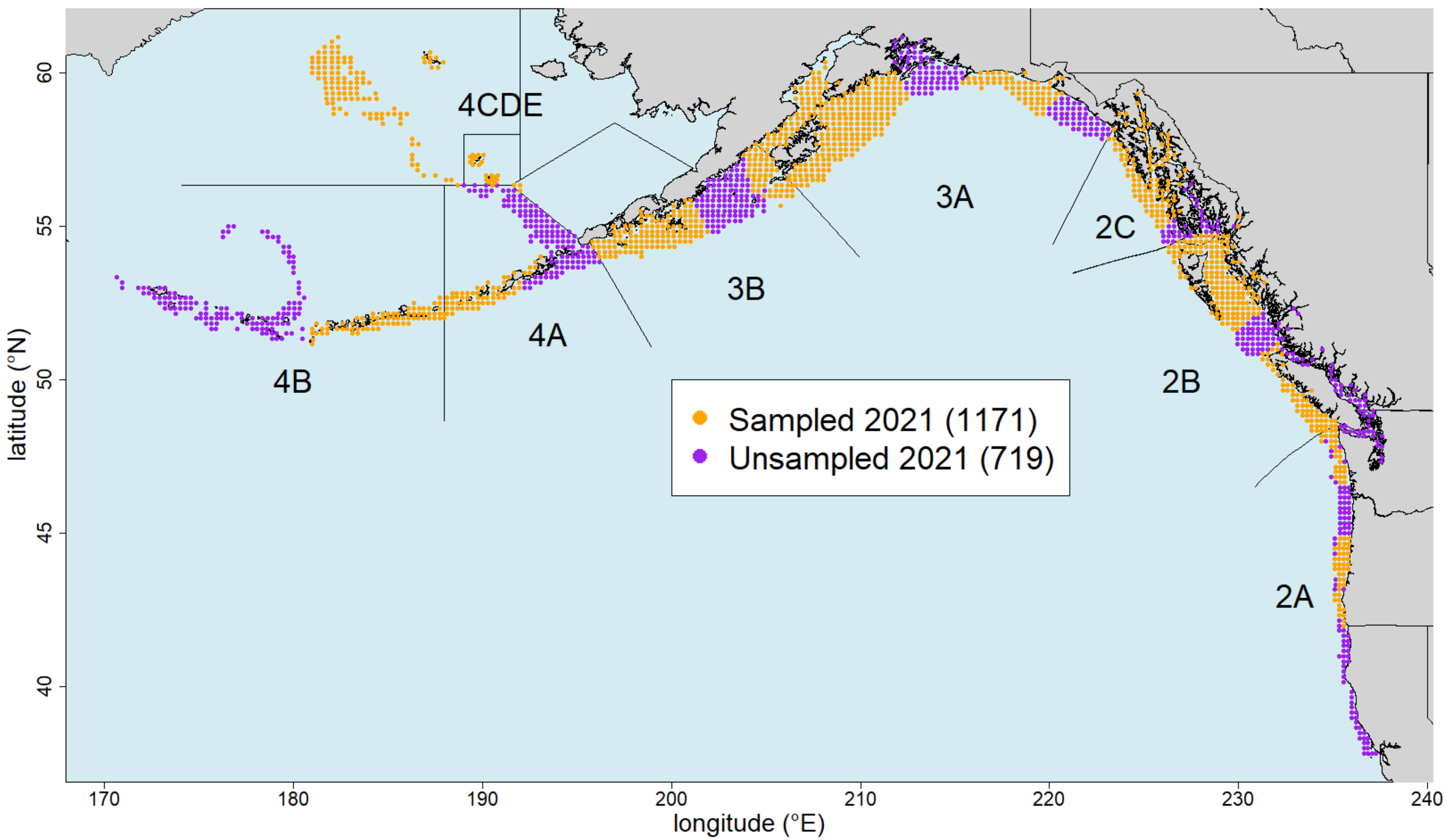

Figure 9. Proposed minimum FISS design in 2020 (orange circles) based on subareas. Purple circles are optional for meeting data quality criteria.

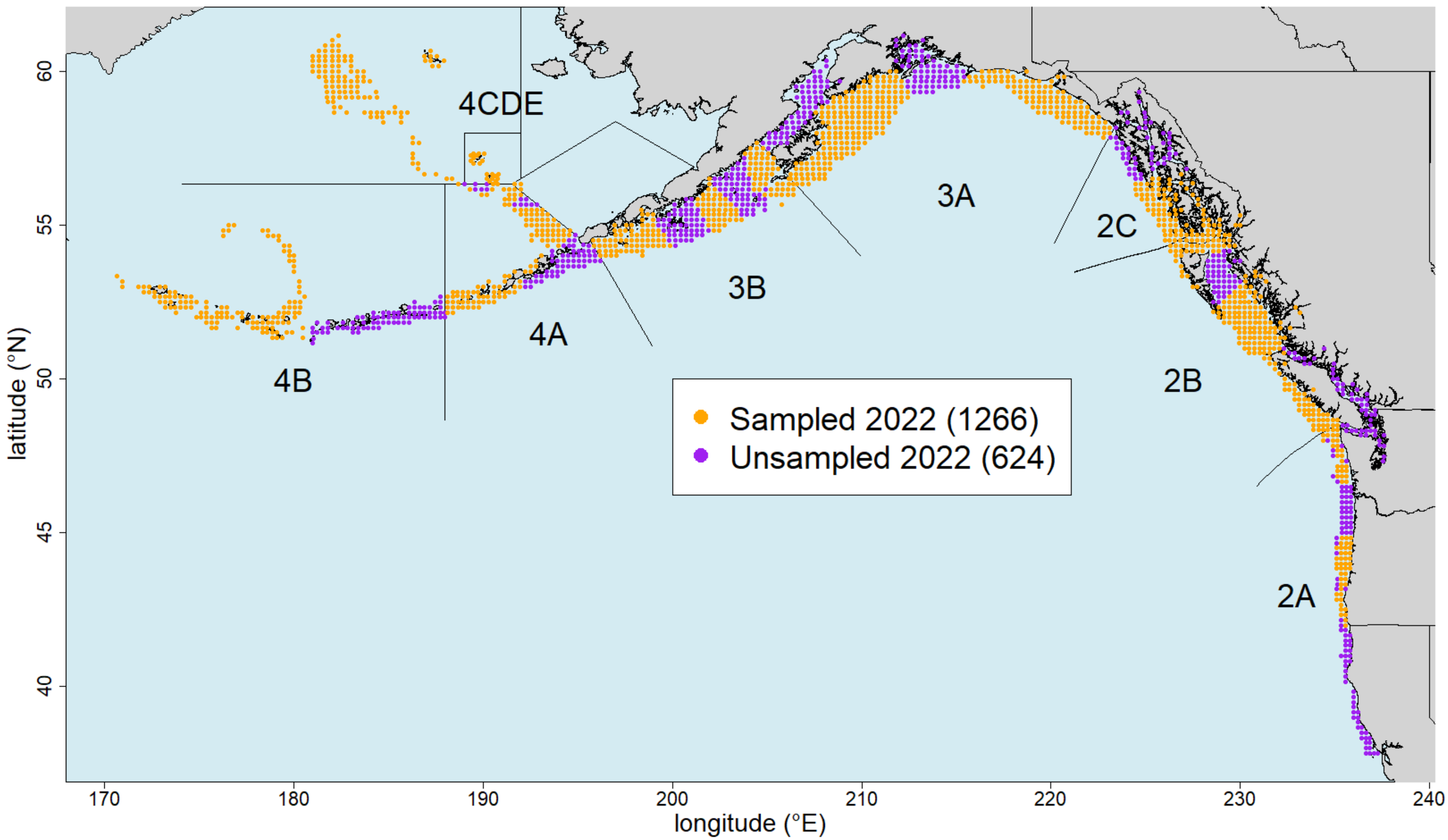

Figure 10. Proposed minimum FISS design in 2022 (orange circles) based on subareas. Purple circles are optional for meeting data quality criteria.

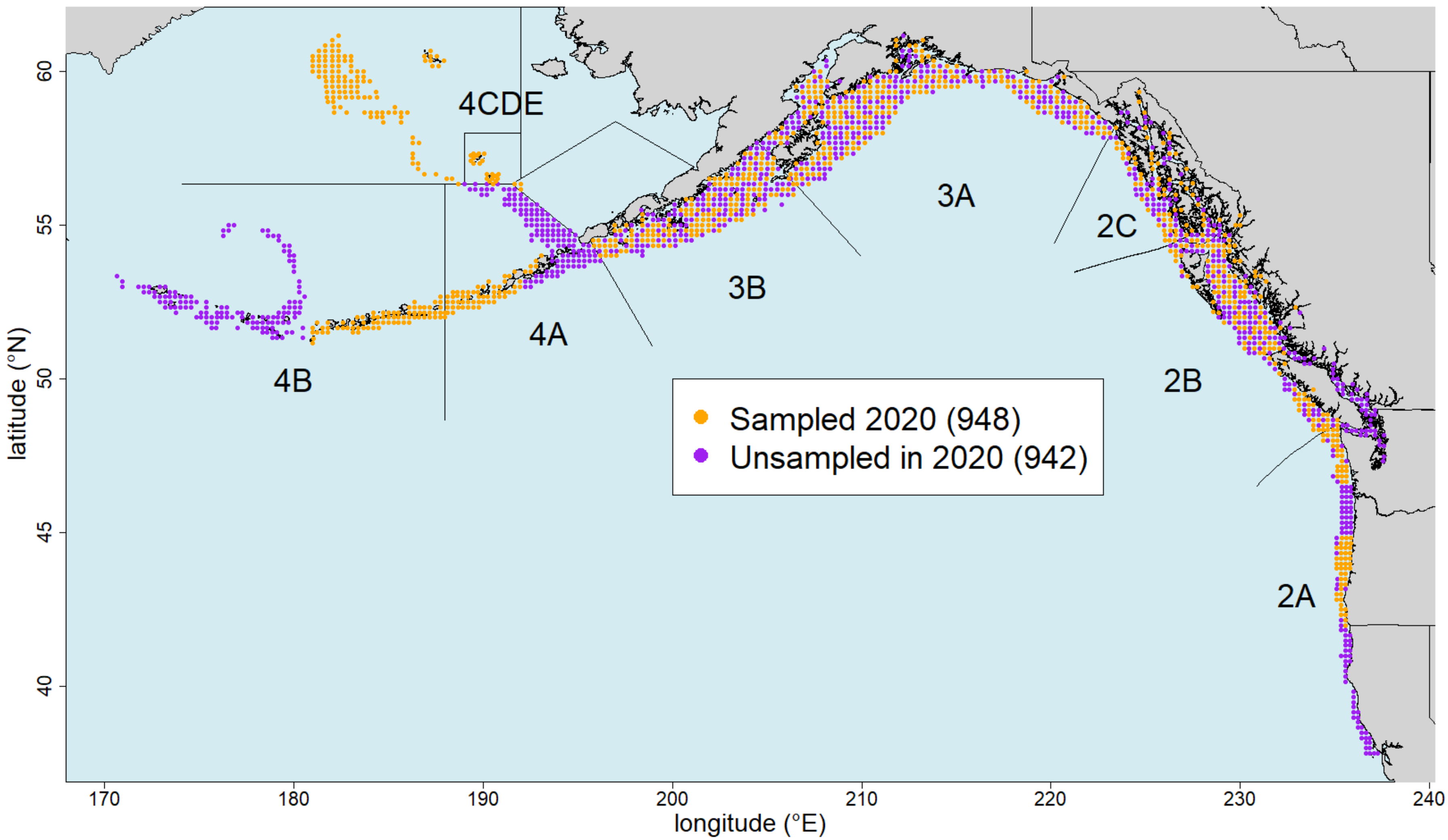

Figure 11. Proposed minimum FISS design in 2020 (orange circles) based on randomized sampling in 2B-3B, and a subarea design elsewhere. Purple circles are optional for meeting data quality criteria.

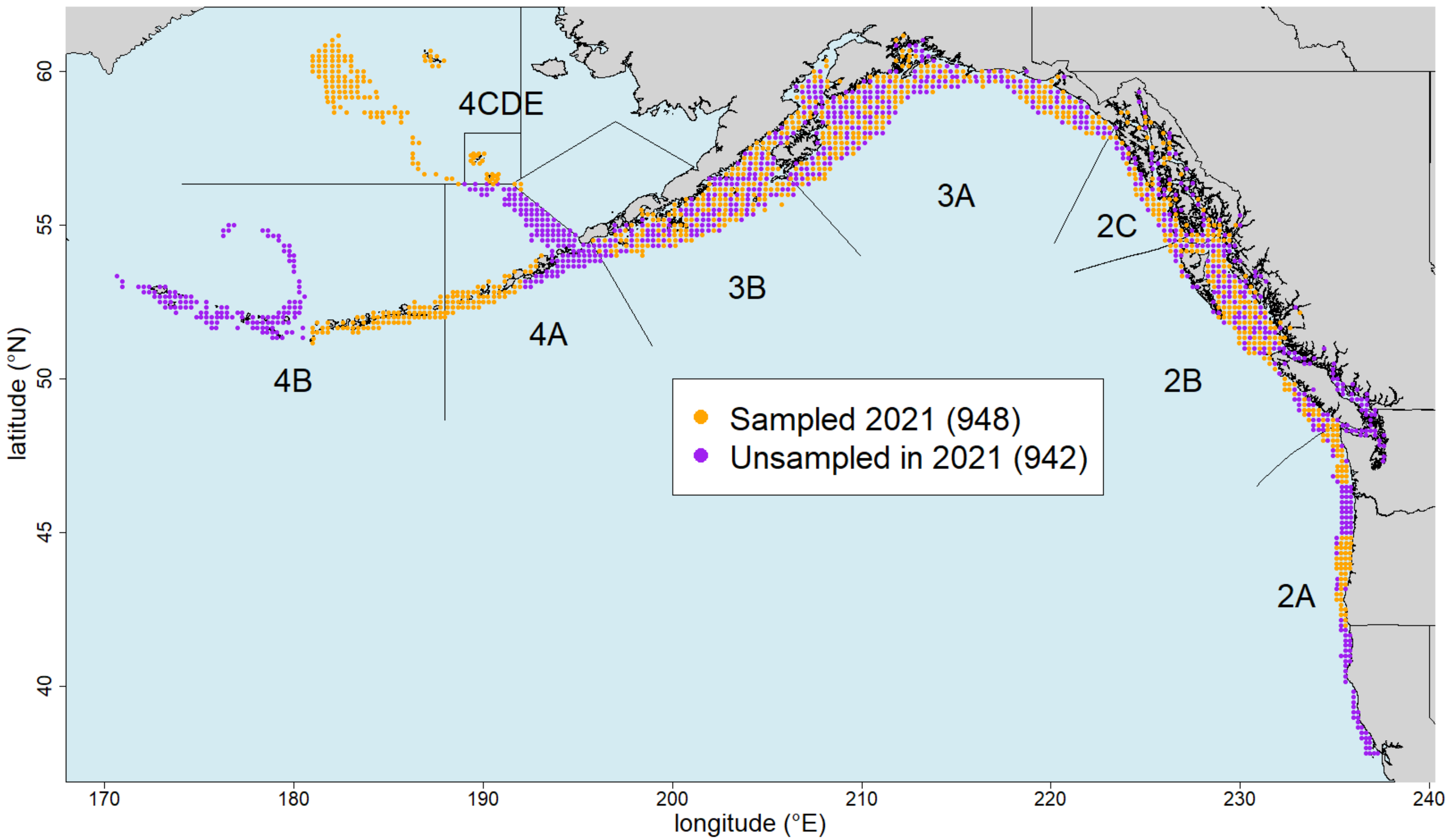

Figure 12. Proposed minimum FISS design in 2021 (orange circles) based on randomized sampling in 2B-3B, and a subarea design elsewhere. Purple circles are optional for meeting data quality criteria.

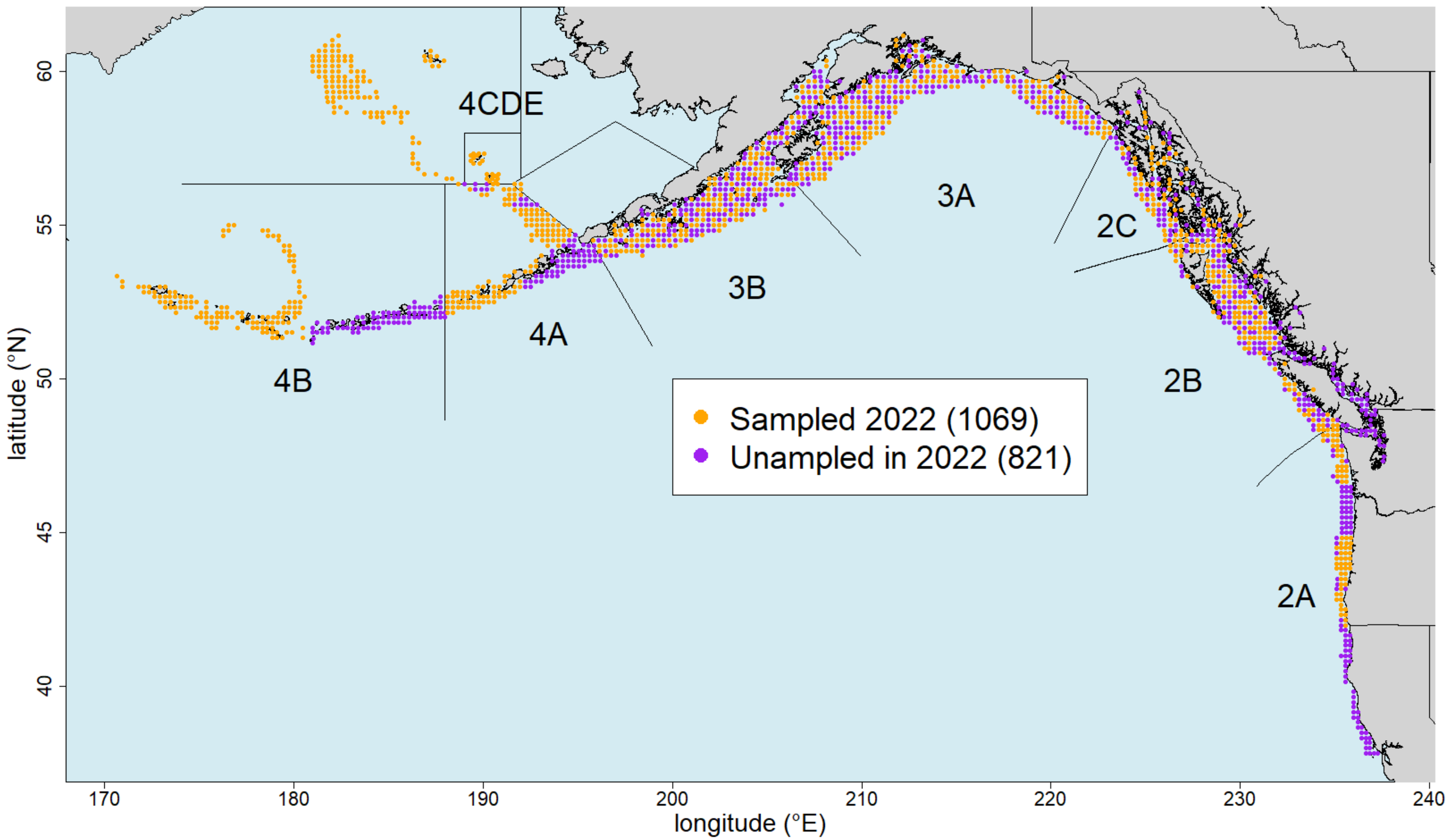

Figure 13. Proposed minimum FISS design in 2022 (orange circles) based on randomized sampling in 2B-3B, and a subarea design elsewhere. Purple circles are optional for meeting data quality criteria.

RECOMMENDATION/S

That the Commission:

a) **NOTE** paper IPHC-2020-AM096-07 which provides alternatives for FISS sampling in 2020 ranging from the full grid to randomized and subarea options.
b) **REQUEST** the type of design that the IPHC Secretariat should employ, commencing in 2020.
c) **REQUEST** any specific additions or modifications to that design that the IPHC Secretariat should consider in evaluating the three design criteria: Scientific, logistical/cost, and resource extraction/policy.

APPENDIX A

Space-time modelling results by IPHC Regulatory Area

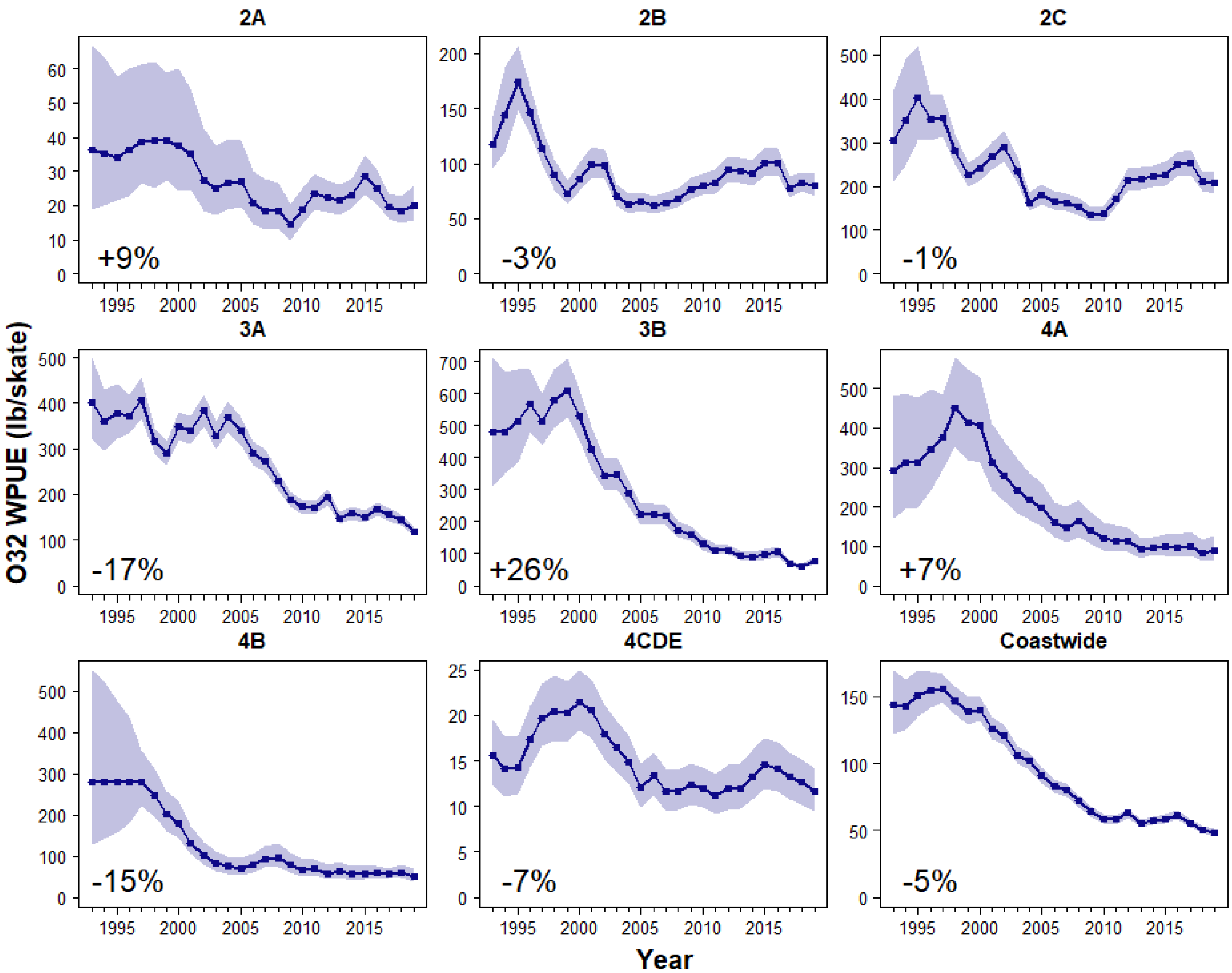

Figure A.1. Space-time model output for O32 WPUE for 1993-2019. Filled circles denote the posterior means of O32 WPUE for each year. Shaded regions show posterior 95% credible intervals, which provide a measure of uncertainty: the wider the shaded interval, the greater the uncertainty in the estimate. Numeric values in the lower left-hand corners are estimates of the change in mean O32 WPUE from 2018 to 2019.

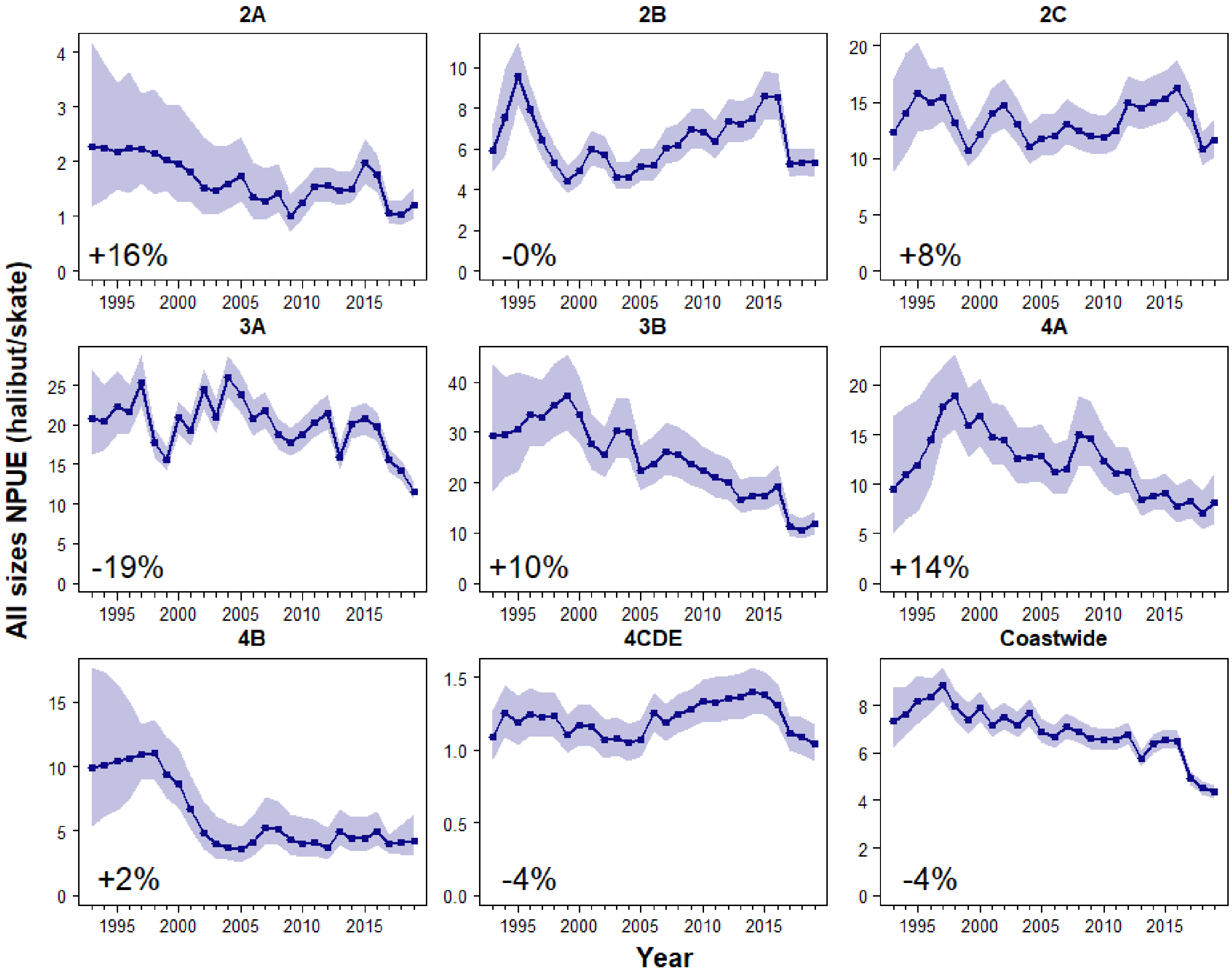

Figure A.2. Space-time model output for total NPUE for 1993-2019. Filled circles denote the posterior means of total NPUE for each year. Shaded regions show posterior 95% credible intervals, which provide a measure of uncertainty: the wider the shaded interval, the greater the uncertainty in the estimate. Numeric values in the lower left-hand corners are estimates of the change in mean total NPUE from 2018 to 2019.

APPENDIX B

Space-time modelling results for Regulatory Area 2C with and without snap gear data.

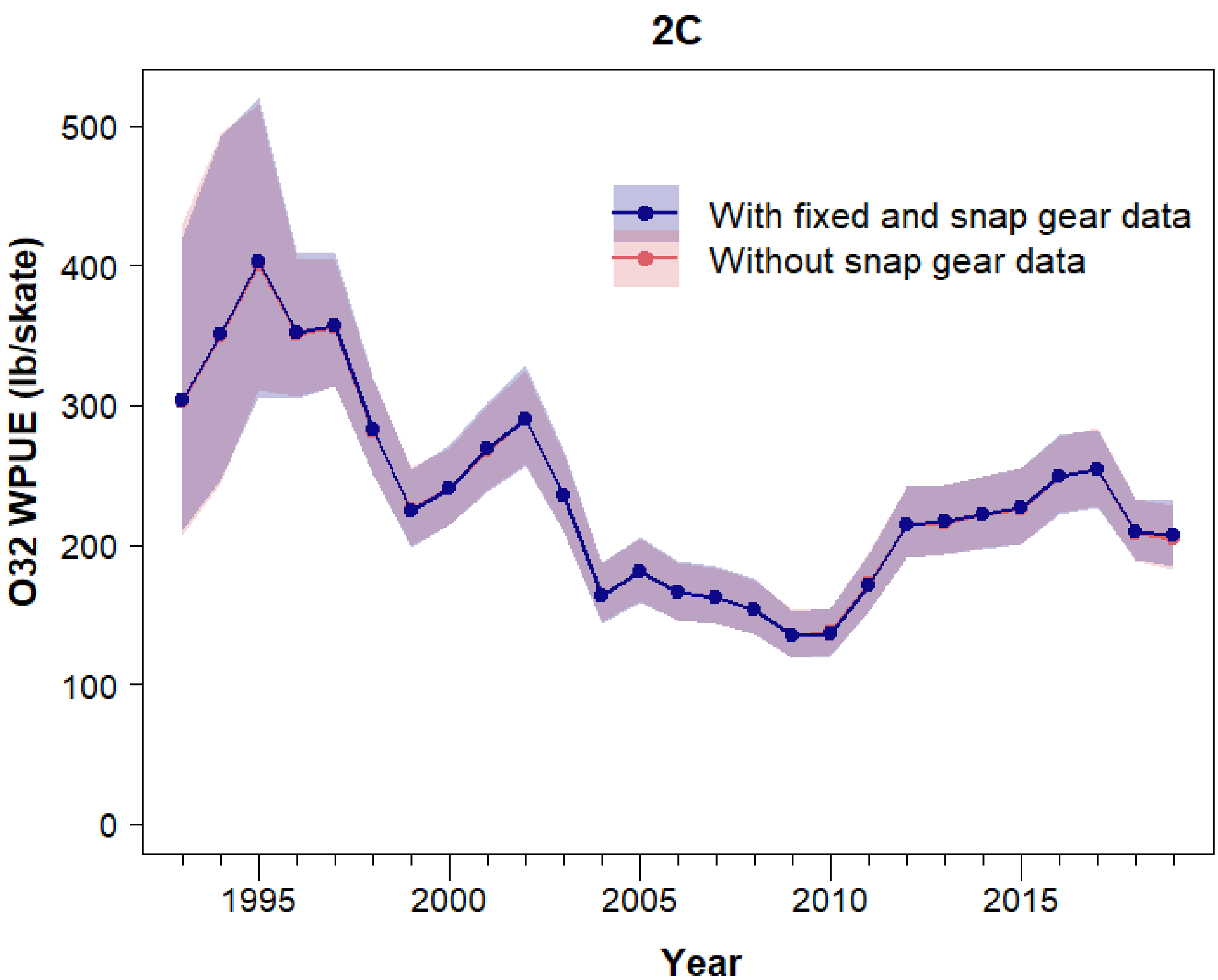

Figure B.1. Space-time model output for O32 WPUE for 1993-2019 for Regulatory Area 2C, comparing output from models with and without snap gear data. Filled circles denote the posterior means of O32 WPUE for each year. Shaded regions show posterior 95% credible intervals, which provide a measure of uncertainty: the wider the shaded interval, the greater the uncertainty in the estimate.

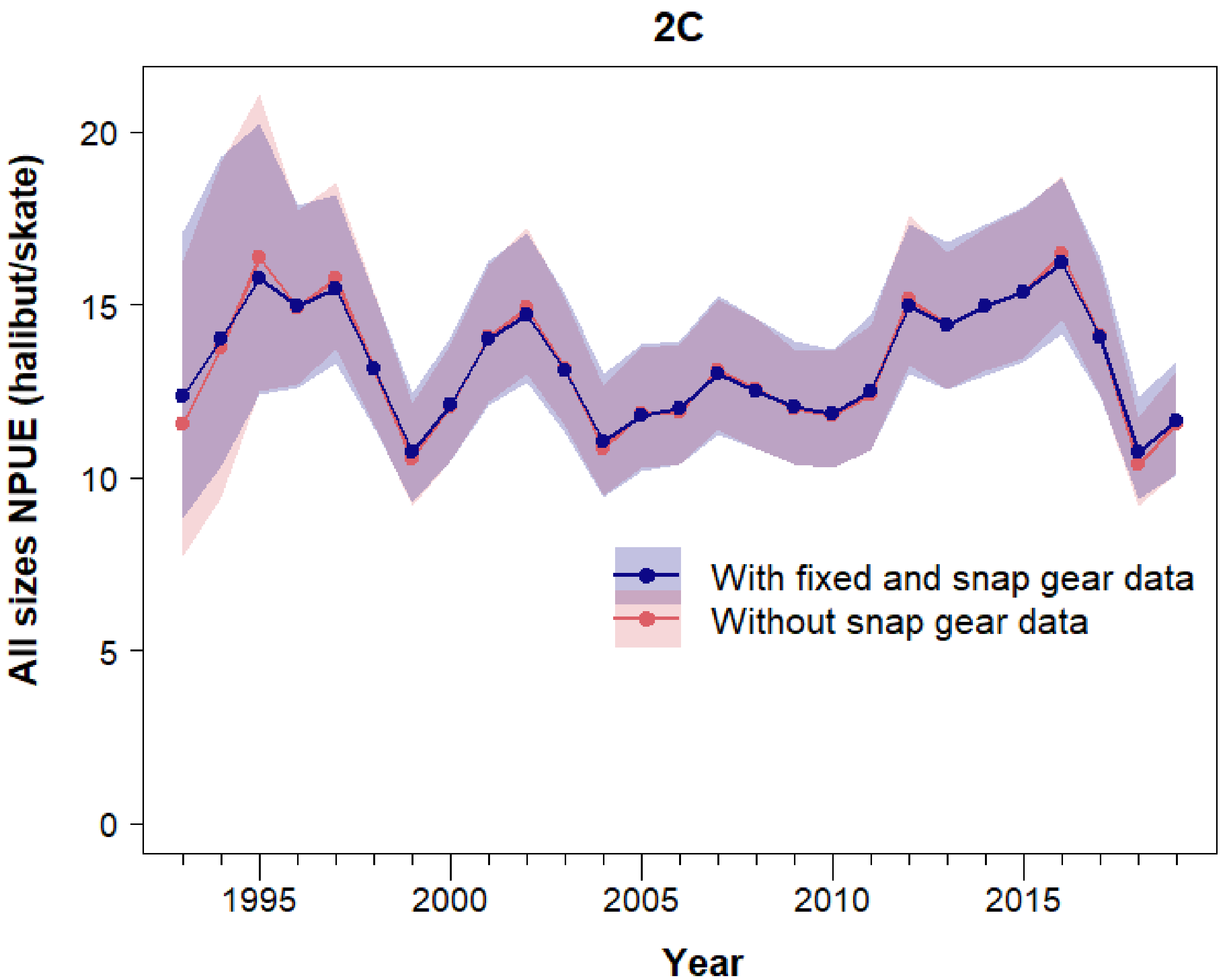

Figure B.2. Space-time model output for all sizes NPUE for 1993-2019 for Regulatory Area 2C, comparing output from models with and without snap gear data. Filled circles denote the posterior means of all sizes NPUE for each year. Shaded regions show posterior 95% credible intervals, which provide a measure of uncertainty: the wider the shaded interval, the greater the uncertainty in the estimate.

APPENDIX C

The effect of 2019 FISS expansions on space-time modelling results by IPHC Regulatory Area

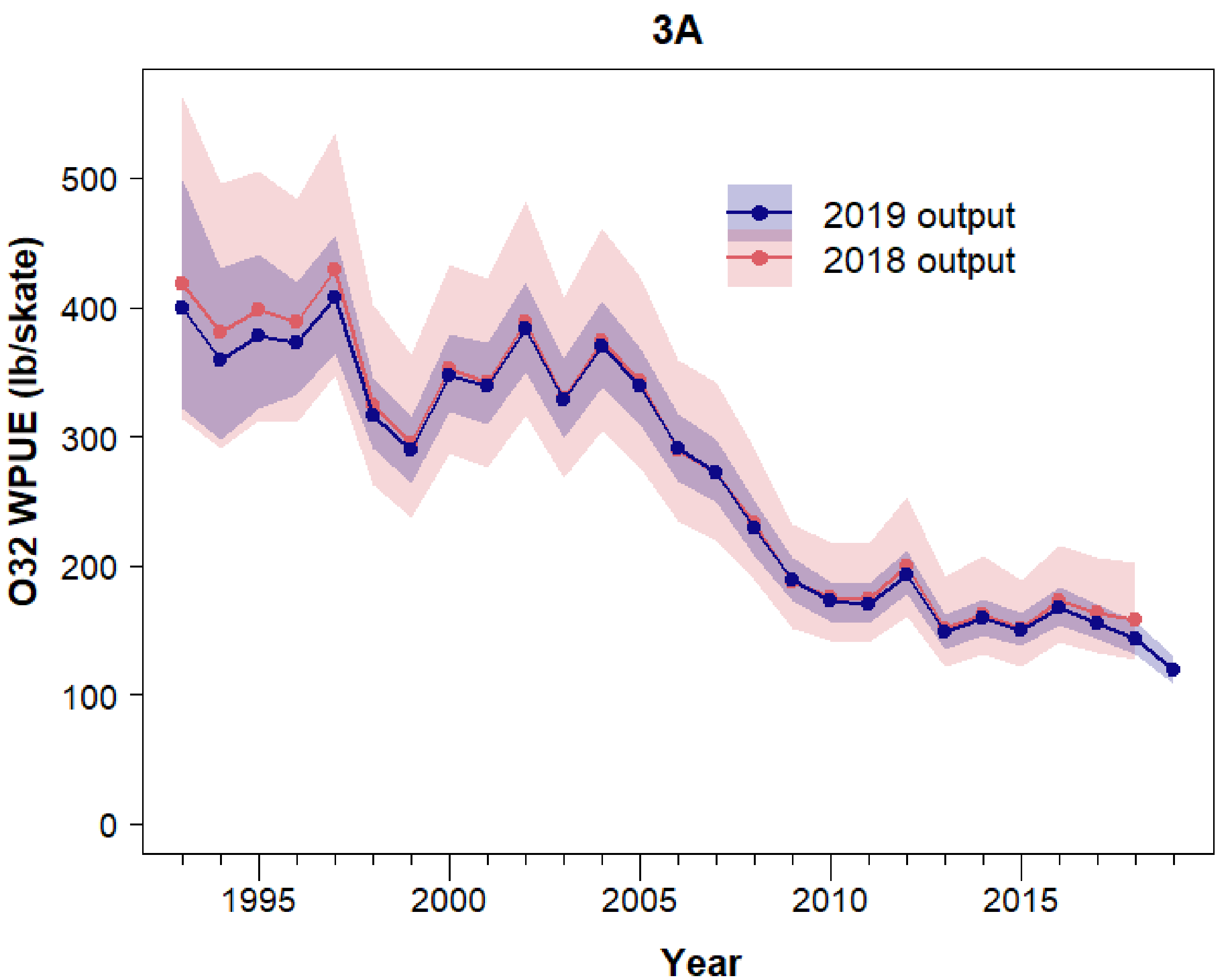

Figure C.1. Time series of posterior means of average O32 WPUE in Regulatory Area 3A from space-time modelling undertaken in 2019, compared with model output from 2018 modelling. The shaded regions show 95% posterior credible intervals.

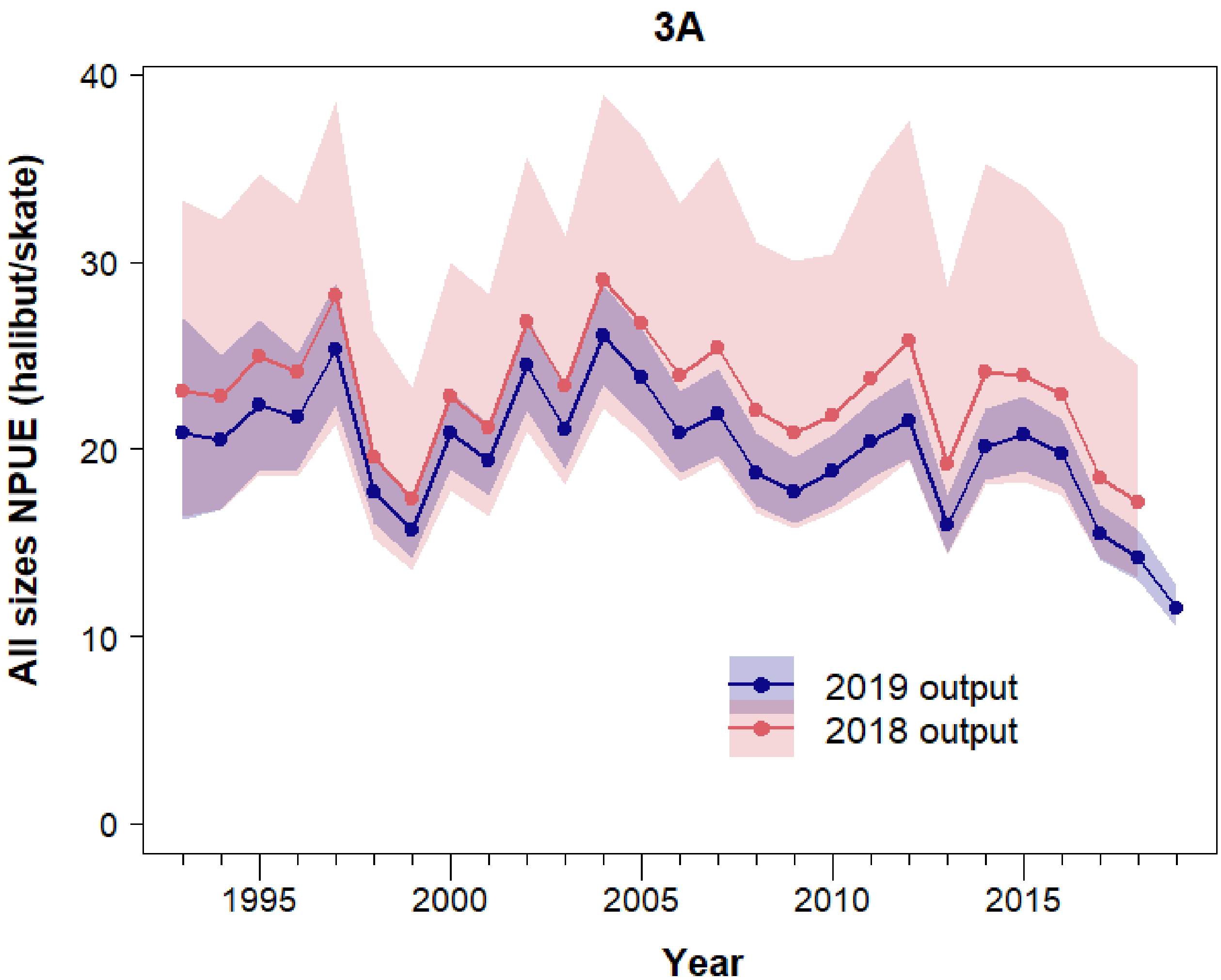

Figure C.2. Time series of posterior means of average all sizes NPUE in Regulatory Area 3A from space-time modelling undertaken in 2019, compared with model output from 2018 modelling. The shaded regions show 95% posterior credible intervals.

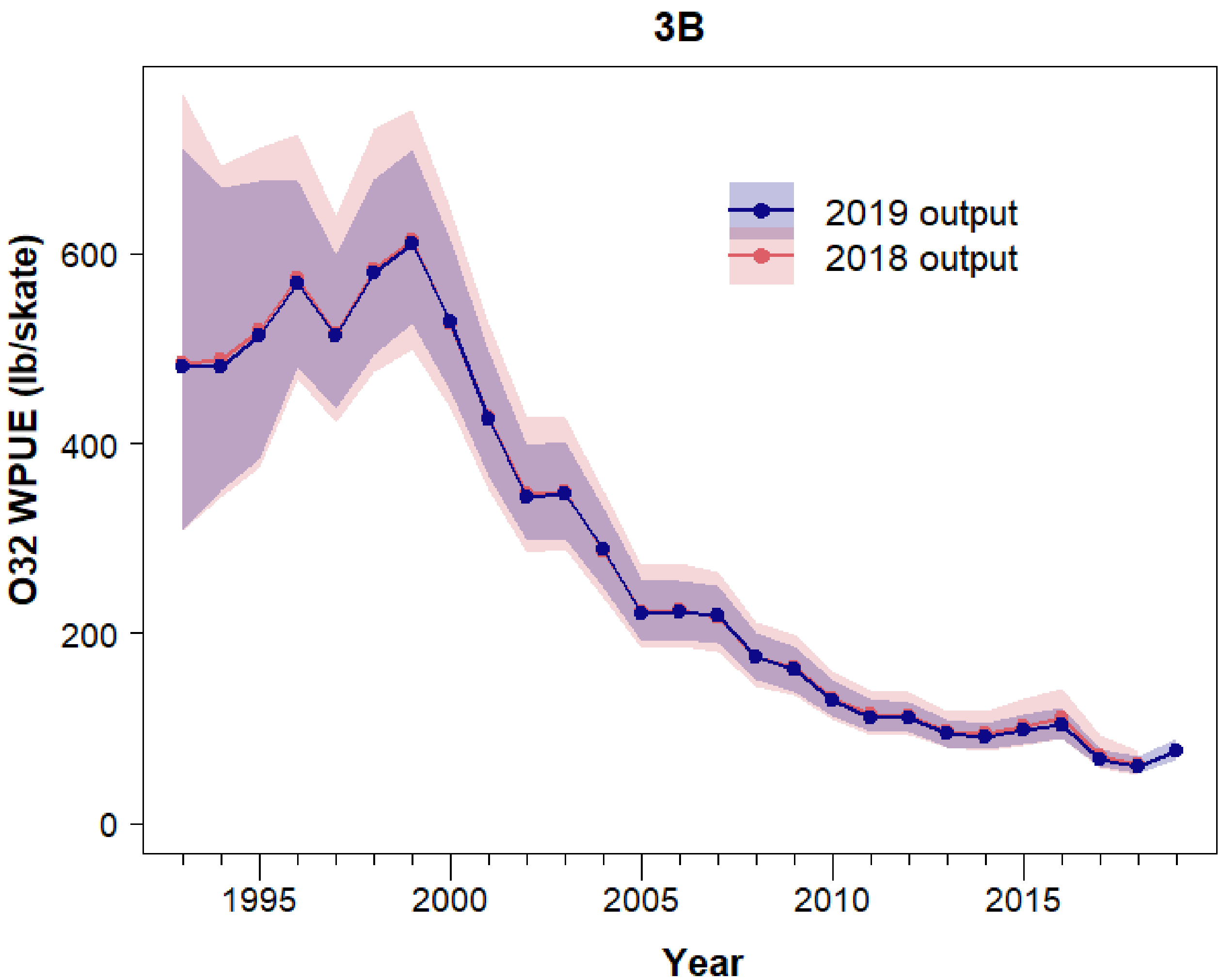

Figure C.3. Time series of posterior means of average O32 WPUE in Regulatory Area 3B from space-time modelling undertaken in 2019, compared with model output from 2018 modelling. The shaded regions show 95% posterior credible intervals.

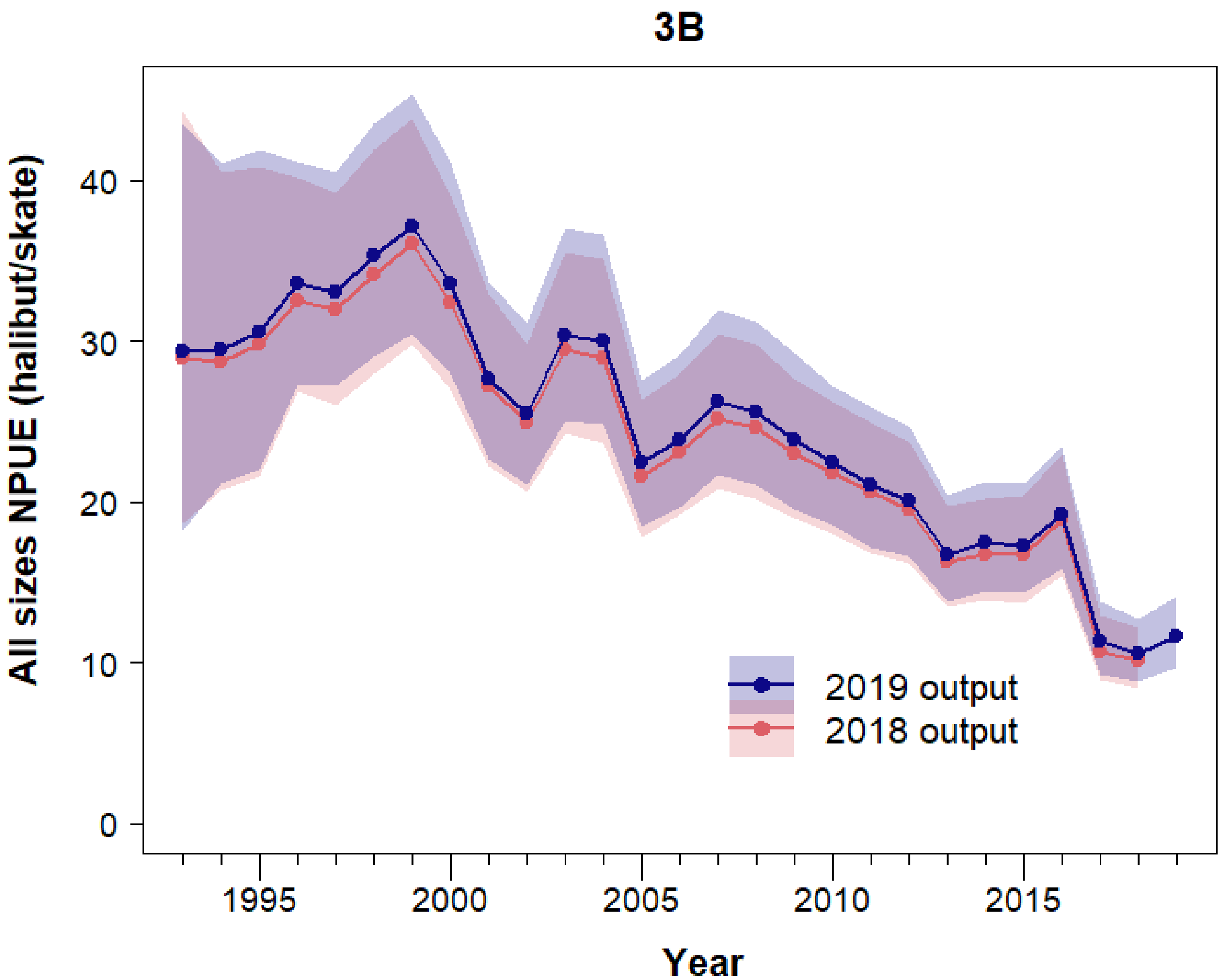

Figure C.4. Time series of posterior means of average all sizes NPUE in Regulatory Area 3B from space-time modelling undertaken in 2019, compared with model output from 2018 modelling. The shaded regions show 95% posterior credible intervals.