2022-24 FISS design evaluation

PREPARED BY: IPHC SECRETARIAT (R. A. WEBSTER; 15 MAY, 15 JUNE 2021)

PURPOSE

To present the proposed designs for the IPHC's Fishery-Independent Setline Survey (FISS) for the 2022-24 period, and an evaluation of those designs, for review by the Scientific Review Board.

BACKGROUND

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

FISS history 1993-2019

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

Examination of commercial logbook data and information from other sources, it became clear by 2010 that the historical FISS design had gaps in coverage of Pacific halibut habitat that had the potential to lead to bias in estimates derived from its data. These gaps included deep and shallow waters outside the FISS depth range (0-20 fathoms and 275-400 fathoms), and unsurveyed stations on the 10 nmi grid within the 20-275 fathom depth range within each IPHC Regulatory Area. This led the IPHC Secretariat to propose expanding the FISS to provide coverage 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, resulting in the sampling of the entire FISS design of 1890 stations in the shortest time logistically possible. The FISS expansion program allowed us to build a consistent and complete picture of Pacific halibut density throughout its range in Convention waters. Sampling the full FISS design has reduced bias as noted above, and, in conjunction with space-time modelling of survey data (see below), has improved precision and fully quantified the uncertainty associated with estimates based on partial annual sampling of the species range. It has also provided us with a complete set of observations over the full FISS design (Figure 1) from which an optimal subset of stations can be selected when devising annual FISS designs. This station selection process began in 2019 for the 2020 FISS and continues with the current review of design proposals for 2022-24. Note that in the Bering Sea, the full FISS design does not provide complete spatial coverage, and FISS data are augmented with calibrated data from National Marine Fisheries Service (NMFS) and Alaska Department of Fish and Game (ADFG) trawl surveys (stations can vary by year – 2019 designs are shown in Figure 1). Both of these supplementary surveys are conducted approximately annually.

Space-time modelling

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

FISS design objectives

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

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

- The Secretariat presents design proposals to the SRB for three subsequent years at the June meeting (recognizing that data from the current summer FISS will not be available for analysis prior to the September SRB meeting).
- The 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 for 'endorsement' occurs at the November Interim Meeting;
- Ad-Hoc modifications possible at the Annual Meeting to the design for the current year (due to unforeseen issues arising);
- Endorsed design for current year modified for cost and logistical reasons prior to summer implementation in FISS (February-April).

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

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

PROPOSED DESIGNS FOR 2022-24

The designs proposed for 2022-24 (Figures 2 to 4) use efficient subarea sampling in IPHC Regulatory Areas 2A, 4A and 4B, and incorporate a randomized subsampling of FISS stations in IPHC Regulatory Areas 2B, 2C, 3A and 3B (except for the near-zero catch rate inside waters around Vancouver Island), with a sampling rate chosen to keep the sample size close to 1000 stations in an average year. This was also used to generate the designs originally proposed for 2020 (but modified as a result of the impact of COVID19 and cost considerations), and for those proposed and approved for 2021. In 2020, designs for 2022-23 were also approved subject to revision. We are proposing one change from that 2022 design, bringing forward by one year (from 2023 to 2022) the sampling of the central and western subareas of IPHC Regulatory Area 4B to reduce the risk of bias in estimates from that area. Thus we propose that:

- In 2022 the lower-density western and central subareas of IPHC Regulatory Area 4B in sampled, followed by the higher-density eastern subarea in 2023-24
- The higher-density western subarea of IPHC Regulatory Area 4A be sampled in all three years, with the medium-density northern shelf edge subarea added in 2023 only
- The highest-density waters of IPHC Regulatory 2A in northern Washington and central/southern Oregon are proposed for sampling in each year of the 2022-24 period
- The near-zero density waters of the Salish Sea in IPHC Regulatory 2B are not proposed for sampling in 2022-24

Following this three-year period, it is expected that the remaining subareas will be included during the subsequent 3-5 years. These include the southeastern subarea of IPHC Regulatory 4A, and lower-density waters of IPHC Regulatory 2A (see below).

The design proposals again include full sampling of the standard FISS grid in IPHC Regulatory Area 4CDE. The Pacific halibut distribution in this area continues to be of particular interest, as it is a highly dynamic region with an apparently northward-shifting distribution of Pacific halibut, and increasing uncertainty regarding connectivity with populations adjacent to and within Russian waters.

While the proposed designs continue to rely on randomised subsampling of stations within the core IPHC Regulatory Areas (2B, 2C, 3A and 3B) and logistically efficient subarea designs elsewhere, other designs have been considered and remain as options. A discussion of these, adapted from previous reports, is in Appendix A.

FISS DESIGN EVALUATION

Precision targets

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

Reducing the potential for bias

In IPHC Regulatory Areas in which stations are not subsampled randomly (IPHC Regulatory Areas 2A, 4A and 4B in the 2022-24 proposals), sampling a subset of the full data frame in any area or region brings with it the potential for bias. This is due to trends in the unsurveyed portion of a management unit (Regulatory Area or 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 ("subarea") 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 change by at least 10% (e.g., from 15 to 25% of the area's biomass)? By sampling each subarea frequently enough to reduce the chance of its percentage changing by more than 10% between successive surveys of the subarea, we minimize the potential for appreciable bias in the Regulatory Area's index.

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

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

Table 2 shows projected CVs following completion of the proposed 2022-24 FISS designs. With these designs, we are projected to maintain CVs within the target range. Estimates from the terminal year are most informative for management decisions, but they also typically have the largest CVs (all else being equal). The final column in Table 2 shows the CV projections immediately following the 2022 FISS, which are also within the target range.

The projected CV for 2024 for IPHC Regulatory Area 2A is close to exceeding the target, and in future revisions of the 2024 design, we may wish to consider adding stations from southern Washington/northern Oregon, and northern California to the design ("subarea 2" for this Regulatory Area). While historical data show this subarea to be highly stable over time in terms of its biomass proportion, by 2024 it will have been five years since any part of it was last sampled, and with no other lower-density subareas planned for sampling that year in IPHC Regulatory Areas 4A and 4B, this may be a logistically feasible year for fishing those stations. Should estimated CVs increase more rapidly than projected, future designs would be revised accordingly.

Table 2. Projected CVs (%) for 2021-24 for O32 WPUE estimated after completion of the proposed 2022-24 FISS designs, and (final column) after completion of the proposed 2022 FISS design only.

Reg. Area	2021	2022	2023	2024	2022 (Estimated in 2022)
2A	13	13	14	15	14
4A	10	9	9	10	10
4B	10	12	10	12	14

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

Based on estimates from the historical times series (1993-2020) of O32 WPUE, the proposed designs for 2022-24 would be expected to maintain low bias by ensuring that it is unlikely that biomass proportions for all subareas change by more than 10% since they were previously sampled (Table 3).

Table 3. Maximum expected changes (%) in biomass proportion since previous sampling of subareas that are unsampled in a given year, based on estimated the 1993-2020 time series.

Reg. Area	2021	2022	2023	2024
2A	8	9	9	9
4A	8	10	6	6
4B	10	9	8	10

Post-sampling evaluation for 2020

The evaluation of precision of proposed designs above is based on using simulated sample data generated under the fitted space-time model for future years. If observed data are more (or less) variable than those generated under the model, actual estimates of precision may differ from those projected from models making use of the generated data. Table 4 compares the estimates of the CV for mean O32 WPUE for the implemented 2020 design based on using simulated data for 2020 and estimated from fitting the models including observed 2020 data. The projected CVs based on simulated data are essentially the same as those estimated when observed data are used for 2020 for the four IPHC Regulatory Areas sampled in 2020.

Table 4. Comparison of projected and estimated CVs (%) for 2020 by IPHC Regulatory Area. Note that FISS sampling in 2020 did not include Areas 2A, 4A, 4B or 4CDE due to unplanned survey reductions, therefore projected and estimated CVs are identical.

Regulatory Area	2020 projected CV (%)	2020 estimated CV (%)
2A		22
2B	6	6
2C	6	5
3A	4	4
3B	10	10
4A		25
4B		25
4CDE		12

CONSIDERATION OF COST

Ideally, the FISS design would be based only on scientific needs. However, some Regulatory Areas are consistently more expensive to sample than others, so for these the efficient subarea designs were developed. The purpose of factoring in cost was to provide a statistically efficient and logistically feasible design for consideration by the Commission. During the Interim and Annual Meetings and subsequent discussions, cost, logistics and tertiary considerations (Table 1) are also factored in developing the final design for implementation in the current year. It is anticipated that under most circumstances, cost considerations can be addressed by adding stations to the minimum design proposed in this report (2020 was an exceptional case). In particular, the FISS is funded by sales of captured fish and is intended to have long-term revenue neutrality, meaning that any design must also be evaluated in terms of the following factors:

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

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

PARAMETER STABILITY AND THE IMPACT OF ADDING NEW DATA

At SRB017, the Scientific Review Board requested information on the stability of space-time model parameter estimates as new data are introduced each year into the modelling. Our model assumes a semi-parametric (or delta) model specifying separate, but spatially linked, processes for zero and non-zero data (see Appendix B, and Webster et al. 2020). The following parameters are estimated directly in the model and provided automatically as model output in R-INLA:

- τ_g: precision parameter of gamma-distributed non-zero WPUE or NPUE process
- τ_u: precision parameter of random walk for depth relationship for probability of zero
- τ_v: precision parameter of random walk for depth relationship with non-zero WPUE or NPUE
- τ_Y: precision parameter of random walk for year relationship (average temporal trend; non-zeros only)
- θ_1, θ_2: parameters governing spatial dependence model
- ρ: temporal correlation parameter
- β_ε: scalar parameter linking non-zero and zero error processes

In practice, the model is typically interpreted through transformed versions of several of these parameters, i.e., variance (inverse of precision, e.g. $\sigma_g^2 = 1/\tau_g$) or standard deviation, and spatial variance and range (transformations of θ_1 and θ_2: see Appendix B) are often used to help understand the processes. However, as stability in the transformed parameter estimates follows from stability in the parameter estimates provided in the model output, it is sufficient (and simpler) to present the values from the model output in order to understand the effect of new data on the model.

The values in Table 5 show high stability in all parameters except when significant changes occur to the input data, in particular when FISS expansions occurred. When new data were added through the FISS expansion program, this included data from deep and shallow stations for the first time, improving our understanding of the relationship between density and depth. This improved understanding was reflected in increases in precision parameters for the non-zero random walk process (τ_u) in particular in IPHC Regulatory Areas 2C and 3A, and the probability of zero process (τ_v) in IPHC Regulatory Areas 2B, 2C and 3A. Note that IPHC Regulatory Area 2C in particular has very few zero values, and the precision parameter for the depth relationship varies much more among years than for other areas as the addition of any new zeros can be quite influential. However, given how unlikely a zero is in this area, this model component is unimportant for final WPUE estimates relative to the non-zero process. We also note that the precision parameter of the temporal trend random walk (τ_Y) increased in these areas following the FISS expansions, reflecting a general reduction in uncertainty when unsurveyed habitat was sampled for the first time.

Other aspects of the SRB017 request will be discussed as part of the presentation at SRB018.

Table 5. Posterior means of space-time model parameters by IPHC Regulatory Area and year. Orange shading highlights years with expanded surveys, and green shading indicates years in which new covariates were added (see footnotes).

Reg. Area	Year	τ_g	τ_u	τ_v	τ_Y	θ_1	θ_2	ρ	β_ε
2A	2017	1.4	0.27	2.2	14	-7.9	5.8	0.90	0.55
	2018	1.4	0.34	2.2	31	-7.6	5.6	0.91	0.55
	2019	1.4	0.34	2.2	29	-7.7	5.7	0.91	0.55
	2020	1.4	0.34	2.2	30	-7.7	5.7	0.91	0.55
2B	2017	1.5	0.18	9.4	1.5	-7.5	5.8	0.93	0.46
	2018	1.7	0.29	8.0	3.0	-7.5	5.4	0.96	0.43
	2019[1]	1.7	0.30	7.2	2.7	-7.7	5.8	0.95	0.46
	2020[2]	1.7	0.24	6.9	2.9	-7.7	5.8	0.95	0.47
2C	2017	2.8	0.11	1.3	2	-8.9	6.6	0.96	0.43
	2018	2.8	0.61	2.1	10	-8.9	6.6	0.96	0.41
	2019[2]	2.8	0.50	2.2	12	-8.9	6.6	0.96	0.42
	2020	2.8	0.22	2.3	13	-8.8	6.5	0.96	0.42
3A	2017	1.9	0.14	0.9	4.4	-7.5	5.6	0.96	0.50
	2018	1.9	0.15	0.8	4.1	-7.3	5.5	0.96	0.53
	2019	1.9	0.20	10.6	5.0	-7.3	5.4	0.96	0.50
	2020	1.9	0.22	10.5	4.6	-7.3	5.4	0.96	0.50
3B	2017	2.4	0.16	1.2		-6.7	4.9	0.95	0.59
	2018	2.3	0.14	1.2		-6.7	4.9	0.95	0.58
	2019	2.3	0.16	1.1		-6.8	4.9	0.95	0.56
	2020	2.3	0.12	1.1		-6.7	4.9	0.95	0.57
4A	2017	1.6	0.14	2.4	4.4	-7.8	5.7	0.95	0.42
	2018	1.6	0.16	2.5	4.2	-7.8	5.7	0.95	0.43
	2019[3]	1.6	0.12	2.3	3.7	-7.8	5.6	0.95	0.37
	2020	1.6	0.12	2.3	3.7	-7.8	5.6	0.95	0.37
4B	2017	1.9	0.16	6.2	3.0	-8.1	5.8	0.90	0.41
	2018	1.9	0.15	6.8	2.9	-8.0	5.9	0.90	0.39
	2019	1.9	0.17	6.9	2.8	-8.0	5.8	0.91	0.38
	2020	1.9	0.17	6.9	2.8	-8.0	5.8	0.91	0.38
4CDE	2017	1.4	0.13	2.2		-6.8	5.1	0.90	0.49
	2018	1.4	0.14	2.2		-6.8	5.1	0.90	0.50
	2019	1.4	0.15	2.3		-6.8	5.1	0.90	0.49
	2020	1.5	0.15	2.3		-6.8	5.1	0.90	0.49

1. Binary covariate for low-density Salish Sea (sampled 2018 only in 2B) added to model.
2. Data from snap gear experiments included, along with covariates for difference between snap and fixed gear.
3. Revision of effectiveness criteria for whale depredation had greatest impact on IPHC Regulatory 4A, leading to removal of data from several sets that were fished just once in deeper waters.

RECOMMENDATION

That the SRB:

1) **NOTE** paper IPHC-2021-SRB018-05 that provides background on and a discussion of the IPHC fishery-independent setline survey design proposals for the 2022-24 period;
2) **ENDORSE** the final 2022 FISS design as presented in Figure 2, and
3) Provisionally **ENDORSE** the 2023-24 designs (Figures 3 and 4), recognizing that these will be reviewed again at subsequent SRB meetings.

REFERENCES

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Webster RA, Soderlund E, Dykstra CL, and Stewart IJ (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.

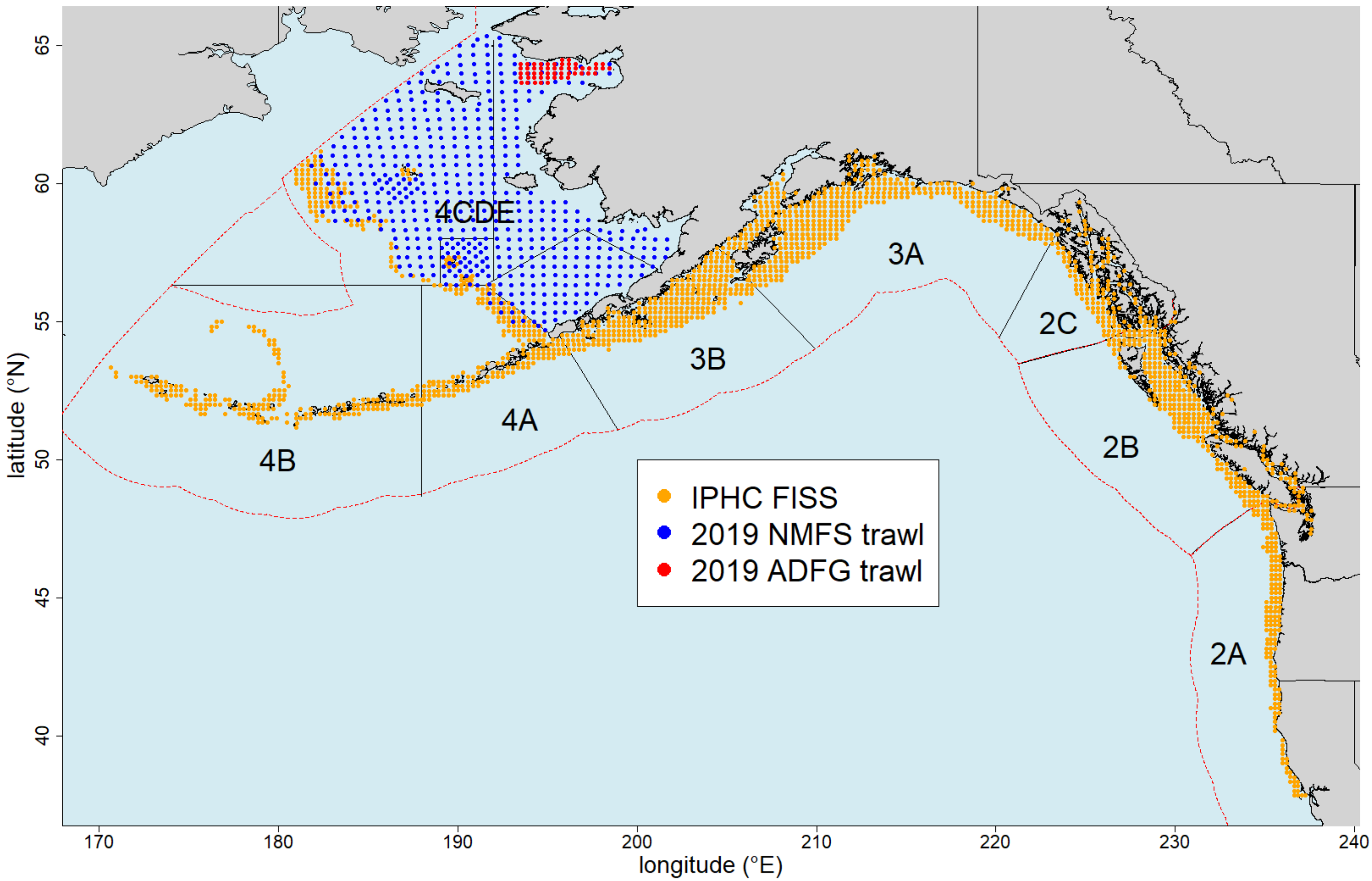

Figure 1. Map of the full 1890 station FISS design, with orange circles representing stations available for inclusion in annual sampling designs, and other colours representing trawl stations from 2019 NMFS and ADFG surveys used to provide complementary data for Bering Sea modelling.

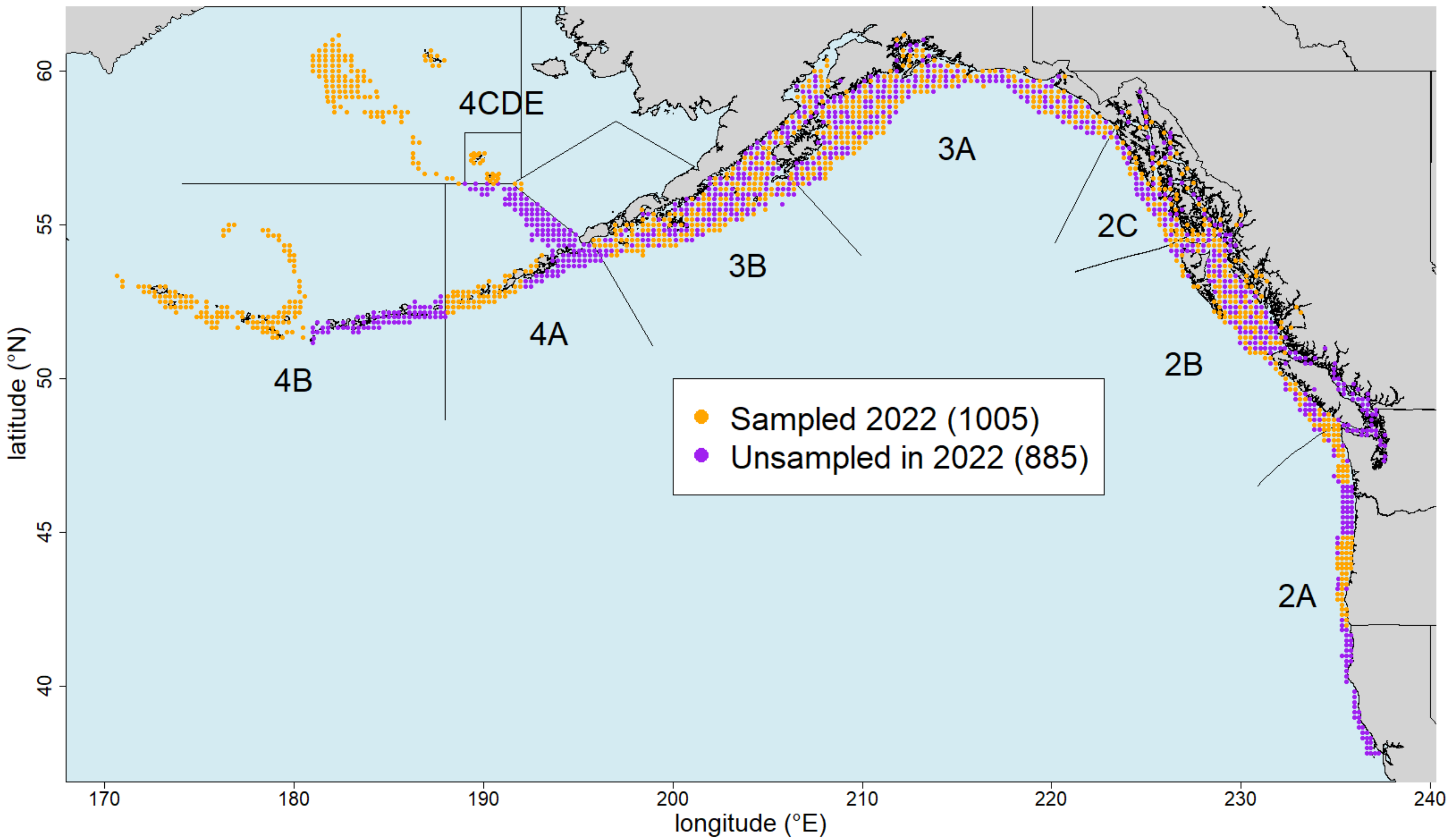

Figure 2. Proposed minimum FISS design in 2022 (orange circles) based on randomized sampling in 2B-3B, and a subarea design elsewhere. Purple circles are optional for meeting data quality criteria.

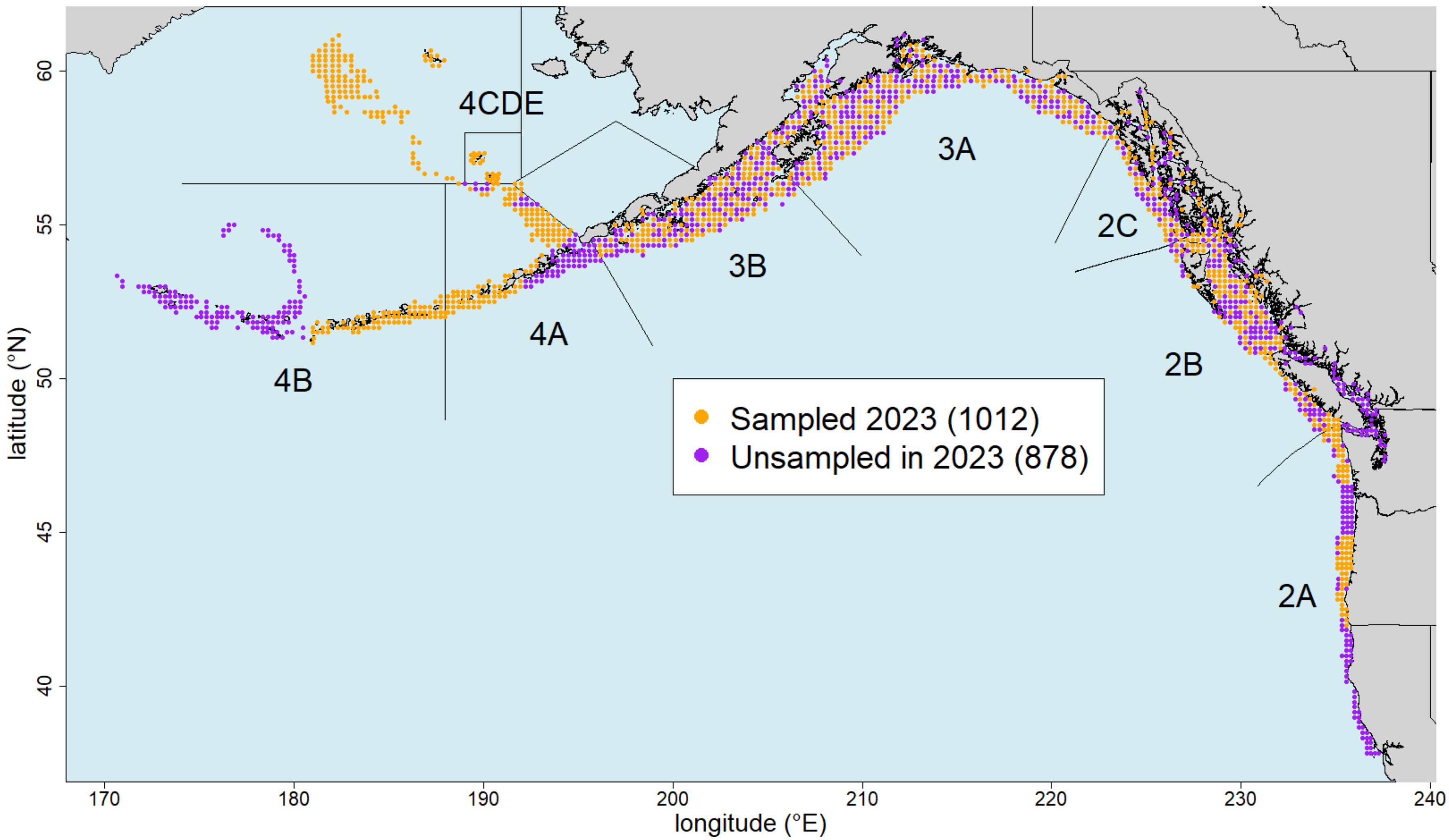

Figure 3. Proposed minimum FISS design in 2023 (orange circles) based on randomized sampling in 2B-3B, and a subarea design elsewhere. Purple circles are optional for meeting data quality criteria.

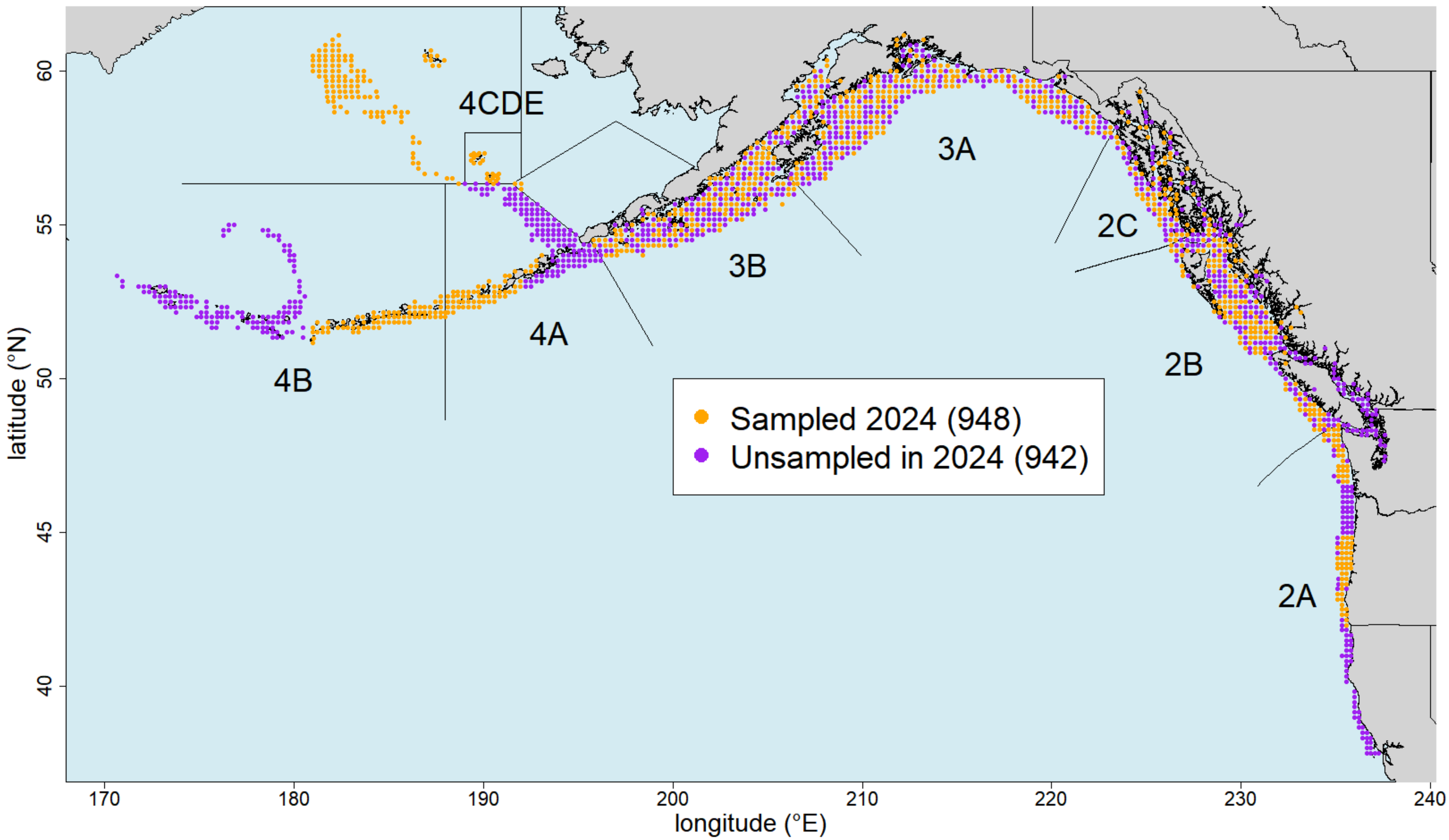

Figure 4. Proposed minimum FISS design in 2024 (orange circles) based on randomized sampling in 2B-3B, and a subarea design elsewhere. Purple circles are optional for meeting data quality criteria.

Appendix A

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 available for consideration in developing such designs include the following:

- Full sampling of the 1890 station design (Figure 1).
- Completely randomized sampling of stations within each IPHC Regulatory Area
- Randomized cluster sampling, 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, 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 that use random sampling, the resulting estimates (eg, WPUE, NPUE indices) are unbiased. Designs based on sampling subareas require an evaluation of the potential for bias.

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.

Appendix B

Spatio-temporal model description

The IPHC's spatio-temporal model for FISS data is built around a semiparametric model (also known as a delta model) in which the probability of catching zero fish and the distribution of non-zero catches are modelled as connected spatio-temporal processes. Let $w(\boldsymbol{s},t)$ be the observed weight-per-unit-effort (WPUE) value at location $\boldsymbol{s}$ (a vector of coordinates) in year t, where $\boldsymbol{s}$ represents the spatial locations of the fished survey stations, taking values $\boldsymbol{s}_1, \ldots, \boldsymbol{s}_n$ (vectors of coordinates) and $t = t_1, \ldots, t_T$. In our model, each $\boldsymbol{s}_i \in S^2$, the set of points on the surface of a sphere. Data from the FISS contain observations of zero WPUE, due to stations in low-density areas catching no Pacific halibut. Two new variables are defined, $x(\boldsymbol{s},t)$ for presence or absence of Pacific halibut in the catch, and $y(\boldsymbol{s},t)$ for the WPUE value when Pacific halibut are present:

$$x(\mathbf{s},t)=\begin{cases}0 & w(\mathbf{s},t)=0\\ 1 & w(\mathbf{s},t)>0\end{cases}$$

$$y(\mathbf{s},t)=\begin{cases}NA & w(\mathbf{s},t)=0\\ w(\mathbf{s},t) & w(\mathbf{s},t)>0\end{cases}$$

The NA indicates that $y(\boldsymbol{s},t)$ is a random variable that can only take non-zero values, and is therefore undefined when $w(\boldsymbol{s},t) = 0$. The variable $x(\boldsymbol{s},t)$ has a Bernoulli distribution, $x(\boldsymbol{s},t) \sim \mathrm{Bern}(p(\boldsymbol{s},t))$, while a gamma distribution is used for the $y(\boldsymbol{s},t)$, $y(\boldsymbol{s},t) \sim \mathrm{gamma}(a(\boldsymbol{s},t), b(\boldsymbol{s},t))$, which has mean $\mu(\boldsymbol{s},t) = a(\boldsymbol{s},t)/b(\boldsymbol{s},t)$. Only the gamma mean is allowed to vary: the variance, $\sigma_g^2 = a(\boldsymbol{s},t)/b^2(\boldsymbol{s},t)$, is assumed invariant over space and time. Note that $\sigma_g^2 = 1/\tau_g$, i.e., the gamma variance is the inverse of the precision parameter listed in Table 5.

Next let the $\varepsilon(\boldsymbol{s},t)$ be a Gaussian Field (GF) which is shared by both component random variables in the following way:

$$u(\mathbf{s},t)=\operatorname{logit}\left(p(\mathbf{s},t)\right)=f_x\left(\boldsymbol{\beta}_x,\mathbf{z}(\mathbf{s},t)\right)+\varepsilon(\mathbf{s},t)$$

$$v(\mathbf{s},t)=\log\left(\mu(\mathbf{s},t)\right)=f_y\left(\boldsymbol{\beta}_y,\mathbf{z}(\mathbf{s},t)\right)+\beta_\varepsilon\varepsilon(\mathbf{s},t)$$

The parameter β_ε is a scaling parameter on the shared random effect, and appears in Table 5. Environmental covariates are introduced into each model component through f_x and f_y, functions of a spatially and temporally indexed covariate data matrix, $\mathbf{z}$, and covariate vectors $\boldsymbol{\beta}_x$ and $\boldsymbol{\beta}_y$.

Temporal dependence is introduced through a simple autoregressive model of order 1 (AR(1)), as described in Cameletti et al. (2013), as follows,

$$\varepsilon\left(\boldsymbol{s},t\right)=\rho\varepsilon\left(\boldsymbol{s},t-1\right)+\eta\left(\boldsymbol{s},t\right)$$

where ρ denotes the temporal correlation parameter and $|\rho| < 1$. For a given year, *t*, the spatial random field (SRF), $\eta(\boldsymbol{s}, t)$, is assumed to be a GF with mean zero and covariance matrix **Σ**. We assume a stationary Matérn model (Cressie, 1993) for the spatial covariance model, which specifies how the dependence between observations at two locations decreases with increasing distance. The two key parameters for this model are the spatial variance parameter, σ_η^2, and the spatial scale parameter, κ. The latter is related to the spatial range parameter, *r*, which for our model is defined in R-INLA as $r=\sqrt{8}/\kappa$ and is the distance (in radians) at which the spatial correlation is approximately 0.13 (and thus can be considered "small"). However, R-INLA instead directly estimates and outputs transformed versions of these parameters, θ_1 and θ_2, where:

$$\sigma_\eta^2=\frac{1}{4\pi e^{2(\theta_1+\theta_2)}}$$

$$\kappa=e^{\theta_2}$$

Posterior means for θ_1 and θ_2 are shown in Table 5.

The relationships with depth were included in the models, and specified using a random walk (of order 1) as data exploration showed that they did not follow an obvious parametric form. Depth from 0 to 732 (400 ftm) is first discretised into *d* equally-spaced levels, with the change due to depth from level *i* to *i*+1 modelled as a zero-mean Gaussian process. Thus, for the zero (*u*) and non-zero (*v*) processes respectively, we have

$$\Delta u_i=u_i-u_{i+1}\sim N(0,\sigma_u^2)$$

$$\Delta v_i=v_i-v_{i+1}\sim N(0,\sigma_v^2)$$

Likewise, a temporal trend in the non-zero component was also included in the model as a random walk (of order 1) in order to improve prediction in unsampled areas (so that in the absence of data, predictions track the same trend as sampled regions rather than drift toward the long-term mean). The variance parameter associated with this random walk (with increments of one year) was σ_Y^2. All three random walk parameters are represented by their reciprocals, the precision parameters τ_u, τ_v and τ_Y, in Table 5.

References

Cameletti, M., Lindgren, F., Simpson, D. and Rue, H. 2013. Spatio-temporal modeling or particulate matter concentration through the SPDE approach. Advances in Statistical Analysis 97:109-131.

Cressie, N. 1993. Statistics for Spatial Data. Wiley, New York, 2nd ed.