Central Coast Catch Monitoring Program

Results and overview of the 2022 season

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Background

In 2019, the Heiltsuk Nation began a dockside monitoring program in Bella Bella to quantify catches in recreational and FSC fisheries in PFMAs 7 and 8 and to sample DNA from harvested fish for genetic stock identification (GSI). Beginning in 2021, the pilot catch monitoring program expanded to include each of the four Central Coast First Nation communities, including Nuxalk, Kitasoo Xai'xais, and Wuikinuxv territory. This expanded four-Nation program was made possible by grant funding from the British Columbia Salmon Restoration and Innovation Fund, as well as logistical and scientific support from the Central Coast Indigenous Resource Alliance (CCIRA). The program uses a combination of fisher interviews (i.e., creel surveys), overflights, and genetic stock ID (GSI) to understand spatial-temporal patterns in fishing effort, salmon harvest, and fisher satisfaction with the fishery. Overall, the catch monitoring program aims to provide high-quality information on mixed-stock harvest, community perceptions, and food security concerns from Indigenous communities that is crucial for collaborative fishery management under the recently implemented Northern Shelf Bioregion Fisheries Resource Reconciliation Agreement (FRRA).

Surveys occurred at access points (e.g., dockside, lodges) after completed fishing trips, and were designed to collect both quantitative and qualitative information on the trip. Quantitative information included: time spent fishing, the number of salmon caught and harvested (by species), fishing location (by Pacific Fishery Management Areas [PFMA] sub-areas), fishing gear, and the number of other fishing vessels observed at those sites (by fisher status). Qualitative information was specific to Indigenous fishers and included perceptions of trip and season-wide satisfaction. A subset of harvested salmon were sampled for GSI, which is commonly used by fisheries managers to assign salmon harvested in mixed-stock fisheries to their population or conservation unit (CU) of origin. GSI sampling continued in 2022 (we submitted 389 samples from the Nations and 1414 from partner lodges), however due to a high volume of samples being submitted to the DFO Molecular Genetics Lab (MGL) results are not available as of the writing of this report.

The 2022 season continued the field methods from 2021 and began collaborations with sportfishing lodges to survey lodge guests. In 2022, we revised our model based on feedback from an external program review that occurred in Winter 2022 – catch and effort estimates of the seasonal and spatial patterns for the recreational and FSC coho and Chinook salmon fisheries were estimated by fitting a Bayesian spatial-temporal conditional autoregressive model to survey and overflight data. These estimates relied upon a wealth of information provided by fisher surveys (e.g., fisher status, observed boating effort, catch rates, site choices, trip duration, and gear efficiency) to scale from individual trips towards seasonal and spatial patterns across the Central Coast. Fisher activity profiles and CPUE were derived from interview data. This approach assumes that interviewed fisher's CPUE and activity profiles generalizes to non-interviewed fishers. Through this program, we provide probabilistic estimates of seasonal and coast-wide impacts of the mixed-stock fishery. The 2022 addition of lodge surveys required several working assumptions to align data structure to the access-point dockside interviews from Klemtu and Bella Bella surveys. Currently, the genetic stock ID baselines are being developed and are not yet integrated into model estimates.

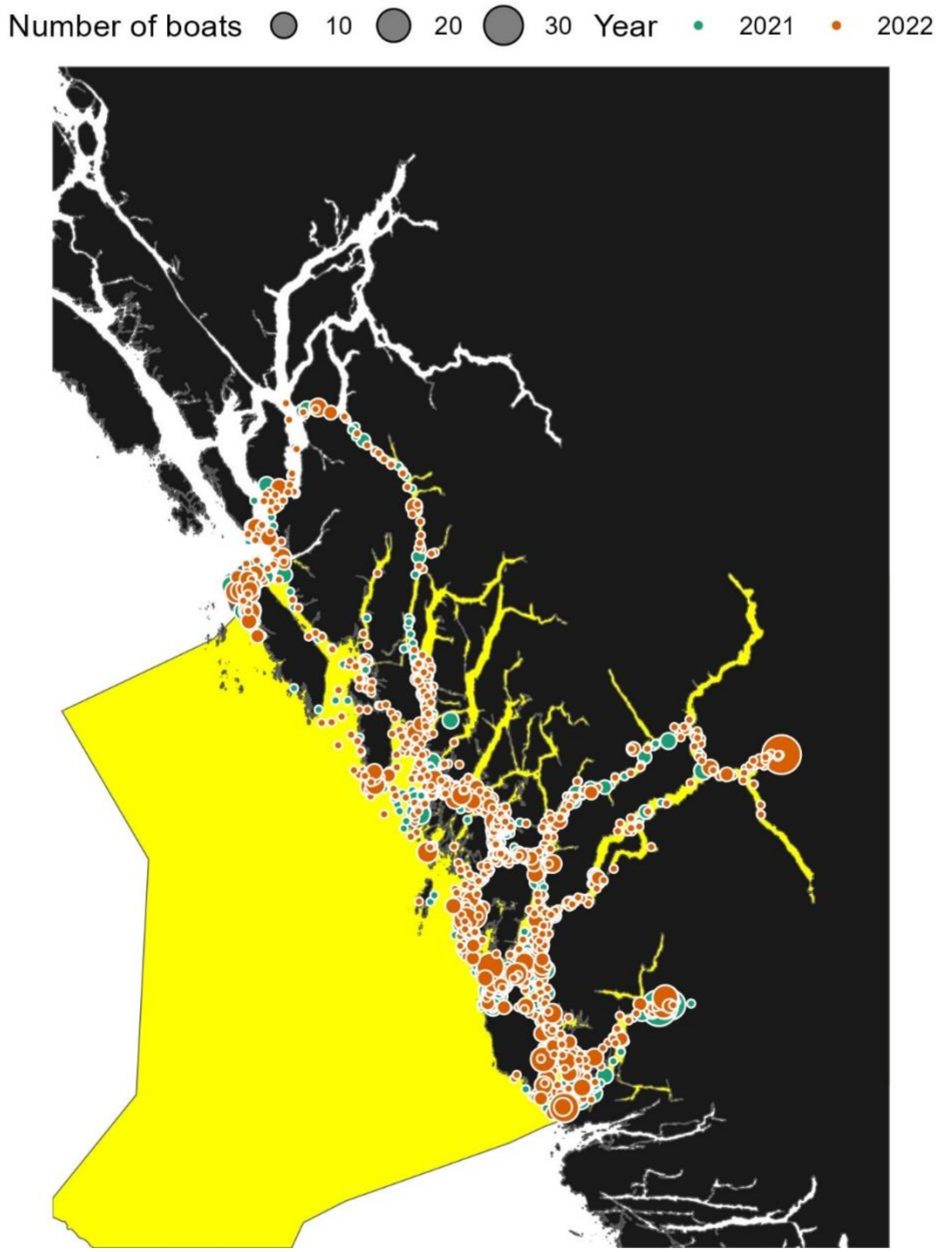

Figure 1. Spatial distribution of fishing boat activity from overflight transects in the Central Coast since 2021. Individual points show georeferenced locations of activity, and the size of the points indicate the number of boats at that location.

Methods

Interviews

In 2019, HIRMD initiated a pilot catch monitoring program to quantify catch of salmon in both the recreational and Food, Social, and Ceremonial (FSC) fisheries within Haíłzaqv territory. Since then, HIRMD staff have conducted 877 dockside surveys of Haíłzaqv and visiting recreational fishers to increase salmon GSI, quantify weekly fishing effort, and catch per unit effort (CPUE) across PFMAs 7 and 8 where individuals reported fishing. The 2022 expansion of the catch monitoring program includes fisher surveys and biosampling from HIRMD, Kitasoo Xai'xais Stewardship Authority (KXSA), and participating lodges (Duncanby, Good Hope, and Legacy Lodge) and spanned PFMAs 6–9, and parts of Area 10. In 2022, HIRMD staff conducted 228 dockside surveys, KXSA conducted 59 surveys in Klemtu, and partner lodges conducted 479 surveys of guest fishers. KXSA surveys followed similar questions as the HIRMD program but through targeted interviews of Kitasoo Xai'xais Nation fishers at the end of their trips, rather than opportunistic dockside sampling. Lodge surveys collected information across the entire duration of guests' multi-day trips (~5 days on average).

The HIRMD surveys and interviews were conducted of both FSC and recreational salmon fishers through the summer months (May – Sept). HIRMD surveys were primarily conducted dockside at three public docks in the Bella Bella area (two in Bella Bella and one on Denny Island) using convenience-sampling approaches (Ryan and Bernard 2003, Wiber et al. 2004, Bernard 2006). Surveys were aimed at all salmon fishery participants, including segments of the Haíłzaqv Nation population participating in salmon food fishing and recreational fishers (both local and non-local). There were no predetermined sample sizes of survey participants, as the surveys intend to create the most comprehensive snapshot of fishing effort across the season.

Survey interviews asked key questions about a fisher's trip and most trips were targeting salmon. Key quantitative data collected during surveys included: number of salmon of each species caught (2022 surveys also inquired about released fish), start and end time for their trip, estimated fuel costs, all fishing areas visited, number of other FSC and sport fishing boats in each of the areas visited, and number of hours fished at each location (effort). All fishers who conduct volunteer dockside creel surveys provide free and informed verbal consent.

Genetic Stock Identification

Samples were collected dockside when fishers returned from their outing, at public docks in Bella Bella and Klemtu, as well as at North King Lodge situated on the Northwest tip of Aristazabal Island (PFMA 6) and Duncanby Lodge, Good Hope Lodge, and Legacy Lodge in Rivers Inlet (PFMA 9). Fish were identified to species and a small fin clip was taken from the dorsal or tail fin for DNA. These fin clips were then mounted to prelabelled whatman sheets which are submitted to MGL at the culmination of the fishing season in late-September. DNA is extracted from these tissues by the MGL and then amplified at hundreds of single nucleotide polymorphism (SNPs) loci. The Chinook panel includes 547 of these amplicons, while the coho SNP panel includes 304 unique loci. Genetic baselines characterizing population-specific allele frequencies are then used to assign individuals to their most likely population and conservation units. For hatchery-born fish, MGL also uses parentage-based tagging (PBT), to identify offspring of hatchery broodstock that are harvested in the fishery. These sources of information are then combined by MGL into a summary report identifying the most likely conservation unit and source population for each sampled individual. We summarized these results using these CU assignments, and estimated the relative proportion of each CU in fisheries catches across the three years and four fishing areas (PFMAs) in our study.

Overflights

In 2022, four overflight routes were surveyed weekly for 13 weeks beginning on June 4th and ending on September 7th to quantify effort in fisheries around the Central Coast region. These four routes provided complete spatial coverage of fishing areas within Pacific Fishery Management Areas 6-9 (including subareas 10-1 and 10-2) that fell within the territories of the Central Coast First Nations (CCFN: Kitasoo Xai'xais, Haíłzaqv, Nuxalk, Wuikinuxv). Due to logistical challenges associated with the timing and availability of the aircraft, pairs of routes were surveyed on consecutive days and each round of flights followed a random stratified design to sample weekends and weekdays. Flight route order and direction were randomized to reduce the potential for spatial-temporal bias in observations of fishing vessels.

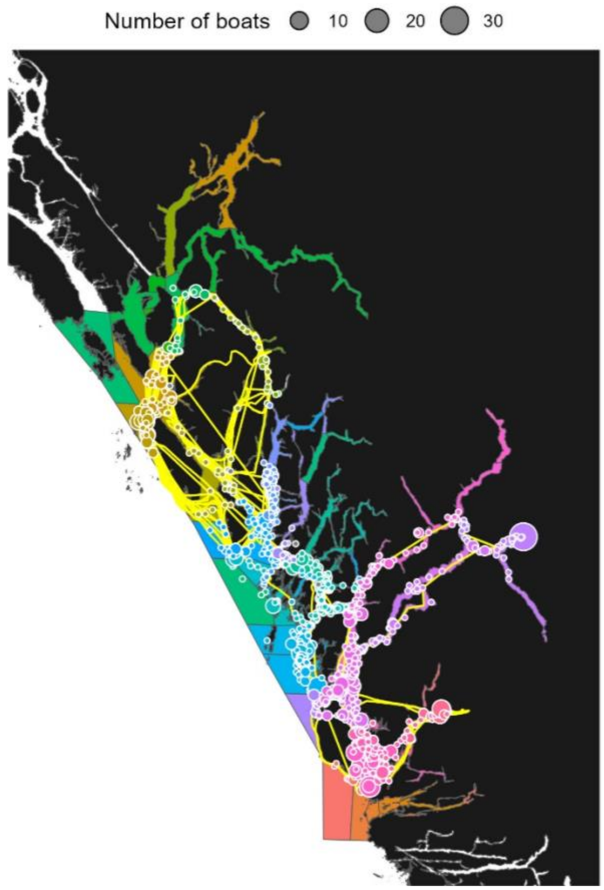

Figure 2. Overflight routes and boat sightings in 2022.

Vessel counts began as soon as the aircraft was airborne. Routes were predefined, with the pilot getting a closer view of a fishing boat or group of boats as needed to better identify the potential fishing activity of the boat. The pilot resumed the survey route once these boats had been digitally recorded. Boat observations were recorded in the CoastTracker App on a Samsung Galaxy enabled tablet. For each boat that the overflight team encountered, they entered a boat observation and recorded:

(1) The general boat type (either: sport fishing, commercial, local)
(2) The activity the boat was engaged in (if any): either traveling, fishing or anchored.
(3) The specific boat type:
    a. If sport fishing boats (lodge, independent or unknown)
    b. If local boat: select either First Nation or non-First Nation boat and record the gear type (troll or gillnet) used under the gear visible field
    c. If commercial boats (either: gillnetter or seiner)
(4) The Number of boats of this type.
(5) If fishing gear was visible (e.g. gillnet or trolling gear), the team recorded this in the app.
(6) Where possible, staff also recorded the number of people on board.
(7) If the catch was visible, this was also noted (e.g. salmon, halibut, rockfish).

Data were uploaded to the Regional Monitoring System Data Portal at the end of each survey.

Activity Profile

We developed daily fishing activity profiles for FSC and sportfishers from the interview data. Specifically, we developed three profiles: (1) the proportion of daily trips active during a given hour (Figure 3), (2) the proportion of active trips that were done by FSC fishers (as opposed to sport fishers) during a given hour (Figure 4), and (3) the proportion of active sportfishing trips that were guided v. unguided and multi-day v. day-trips. Profiles were calculated from interview data and each profile was stratified based on whether interviews were conducted (1) near the Central Coast Nations, (2) weekday versus weekend trips, and (3) early-season (May or June) or late-season (July–September) as lodge activity peaked later in the season.

Activity profiles were derived from the number of fishers that were actively fishing during hour *h*, at date *t*, area *a*, and season *s*. The number of active fishers A were the total FSC and sportfishing boats observed by interviewed fishers (inclusive of themselves) and the activity weight was thus:

(1) $$W_{htas} = \frac{A_{htas}}{\sum_{h=1}^{24} A_{htas}}$$

Based on the reported activity from operators at Duncanby Lodge, Good Hope, and Legacy Lodge, we assumed that all lodge fishing trips were active from 6:00am to 5:30pm. The proportion of active trips that were FSC fishers during a given hour *h*, at date *t*, area *a*, and status *s* followed:

(2) $$P_{hta} = \frac{A_{hta,s=FSC}}{\sum A_{hta}}$$

Several assumptions were made for certain FSC and sportfishing activity profiles in areas near Wuikinuxv and Klemtu, respectively. First, we assumed that the proportion of FSC trips for PFMA sub-areas near Wuikinuxv was 5% based on local insights from Ted Walkus (owner-operator of Good Hope) that relatively few ocean-faring trips in Rivers Inlet are FSC. Second, we assumed that the proportion of FSC trips for the CCFN activity profile was 95% owing to local insights from KXSA that relatively few trips near Klemtu are from the sportfishery.

We then used DFO iREC and interview data to derive a profile of the proportion of active sportfishing trips that were guided v. unguided, lodge-affiliated or private, and multi-day v. day-trips. However, we note that this did not vary by hour *h*.

We then derived composite PFMA sub-area specific profiles that combined CCFN or Lodge-based profiles by weighing the travel-costs from the nearest access points (based on a least-cost travel path analysis of the entire Central Coast to each of 23 access points [Table 1]). For example, a PFMA sub-area that was 50km from the nearest lodge and 100 km from the nearest from the nearest access point would have an activity profile that was weighted 2/3 from the lodge profile and 1/3 from the CCFN profile for that hour, season, and day-type.

Table 1. Important fishing access locations in the Central Coast.

Place	Context	PFMA	Lat	Long
Klemtu	CCFN	6	52.59	-128.52
Bella Bella	CCFN	7	52.16	-128.13
Bella Coola	CCFN	8	52.38	-126.79
Wuikinuxv	CCFN	9	51.68	-127.24
North King Lodge	Lodge	6	52.73	-129.28
Shearwater	Lodge	7	52.15	-128.09
King Pacific Lodge	Lodge	7	52.18	-128.47
Duncanby Lodge	Lodge	9	51.41	-127.65
Black Gold Lodge	Lodge	9	51.40	-127.67
Great Bear Lodge	Lodge	9	51.36	-127.12
Good Hope Lodge	Lodge	9	51.57	-127.52
Legacy Lodge	Lodge	9	51.51	-127.64
Hakai Lodge	Lodge	7	51.67	-128.08
Hakai Land & Sea	Lodge	7	51.68	-128.12
Goose Bay Cannery	Lodge	9	51.38	-127.66
Sportsmans Club	Lodge	9	51.40	-127.70
Joes Salmon Lodge	Lodge	9	51.75	-128.03
Oles Lodge	Lodge	7	51.71	-128.05
Dawsons Landing	Gas Dock	9	51.58	-127.59
Dean Anchorage	Rec	8	52.83	-126.97
Hartley Bay	Nation	6	53.42	-129.25
Kitimat	Town	6	54.00	-128.68

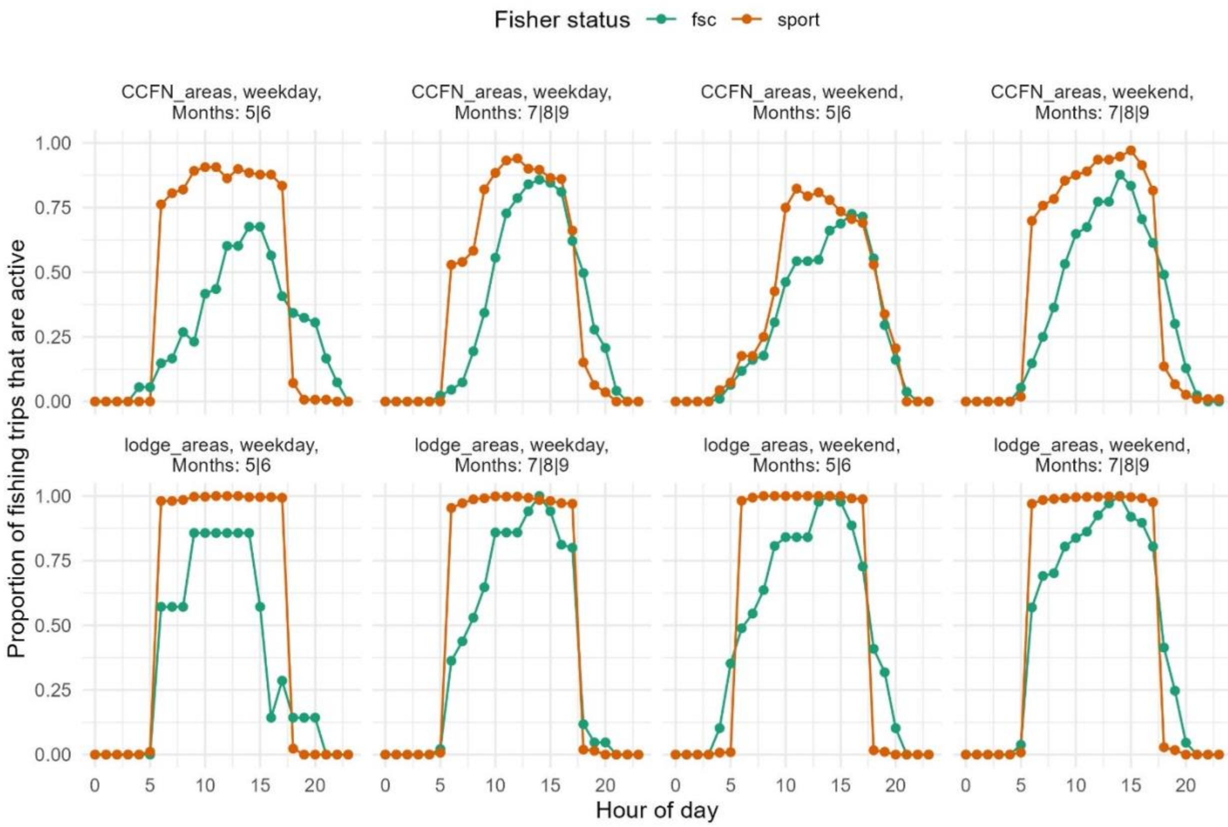

Figure 3. Hourly activity profiles for interviewed FSC and sportfishers stratified by early- or late-season (May–June or July–September, respectively), weekday or weekend, and interview areas including CCFN (interviews from Bella Bella or Klemtu dockside surveys) or lodges (interviews from Duncanby or Legacy Lodge).

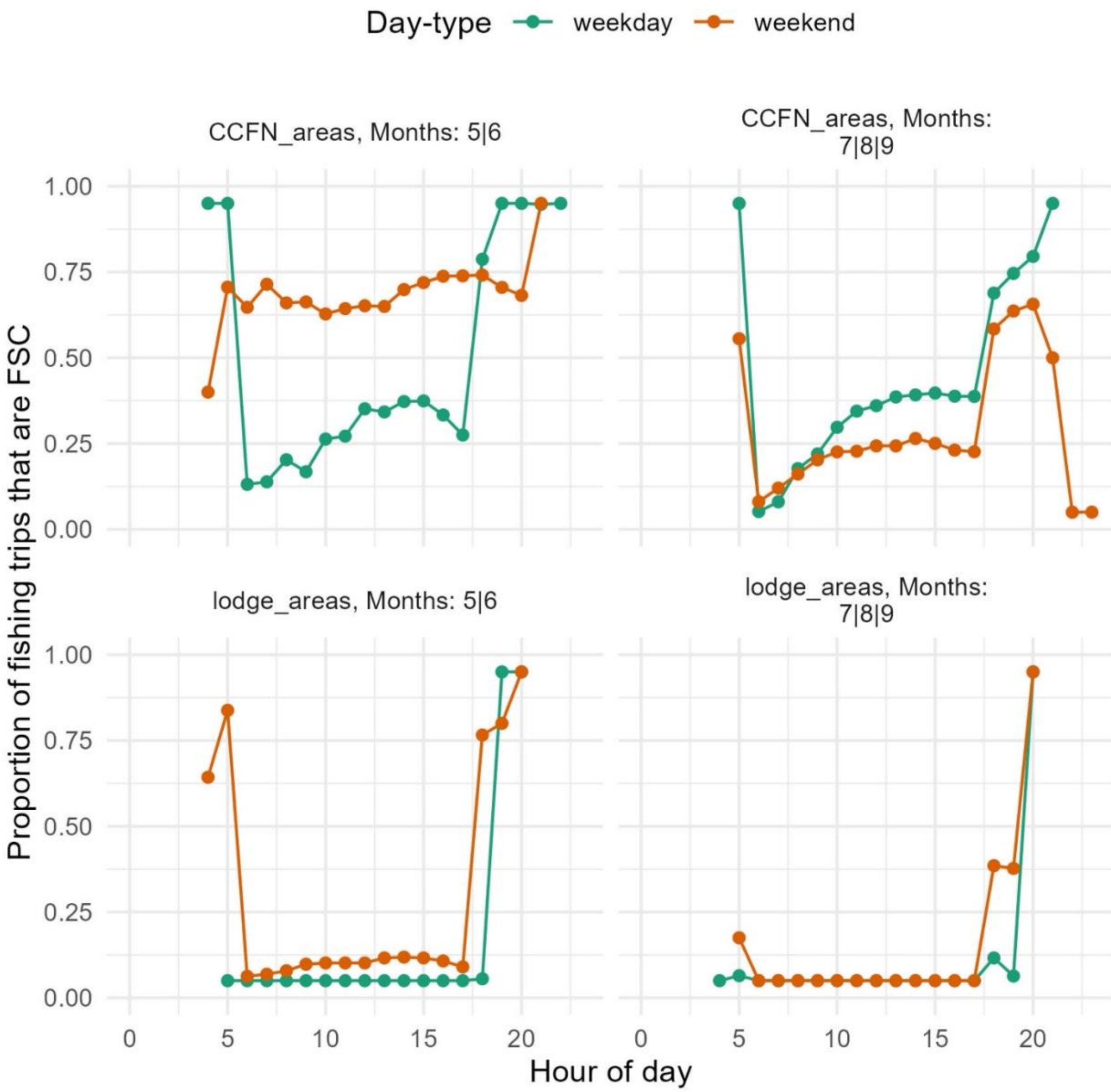

Figure 4. Hourly activity profiles for proportion of active trips that are FSC fishers stratified by early- or late-season (May–June or July–September, respectively), weekday or weekend, and interview areas including CCFN (interviews from Bella Bella or Klemtu dockside surveys) or lodges (interviews from Duncanby or Legacy Lodge).

Bayesian model

Model overview

We developed an integrated Bayesian model to estimate the spatial and temporal patterns in catch and effort for the coho and Chinook fishery among 100 sub-areas for PFMAs 6–10. This model relied upon a wealth of information provided by the Central Coast catch monitoring program (e.g., observed boats, catch rates, site choices, trip duration, and gear capture efficiency). We used this information to scale from observations of individual fisher trips to estimates of seasonal and spatial distribution of catch and effort. This approach leverages model-based inferences rather than design-based, which is an advantage for creel programs covering spatially extensive areas, that rely upon mixed methods (e.g., phones, dockside, overflight), that have non-random sampling, and which allows for non-Gaussian errors (Trudeau et al. 2021). The assumption of our model-based approach was that macroscale patterns in catch and effort emerged from the interplay between daily and site-specific choices, fishing activity of individual fishers, and salmon catch rates (Carruthers et al. 2019). In other words, the fishery was assumed to be a complex system with large-scale patterns emerging from smaller-scale processes (in this case fisher trips) that were estimable by fitting shape parameters of probability distributions to survey data. We could thus estimate large-scale patterns from understanding and integrating these smaller-scale processes (Arlinghaus et al. 2017, Carruthers et al. 2019).

Specifically, our integrated Bayesian model generated posterior samples for daily, weekly, and seasonal effort and catch patterns by integrating two sub-models on a joint posterior. These sub-models included: **(1)** spatial-temporal patterns in salmon catch-per-unit-effort for each of three fishing gears (rods, snubbers, and gillnet/long-lines) and **(2)** expected salmon fishing boats observed by the overflights corrected by activity profiles during the survey. We then used the posterior samples from each sub-model to estimate the spatial distribution of effort and catches for each day of the season for each fisher type (FSC and sport fishers). We allocated FSC catches into the proportion that fished with just rod and reel gear or snubbers (a gear modification used by some Nation fishers). We subdivided sport fishing effort and catches into the proportion of trips that were guided v. unguided, multi-day or day-trip, and lodge-affiliated or private (this profile was based on a combination of interview data and DFO iREC surveys). Hence, the summed catch or effort across each day of the season (or within a given week) generates the expected effort, catch, and harvest patterns across the season for the entire Central Coast.

CPUE

The total Chinook and coho catches·boat-day^{-1} (CPUE) were modelled as a generalized linear model with a negative binomial distribution and the number of boat-days as the effort offset. Effort data was available from most survey interviews, and we converted fishing hours into partial boat-days based on the proportion of the hours spent at a specific location to the total fishing hours for the whole trip. Some lodge-surveyed fishers did not record their hours fished per location. In those situations, we back-filled effort estimates based on the mean proportion of a lodge trip fishing for that location, corrected for the duration of the trip for that guest. We explored the best set of covariates and probability distribution (Poisson or negative binomial) to include in the CPUE model based on model selection of preliminary model fits in the 'brms' package using approximate leave-one-out cross-validation (Table 2; Bürkner 2017; Vehtari et al. 2017). With the effort offset, the GLM models CPUE as a function of covariates including: gear used, fisher status (local FSC, guided sport fishers, or unguided sport fishers), week of season (modelled as an autoregressive random walk), and PFMA spatial sub-areas. The seasonal effects for week 1 were fixed at zero to improve identifiability of weekly deviations in estimated CPUE to subsequently follow a random walk. The PFMA sub-areas effects were modelled as a spatial conditional autoregressive model – spatial CAR coefficients were estimated based on the inverse distance between sub-area centroids and a sparse adjacency matrix based on the 'geostan' package (Donegan 2022), which modelled the average correlation in CPUE between neighboring sub-areas. Each species had their own correlation and variance parameters underlying the CAR sub-model.

Table 2. Model selection of Chinook and coho salmon catch as a function of covariates using approximate leave-one-out cross-validation. Models ordered by expected predictive performance.

Model	ELPD Diff.	Std. Err. Diff.
NB(μ~ f(gear, guided, trip-type, FSC, week, offset(effort)), φ~ f(gear))	0	0
NB(μ ~ f(gear, guided, trip-type, FSC, week, offset(effort)))	-1.9	7.9
NB(μ ~ f(gear, guided, trip-type, FSC, week), φ ~ f(gear))	-2.4	15
NB(μ ~ f(gear, trip-type, FSC, week), φ ~ f(gear:trip-type))	-4.3	6.4
NB(μ ~ f(gear, FSC, week, offset(effort)))	-6.7	9
NB(μ ~ f(gear, trip-type, FSC, week, offset(effort)), φ ~ f(gear))	-6.9	9.2
NB(μ ~ f(gear, trip-type, FSC, week), φ ~ f(trip-type))	-9.5	16
NB(μ ~ f(gear, trip-type, FSC, week, offset(effort)))	-11.3	15.9
NB(μ ~ f(gear, trip-type, FSC, week), φ ~ f(gear))	-17.5	17.1
NB(μ ~ f(gear, trip-type, FSC, poly(week,2), offset(effort)), φ ~ f(gear))	-23.2	13
NB(μ ~ f(gear, guided, trip-type, FSC, poly(week,3), offset(effort)), φ ~ f(gear))	-39.2	17.8
NB(μ ~ f(gear, guided, trip-type, FSC, poly(week,2), offset(effort)))	-42	14.4
Poisson(lambda ~ f(gear, guided, trip-type, FSC, week, offset(effort)))	-3558.4	323.8

Effort

Similar to the CPUE model, we modelled the number of boats per PFMA sub-area from each overflight as a generalized linear model with a negative binomial distribution. In this case, there was no offset and the only covariates used were day-type (weekday or weekend), week of season, and PFMA sub-area. The seasonal effects for week 1 were fixed at zero to improve identifiability of weekly deviations in estimated boat counts to subsequently follow a random walk. The PFMA sub-areas effects were modelled as a spatial conditional autoregressive model – spatial CAR coefficients were estimated based on the inverse distance between sub-area centroids and a sparse adjacency matrix based on the 'geostan' package (Donegan 2022), which modelled the average correlation in boat counts between neighboring sub-areas. Specifically, the observed boats for flight i in area j followed a negative binomial distribution with mean $\mu_{i,j}$, the proportion of active boats W_{ij} (time of the observation) and dispersion parameter $\phi_b$such that:

(3) $$C_{ij} \sim NB(\mu_{ij} W_{ij}, \phi_b)$$

The expected number of boats per flight *i* in area *j* followed a log-link function with coefficients for day-type, week of season (*w*), and spatial area such that:

$$(4) \qquad \ln(\mu_{ij}) = \beta X_i + \beta_w + \beta_j$$

Seasonal estimates of catch and harvest

Daily spatial effort dynamics of fisher status *s* fishing at site *j* during day *d* followed:

$$(5) \qquad E_{sjd} = \mu_{jd} P_{sdj}$$

Where μ_{jd} was the estimated number of boats for site *j* during day *d* and P_{sdj} was the proportion of active trips that were of fisher status *s*. Total effort for status *s* at each site was thus the sum of all seasonal effort across the season (summed by day or by week)

$$(6) \qquad E_{sj} = \sum_d^D E_{sjd}$$

Total effort across sites was the sum of all effort among all sites *J* (DFO PFMA sub-areas in the Central Coast).

$$(7) \qquad E_s = \sum_j^J E_{sj}$$

Total estimated catches of species *p* at site *j* on day *d* from fishers of status *s* (N_{spdj}) followed:

$$(8) \qquad N_{spdj} = \begin{cases} (1-p_g)\mu_{C,gspdj}E_{sjd} + p_g\mu_{C,gspdj}E_{sjd} & \text{if } s = FSC \\ \mu_{C,gspdj}E_{sjd} & \text{if } s = sport \end{cases}$$

where p_g was the observed proportion of FSC fishers using snubbers and $\mu_{C,gspdj}$ was the expected catch per boat-trip for a fisher of status *s* targeting species *p* fished by gear *g* on day *d* in area *j*. The CPUE for sportfishing reflected the weighted mean of guided v. unguided, multi-day v. day-trip fishers. We then used the posterior samples to describe spatial-temporal variation in salmon catches by summing the expected catches by days, weeks, sites, gear, and fisher status. Total catches from fishers of status *s* at each site was thus the sum of all catches across the season (summed by day or by week)

$$(9) \qquad N_{spj} = \sum_d^D N_{spjd}$$

Total catch across sites was the sum of catches among all sites *J* (DFO PFMA sub-areas in the Central Coast).

$$(10) \qquad N_{sp} = \sum_j^J N_{spj}$$

Daily harvest

We used the cumulative distribution function of the negative binomial to apply daily retention limits to estimate total harvest of coho and Chinook salmon from total catches per boat trip. Poisson or negative binomial cumulative distribution functions are commonly used to model the effects of daily bag limits on sportfishing harvest and retention rates (Post et al. 2008, Carruthers et al. 2019). The cumulative distribution modelled the probability that the distribution of coho or Chinook catches *Y* equal or exceed the daily limit *y* for species *p* as a function of retention preference r_{sp}, mean catch $\mu_{C_{pdj}}$ and overdispersion ϕ_{C_p}:

$$(11) \qquad P(Y_{pdj} \leq y_p) = f(r_{sp}\mu_{C_{pdj}}, \phi_{C_p})$$

To do this, we made a few simplifying assumptions. First, that fishers of status *s* would release a portion of their total catch either due to factors like length-limits (for Chinook) or other selective harvest preferences, e.g., “take what you need” – this downweighed the expected total catch into an expected retainable catch. We calculated r_{sp} based on empirical observations of release rates from surveyed fishers (for sport fishers, we derived this from fishing trips that did not exceed their bag limits) – r_{sp} for Chinook salmon was 0.49 and 0.63 for sportfishers and FSC fishers respectively; for coho salmon this was 0.51 and 0.91, respectively. Second, that all retainable salmon caught by FSC fishers would be harvested. Third, that on average there were two licensed sport fishers on each boat, which effectively doubled the daily limits. We based this number on observations in the Duncanby Lodge and Legacy Lodge surveys, which suggest ~2.0 licensed anglers per boat. Fourth, that all caught Chinook within the daily limit of two per licensed angler would be retained. Fifth, that only some coho would be retained with retention rates based on the conditional cumulative probabilities of coho and Chinook catches being greater than or equal to the remaining total daily limits for all salmon. For example, the proportion of trips that catch zero Chinook (based on the Chinook-specific shape parameters in Table 2) could retain up to eight coho, which depended on the proportion of trips that catch eight (or more) coho (based on the coho shape parameters in Table 2). Conversely, the proportion of trips that caught and retained four Chinook (two per licensed fisher) could only retain four additional coho salmon.

Each combination of Chinook and Coho catches within the daily limits were modelled to estimate legal retention of Coho for sport fishers. Specifically, total expected harvest *H* of species *p* arises as the product between retention rate and total catches *N* such that:

$$H_{spjd} = \begin{cases} r_{sp} N_{spjd} & \text{if } s = FSC \\ P(Y_{pd} \leq y_p) r_{sp} N_{spjd} & \text{if } s = sport \end{cases} \tag{12}$$

And released salmon *R* becomes the difference total catch and total harvest:

$$R_{spjd} = N_{spjd} - H_{spjd} \tag{13}$$

We then assumed that some released fish die due to discard mortality (assumed to be 18% for all released fish; Bartholomew & Bohnsack (2005)) such that total mortalities *M* from any fishing activity followed:

$$M_{spjd} = H_{spjd} + 0.18 R_{spjd} \tag{14}$$

Total harvest of species *p* from fishers of status *s* at each site was thus the sum of harvest from all trips across the season (summed by day or by week)

$$H_{spj} = \sum_d^D H_{spjd} \tag{15}$$

And total catch across sites was the sum of all harvest among all sites *J* (DFO PFMA sub-areas in the Central Coast).

$$H_{sp} = \sum_j^J H_{spj} \tag{16}$$

Similarly, total mortality of species *p* from fishers of status *s* at each site was thus the sum of all mortalities across the season:

$$M_{spj} = \sum_d^D M_{spjd} \tag{17}$$

And total mortality across sites was the sum of all mortalities among all sites *J* (DFO PFMA sub-areas in the Central Coast).

$$M_{sp} = \sum_j^J M_{spj} \tag{18}$$

Model inference & diagnostics

We estimated the integrated model on a joint Bayesian posterior in Stan with 4 Markov Chain Monte Carlo (MCMC) chains using the 'rstan' package version 2.26.22 in R version 4.3.0 (Carpenter et al. 2017, R Core Team 2023, Stan Development Team 2023). Each chain took 1,000 posterior samples with a warmup period of 50% and thinning every 2nd sample for a total of 4,000 total samples. Parameter values for all model coefficients were randomized and jittered for each chain. We used several complementary methods to diagnose model suitability. MCMC chain convergence was inspected visually on traceplots. In addition, we ensured effective sample sizes were ~1,000 for each parameter to ensure we effectively described the posterior tails (Gelman et al. 2013). We used the Gelman-Rubin diagnostic test on each parameter to determine whether independent chains converged to a common posterior mode, with potential scale reduction factors (PSRF) < 1.1 suggesting convergence. We then used graphical posterior predictive checks to test for model misspecification by comparing the predictive distribution of each sub-model to the observed distribution. For example, we simulated random site choices from the posterior sample for each fisher's trips to observed site choices to evaluate discrepancies in spatial effort patterns. As a further diagnostic, we compare estimated harvest and effort patterns to harvest and effort datasets available from pre-COVID averages from DFO iRec surveys (with pending data requested from DFO for 2022 updates to iRec surveys and DFO logbooks of regional lodge and charter operations).

Results

Overview

The Coho and Chinook fisheries along the Central Coast showed catch, harvest, and effort patterns that varied by space, season, year, and fisher status (Figure 1; Table 3). The 2019 season sampled the fewest amount of days (52) and subsequent years increased the temporal coverage of the interview and monitoring season. In comparison to overflights, the creel interviews tended to cover catch and activity information from fewer PFMA sub-areas (Table 3). The overflight data picked up high fishing activity in PFMA sub-areas 8-11, 9-1, 7-12, 7-17, and 6-13 (each averaged >5 boats·flight-day^{-1}).

Table 3. Summary statistics from 2019-2022 survey sampling (including overflights) including: number of interviews (or number of routes flown), number of days sampling, number of salmon harvested, number of boats observed, and number of PFMA sub-areas with observed fishing activity. The 2022 survey sample sizes included: 263 from HIRMD, 57 from KXSA, 463 from Duncanby Lodge, and 37 from Legacy Lodge.

Description	2019 (survey)	2020 (survey)	2021 (survey)	2021 (overflight)	2022 (survey)	2022 (overflight)
Sample sizes	189	309	285	30	820	42
Days of sampling	52	87	86	16	109	23
Coho harvested	428	332	643	-	2,985	-
Chinook harvested	388	385	565	-	1,648	-
Total FSC boats observed	218	898	754	885 (total)	767	1,754 (total)
Total sport boats observed	754	222	387		8,782	
PFMA sub-areas with fishing	18	20	16	52	42	61

Seasonal trends

Coho and Chinook salmon catch rates varied over the fishing season in different ways (Figure 5). Chinook salmon catches peaked in May and June and declined moderately by August – catch rates averaged 1.5-2.0 Chinook· boat-day^{-1} for much of the season. Coho salmon peaked much later in the season, with catch rates exceeding 10 coho·boat-day^{-1} by early September.

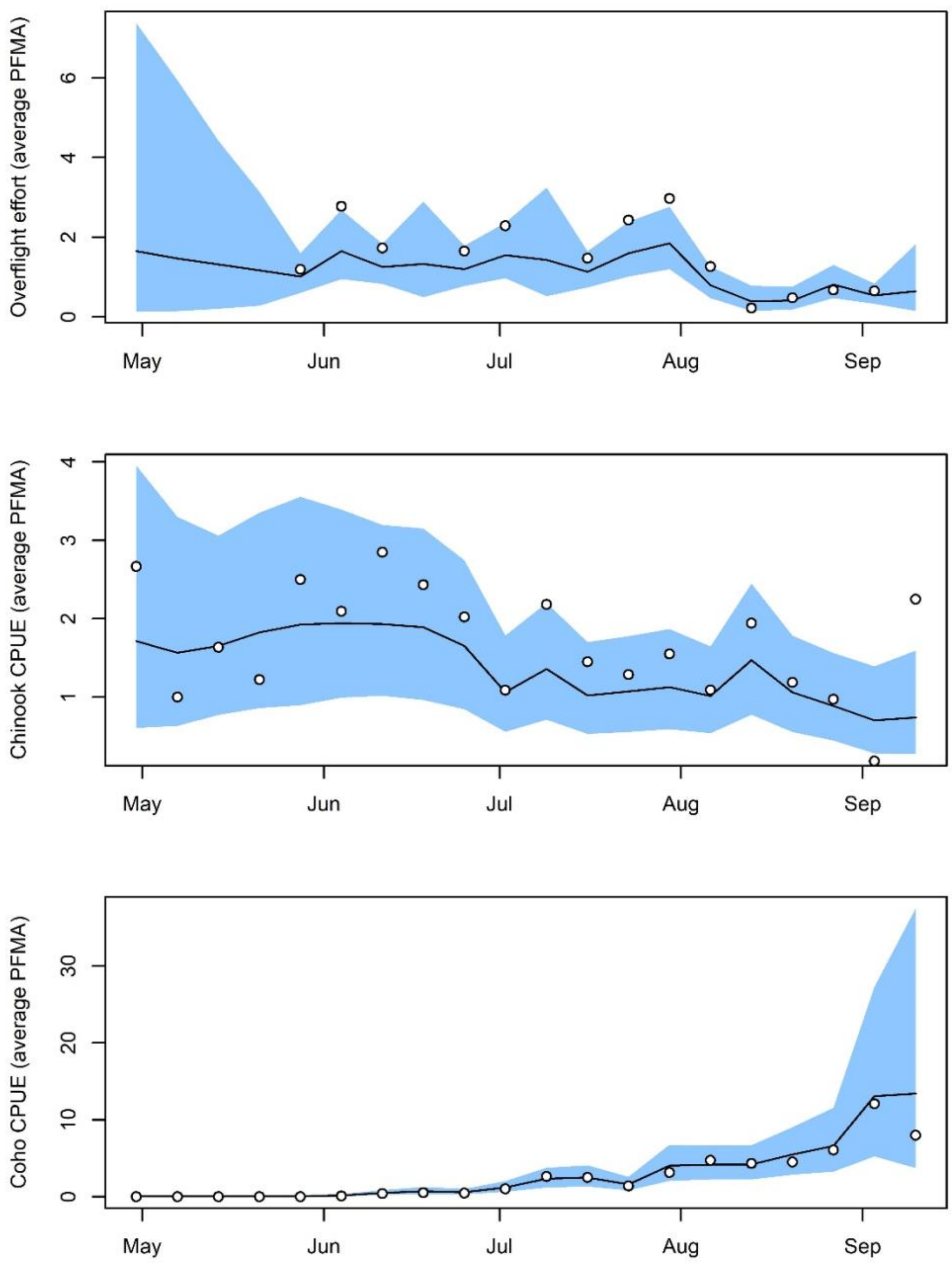

Figure 5. Seasonal trends in posterior mean and observed (points) boats counted per area, Chinook caught·boat-day^{-1}, and coho caught·boat-day^{-1} across the Central Coast. Seasonal estimates and data shown were for rod-and-reel gears only (not snubbers, gillnets, or longlines).

Food fishers and unguided sportfishers on day-trips with rod-and-reel caught relatively similar amounts of Chinook and coho per boat-day. Food fishers harvested Chinook at slightly higher levels and harvested coho at much higher rates compared to visiting sportfishers. Guided day-trip fishers had relatively high catch rates for both Chinook and coho. Sportfishers that were on multi-day trips were relatively less efficient at catching fish per boat-day, and harvested fewer fish compared to day-trips. Gillneters and longliners had relatively high catch rates for coho salmon. Overall, CPUE varied substantially by area (Figure 7).

Table 4. Catch and harvest for Chinook and coho salmon from sportfishers and FSC, based on survey interview data. The gear type “other” includes gillnets and longlines.

Species catch	Sport				FSC		
	Unguided		Guided				
	Day-trip	Multi-day	Day-trip	Multi-day	Rods	Snubbers	Other
Chinook Caught	2.27	1.47	2.6	1.47	1.81	1.54	0.355
Chinook Kept	1.29	0.669	1.2	0.838	1.06	1.18	0.355
Coho Caught	3.47	2.87	4.2	1.86	3.29	1.9	4.47
Coho Kept	2.06	1.23	2.45	1.16	2.93	1.64	4.47

Diagnostics

In general, estimated model parameters passed most goodness-of-fit and diagnostic tests indicated that the models provided reasonable fits to data from the Central Coast catch monitoring program (Figures 6 and 7). Most estimated parameters had PSRF < 1.1, suggesting parameter estimates from independent MCMC chains converged towards a common posterior mode. Inspecting visual traceplots also suggested posterior convergence. As well, the effective sample sizes for each parameter was ~1,000 suggested the posterior mean and tails of the posterior distribution were reasonably well explored for inferences. No parameters had convergence issues.

The Bayesian model passed all graphical posterior predictive checks (Figures 6) suggesting that the models used provided a reasonable approximation of the data generating process – this included checks for Chinook and coho catch rates (Figure 6,upper panels) and observed boats in the overflight data (Figure 6, lower panels). Overall, the model predicted somewhat weak to moderate of the non-spatial and non-temporal effects on CPUE and effort, suggesting that the variation in the data was defined mostly by strong seasonal or spatial patterns. We tended to overestimate variance among Chinook catches compared to observations (Figure 6) although the mean CPUE was generally covered by our predictive distribution. We tended to overestimate the mean and variance among coho catches compared to observed, but this was also within the range of expectations for the model.

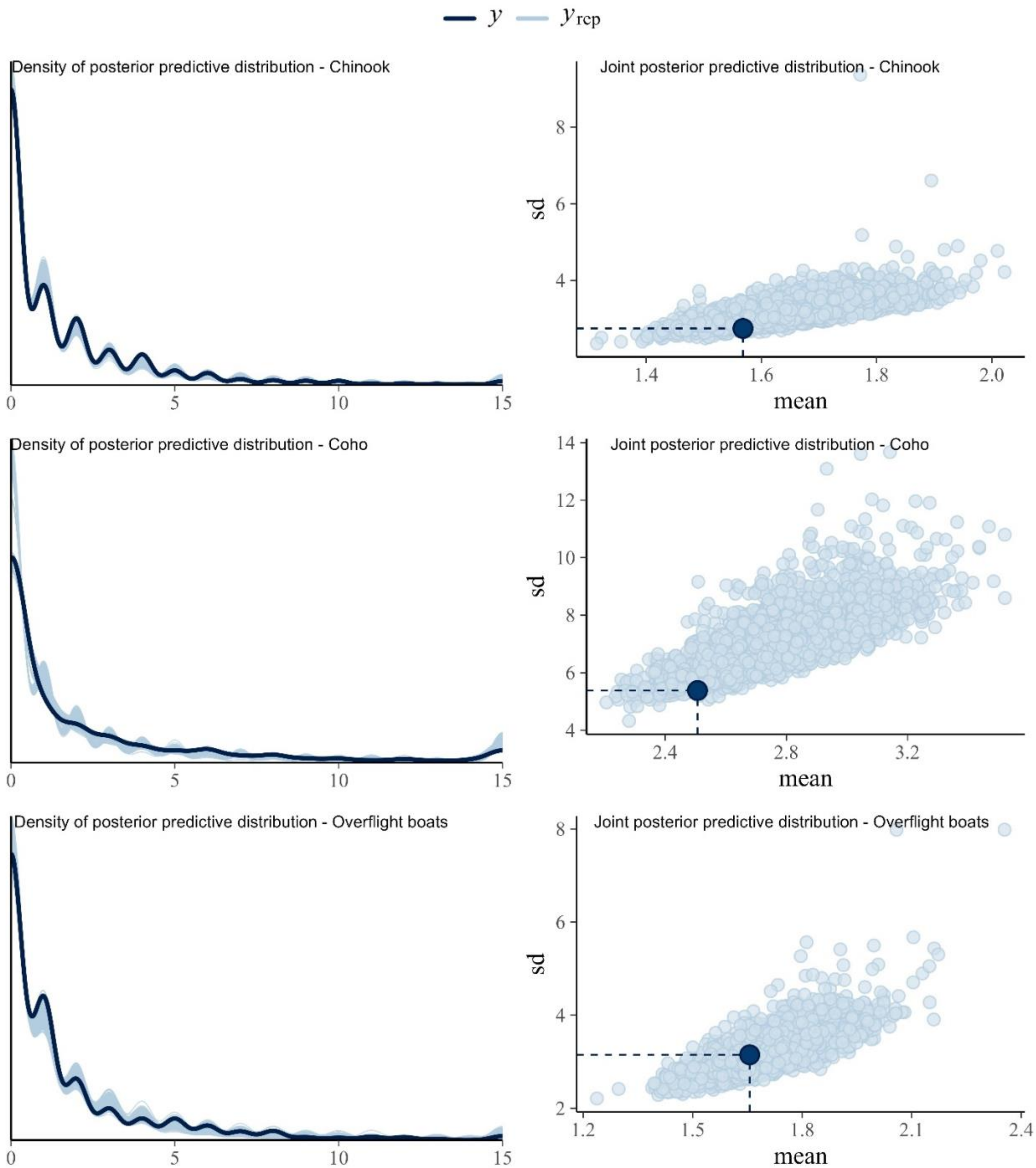

Figure 6. Goodness-of-fit and posterior predictive model diagnostics between observed (dark blue lines and points) and simulated (light blue lines and points) salmon catches and total number of boat trips observed in the 2022 season. Observations within the range of simulated data suggest a reasonable model fit.

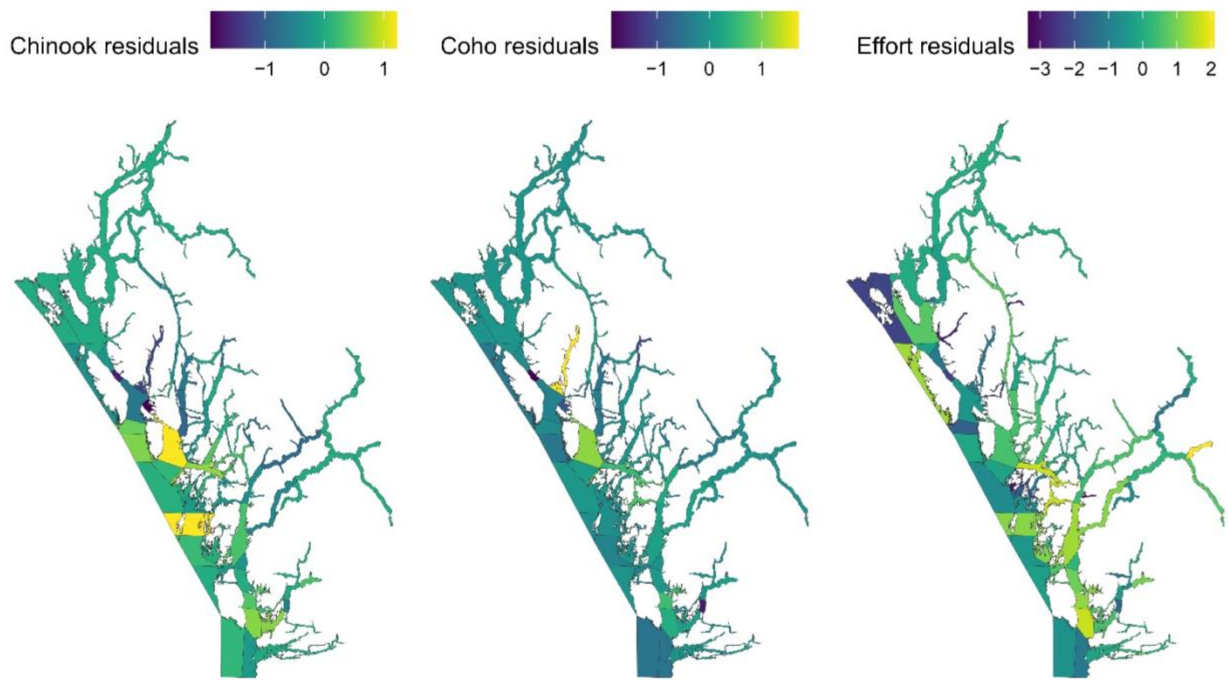

Figure 7. Residual model diagnostics between observed and predicted spatial effects for salmon catches and total number of boat trips. The lack of any large patterning or clustering in residuals provides reasonable indicator for model fits.

Effort, Catch, and Harvest

In 2022, local FSC fishing effort averaged ~28% of the total effort in the Central Coast mixed stock fishery. By most accounts, the sportfishery has returned to full capacity and most lodges and charters are operational after the pandemic Overall, coast-wide sportfishing effort appeared similar, if slightly slower, to pre-COVID-19 averages according to DFO iRec (Table 4).

Estimated Chinook and coho salmon harvest from sport fishers appeared typical, if somewhat low, compared to pre-COVID averages based on DFO iRec (Table 5). Across the Central Coast Nations harmonized marine use area, sportfishers harvested 11,360 Chinook and 15,462 coho. Estimated harvest of Chinook in Area 8 was larger than is seen in recent years, largely due to high effort estimates from Bella Coola and Dean Channel. The extent to which fishing boats observed in these areas target and harvest Chinook is somewhat uncertain – we have relatively sparse coverage for interviews (either FSC or sportfishing) that fish in areas around King Island beyond Ocean Falls (this issue is also pertinent to areas 6-21 and 6-22 where total effort estimates are unreasonably high). Estimated effort thus omits areas where we lacked any sample coverage and merits follow-up work to generate credible estimates.

Estimated food fishing harvest within the Central Coast marine use area was 5,841 for Chinook salmon and 9,449 for coho salmon. Harvest totals from food fishers were approximately 44% and 61% compared to the sportfishery. Overall, food harvest varied by area with local fishers harvesting 508, 2338, 1813, and 1138 Chinook salmon and 1090, 3567, 3166, and 1579 coho salmon from Areas 6, 7, 8, and 9, respectively.

Table 4. Posterior mean (95% credible intervals in parentheses) estimates of FSC and sportfishing effort in the Central Coast during 2022 (including DFO PFMA Areas 6–9) and comparisons with 2012–2019 average estimates from DFO iRec. We converted DFO iRec effort estimates from licensed angler days to boat-days presuming 2.17 licensed anglers per boat (the average from our dockside and lodge surveys). We include estimates spanning all of PFMA Area 6 and the subset that overlapped with the Central Coast Nations harmonized marine use areas. Area 9 estimates include Areas 10-1 and 10-2 due to proximity to recreational lodges located in Area 9 that frequently fish in those sub-areas.

PFMA Area	Catch Monitoring		DFO iRec
	FSC (boat-days)	Sport (boat-days)	Sport (boat-days)
Area 6	2,209 (396-7,684)	5,812 (1,367-12,998)	7,581
Area 6 (CCFN)	978 (168-3,748)	2,586 (640-6,885)	-
Area 7	2,780 (589-9,016)	7,245 (2,256-15,118)	7,875
Area 8	1,567 (346-5,047)	4,109 (1,326-8,430)	4,904
Area 9	2,175 (359-8,079)	5,646 (1,344-13,410)	5,000
Central Coast	6,895 (1,573-21,369)	18,018 (6,151-32,143)	25,360

Table 5. Posterior mean estimates of total Chinook and Coho salmon harvest from the sport fishery in the Central Coast during 2022 (including DFO PFMA Areas 6–9) and comparisons with 2012–2019 average estimates from DFO iRec. We include estimates spanning all of PFMA Area 6 and the subset that overlapped with the Central Coast Nations harmonized marine use area. Area 9 estimates include Areas 10-1 and 10-2 due to proximity to recreational lodges located in Area 9 that frequently fish in those sub-areas.

PFMA Area	Chinook		Coho	
	Catch Monitoring	DFO iRec	Catch Monitoring	DFO iRec
Area 6	3,962	4,464	5,638	6,680
Area 6 (CCFN)	1,584	-	2,398	-
Area 7	4,708	6,591	6,279	7,977
Area 8	2,499	1,574	3,499	5,501
Area 9	2,512	2,859	3,233	5,941
Total	13,084	15,490	18,651	26,101
CCFN Total	11,360	-	15,462	-

Genetic Stock Identification: Chinook

Across three years of sampling a total of 477 Chinook salmon from PFMAs 7-9 were genotyped and assigned to their population and CU of origin. GSI revealed a high number of CUs contributing to fishery harvests as well as preliminary evidence of geographic differences in the distribution of different populations within Central Coast fisheries (Table 6), and modest interannual variability in the respective contribution of each CU to Chinook catches (Table 7).

For example, >30% of Chinook harvest in both PFMA 7 and PFMA 9 were assigned to the Southern West Coast Vancouver Island CU (WCVI-South), with large contributions from both Robertson Creek and Nitnat hatcheries, as well as other wild populations. No WCVI-South originating fish were detected among the relatively limited number of samples originating in PFMA 8 (n = 27), where Chinook catches were dominated by fish returning to the Bella Coola-Bentick (70.37%), and Dean (11.11%) CUs. Likewise, Bella Coola-Bentick fish contributed a relatively modest share of the overall catch in PFMA 7 (13.14%) when compared to Vancouver Island CUs and were not detected at all among the 125 samples collected in PFMA 9 in 2021 (Table 7). Indeed, Chinook from six CUs on the West and East Coasts of Vancouver Island contributed significantly to catches in both PFMA 7 (60.57%) and PFMA 9 (78.4%), with an apparent pattern towards lower catches of WCVI CUs in more inner-coastal subareas of PFMA 7 such as 7-17 and PFMA 9, and higher contributions of Bella Coola and East Coast Vancouver Island CUs in these inside waters (Table 8).

Genetic Stock Identification: Coho

Unlike Chinook, coho catches were dominated by Central Coast CUs, with >80% of catches assigned to Central Coast CUs among PFMA9 samples, and almost 90% of PFMA6 and PFMA7 samples assigned back to Central Coast stocks. The Hecate Strait + Lowlands CU made the largest single contribution to PFMA7 catch, with an average annual contribution of 34%. Notably, the relative contribution of this CU was lower in 2019 and 2020, when coho populations in the Hecate Lowlands experienced extremely low returns, and the contribution of the Hecate CU to catches rebounded significantly in 2021 concurrent with rebuilding among these stocks (41.6%). Bella Coola-Dean River (25.2%) and Rivers Inlet (12.8%) CUs made significant contributions to coho catch in PFMA7, which were relatively stable across years (Table 9). The largest CU contributing to coho catches in PFMA6 was also the Hecate Strait + Lowland group (38.3%), followed by Northern Coastal (19.75%), and Douglass Channel + Kitimat Arm CUs (18.5%) (Table 10). Unsurprisingly, Rivers Inlet coho made the largest contribution to catches in PFMA9 (34%), followed by Bella Coola – Dean Rivers (20.19%) and Hecate Strait + Lowlands (12.65%) (Table 11).

Insights from GSI

Preliminary GSI results from CCFN-led catch monitoring efforts reveal crucial information for fishery co-governance and conservation, information which was lacking prior to the outset of these projects. Initial findings suggest high contributions of Vancouver Island Chinook stocks to Central Coast fisheries, but that coho fisheries in the region are typically >80% local CUs. Increased sample sizes and improved spatial and temporal resolution to sampling in future years will enable further exploration of spatio-temporal differences in the distribution of Chinook and coho populations in Central Coast fisheries. However, preliminary patterns suggest a gradation towards a higher percentage of WCVI Chinook in outer areas of the Central Coast, and a higher proportion of Bella Coola-Bentick and ECVI Chinook in the inside waters. For mixed-stock coho collections, the most proximate CU to the fishing grounds consistently made the largest contribution to catches.

Improved genetic baselines, particularly for coho salmon, will support further improvements to GSI tools and CCFN have worked actively to expand genetic baselines in the last two years. These efforts have added more than 1000 new DNA samples to the genetic baseline, and work to expand these collections are ongoing. When combined with increased sampling intensity in FSC and recreational marine fisheries across the fishing season, these data can support collaborative decision making and conservation for Central Coast fisheries to meet co-governance objectives defined by the CCFN and DFO.

Table 6. Genetic stock composition of Chinook salmon harvested in PFMAs 7-9.

Conservation unit	Area 7		Area 8		Area 9	
	N	%	N	%	N	%
WCVI-South	55	31.43%	0	0.00%	38	30.40%
Bella_Coola-Bentinck	23	13.14%	19	70.37%	0	0.00%
ECVI-North	17	9.71%	0	0.00%	41	32.80%
WCVI-Nootka & Kyuq	17	9.71%	0	0.00%	0	0.00%
ECVI-Quali_&_Puntl_FA	12	6.86%	1	3.70%	16	12.80%
NCC-early_timing	7	4.00%	1	3.70%	0	0.00%
North_Puget_Sound	7	4.00%	0	0.00%	2	1.60%
South_Thompson 0.3	6	3.43%	0	0.00%	5	4.00%
WCVI-North	4	2.29%	0	0.00%	3	2.40%
South_Puget_Sound	4	2.29%	1	3.70%	2	1.60%
Dean_River	3	1.71%	3	11.11%	0	0.00%
Klinaklini	3	1.71%	0	0.00%	1	0.80%
U_Columbia_SU_FA	3	1.71%	0	0.00%	3	2.40%
Lower_Fraser_River_FA	2	1.14%	0	0.00%	3	2.40%
NCC-lake	2	1.14%	0	0.00%	0	0.00%
South_Mainland-Fjords	2	1.14%	0	0.00%	3	2.40%
EVI-Georgia_Strait_SU0.3	1	0.57%	0	0.00%	0	0.00%
Juan_de_Fuca	1	0.57%	0	0.00%	0	0.00%
Low_Fraser-U_Pitt	1	0.57%	0	0.00%	0	0.00%
S_Main-Georgia_Strait_F	1	0.57%	0	0.00%	0	0.00%
S_Oregon_coast	1	0.57%	0	0.00%	0	0.00%
Snake_River_Fall	1	0.57%	1	3.70%	0	0.00%
Shuswap_River	1	0.57%	0	0.00%	0	0.00%
Wannock River	1	0.57%	0	0.00%	5	4.00%
Lower Columbia River	0	0.00%	0	0.00%	2	1.60%
Lower Fraser SU	0	0.00%	0	0.00%	1	0.80%
California_Central_Valley_Fall	0	0.00%	1	3.70%	0	0.00%
Total	175		27		125	

Table 7. Annual GSI estimates of CU contributions to Chinook catches for fish sampled in Bella Bella (PFMAs 7 and 8).

Conservation Unit	2019		2020		2021		Weighted Mean
	N	%	N	%	N	%	
WCVI-South	67	29.00%	6	21.43%	42	45.16%	32.63%
Bella_Coola-Bentinck	45	19.48%	4	14.29%	7	7.53%	15.93%
WCVI-Nootka_&_Kyuq	19	8.23%	5	17.86%	4	4.30%	7.96%
ECVI-North	18	7.79%	1	3.57%	11	11.83%	8.51%
ECVI-Quali_&_Puntl_FA	16	6.93%	1	3.57%	7	7.53%	6.82%
NCC-early_timing	9	3.90%	2	7.14%	4	4.30%	4.26%
North_Puget_Sound	7	3.03%	1	3.57%	1	1.08%	2.56%
South_Thompson 0.3	7	3.03%	0	0.00%	3	3.23%	2.84%
Dean_River	6	2.60%	0	0.00%	1	1.08%	1.99%
South_Puget_Sound	5	2.16%	1	3.57%	0	0.00%	1.71%
U_Columbia_SU_FA	5	2.16%	2	7.14%	3	3.23%	2.84%
WCVI-North	4	1.73%	0	0.00%	4	4.30%	2.27%
Klinaklini	3	1.30%	0	0.00%	0	0.00%	0.85%
NCC-lake	3	1.30%	0	0.00%	0	0.00%	0.85%
S_Main-Georgia_Strait_F	3	1.30%	0	0.00%	3	3.23%	1.70%
South_Mainland-Fjords	3	1.30%	1	3.57%	1	1.08%	1.42%
Lower_Fraser_River_FA	2	0.87%	1	3.57%	0	0.00%	0.85%
Snake_River_Fall	2	0.87%	0	0.00%	1	1.08%	0.85%
California_CV_Fall	1	0.43%	0	0.00%	0	0.00%	0.28%
EVI-Georgia_Strait_SU0.3	1	0.43%	1	3.57%	0	0.00%	0.57%
Juan_de_Fuca	1	0.43%	1	3.57%	0	0.00%	0.57%
Low_Fraser-U_Pitt	1	0.43%	0	0.00%	0	0.00%	0.28%
S_Oregon_coast	1	0.43%	0	0.00%	0	0.00%	0.28%
Shuswap_River	1	0.43%	1	3.57%	0	0.00%	0.57%
Wannock River	1	0.43%	0	0.00%	1	1.08%	0.28%
Total	231		28		93		352

Table 8. CU-level contributions to Chinook harvest in mixed-stock fisheries across the four most fished subareas of PFMA7. Sample sizes varied across subareas and are reported in the bottom row.

	Area 7-12		Area 7-17		Area 7-25		Area 7-32	
Conservation Unit	**N**	**%**	**N**	**%**	**N**	**%**	**N**	**%**
WCVI-South	17	32.69%	5	16.13%	6	30.00%	14	40.00%
Bella_Coola-Bentinck	6	11.54%	9	29.03%	2	10.00%	1	2.86%
ECVI-North	5	9.62%	3	9.68%	4	20.00%	4	11.43%
Dean_River	3	5.77%	0	0.00%	0	0.00%	0	0.00%
NCC-early_timing	3	5.77%	3	9.68%	1	5.00%	0	0.00%
WCVI-Nootka_&_Kyuq	3	5.77%	1	3.23%	3	15.00%	5	14.29%
ECVI-Quali_&_Puntl_FA	3	5.77%	6	19.35%	1	5.00%	1	2.86%
South_Thompson	3	5.77%	0	0.00%	1	5.00%	1	2.86%
Lower_Fraser_River_FA	2	3.85%	0	0.00%	0	0.00%	0	0.00%
North_Puget_Sound	2	3.85%	1	3.23%	0	0.00%	0	0.00%
WCVI-North	0	0.00%	0	0.00%	0	0.00%	2	5.71%
Juan de Fuca	0	0.00%	0	0.00%	0	0.00%	1	2.86%
Kliniklini	0	0.00%	0	0.00%	1	5.00%	1	2.86%
NCC-lake	0	0.00%	0	0.00%	1	5.00%	1	2.86%
South_Mainland-Fjords	1	1.92%	0	0.00%	0	0.00%	1	2.86%
South_Puget_Sound	1	1.92%	1	3.23%	0	0.00%	1	2.86%
Snake_River_Fall	1	1.92%	0	0.00%	0	0.00%	0	0.00%
U_Columbia_SU_FA	1	1.92%	0	0.00%	0	0.00%	1	2.86%
EVI-Georgia_Strait_SU0.3	0	0.00%	1	3.23%	0	0.00%	0	0.00%
Low_Fraser-U_Pitt	0	0.00%	0	0.00%	0	0.00%	1	2.86%
Shuswap River	0	0.00%	1	3.23%	0	0.00%	0	0.00%
Wannock River	1	1.92%	0	0.00%	0	0.00%	0	0.00%
Total	52		31		20		35	

Table 9. Estimated contribution of regional coho salmon CUs to catches in PFMA 7 from 2019 to 2021. Sample sizes are reported in the bottom row, and three-year average contributions (weighted by sample size) are reported in the far right column.

Conservation Unit	2019		2020		2021		Weighted Mean
	N	%	N	%	N	%	
HecLow+HStr	25	24.04%	5	17.86%	82	41.62%	34.04%
Bella_Coola-Dean_Rivers	24	23.08%	8	28.57%	51	25.89%	25.23%
Rivers_Inlet	14	13.46%	4	14.29%	24	12.18%	12.77%
Northern_Coastal	20	19.23%	1	3.57%	11	5.58%	9.73%
Doug_Channel-Kit_Arm	10	9.62%	7	25.00%	8	4.06%	7.60%
Homathko-Klinaklini	3	2.88%	0	0.00%	9	4.57%	3.65%
SCoast-QCS-Johnst-S_Fjords	0	0.00%	0	0.00%	8	4.06%	2.43%
Howe_Sound-Burrard	4	3.85%	0	0.00%	1	0.51%	1.52%
Nahwitti_Lowland	1	0.96%	3	10.71%	0	0.00%	1.22%
EVI-Georgia_Strait	2	1.92%	0	0.00%	0	0.00%	0.61%
Mussel-Kynoch	0	0.00%	0	0.00%	2	1.02%	0.61%
Lower_Fraser	1	0.96%	0	0.00%	0	0.00%	0.30%
Georgia_Strait_Main	0	0.00%	0	0.00%	1	0.51%	0.30%
Total	104		28		197		329

Table 10. Estimated contribution of regional coho salmon CUs to catches in PFMA 6 during 2021.

Conservation unit	N	%
HecLow+HStr	31	38.27%
Northern_Coastal	16	19.75%
Doug_Channel-Kit_Arm	15	18.52%
Bella_Coola-Dean_Rivers	4	4.94%
Howe_Sound-Burrard	4	4.94%
Rivers Inlet	4	4.94%
Mussel_Kynoch	2	2.47%
ECVI+GeorgiaStr	1	1.23%
Lower_Skeena	1	1.23%
Middle_Skeena	1	1.23%
Nahwitti	1	1.23%
Scoast-QCS-Johnst-S+S_Fjords	1	1.23%
Total	81	

Table 11. Estimated contributions of regional coho salmon CUs to mixed-stock catches in Rivers Inlet (PFMA 9) during summer of 2021.

Conservation Unit	N	%
Rivers Inlet	140	34.06%
Bella_Coola-Dean_Rivers	83	20.19%
HecLow+HStr	52	12.65%
Doug_Channel-Kit_Arm	34	8.27%
Northern_Coastal	27	6.57%
Scoast-QCS-Johnst-S+S_Fjords	22	5.35%
Howe_Sound-Burrard	18	4.38%
Homathko-Kliniklini	11	2.68%
ECVI+GeorgiaStr	10	2.43%
Smith Inlet	9	2.19%
Lower Fraser River	3	0.73%
ECVI+SFj	1	0.24%
Middle_Skeena	1	0.24%
Total	411	

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Stan model

```
functions {
/**
 * Log probability of the conditional autoregressive (CAR) model
 *
 * @param y Process to model
 * @param mu Mean vector
 * @param tau Scale parameter
 * @param rho Spatial dependence parameter
 * @param ImC Sparse representation of (I - C): non-zero values only
 * @param ImC_v Column indices for values in ImC
 * @param ImC_u Row starting indices for values in ImC
 * @param Cidx Indices for the off-diagonal elements in ImC
 * @param D_inv Diagonal elements from the inverse of Delta, where `M = Delta * tau^2` is a diagonal
matrix containing the conditional variances.
 * @param log_det_D_inv Log determinant of Delta inverse (of matrix D_inv).
 * @param lambda Eigenvalues of C (or of the symmetric, scaled matrix Delta^{-1/2}*C*Delta^{1/2}).
 * @param n Length of y
 *
 * @return Log probability density of CAR prior up to additive constant
*/
real car_normal_lpdf(vector y, vector mu,
                     real tau, real rho,
                     vector ImC, int[] ImC_v, int[] ImC_u, int[] Cidx,
                     vector D_inv, real log_det_D_inv, vector lambda,
                     int n) {
  vector[n] z = y - mu;
  vector[num_elements(ImC)] ImrhoC = ImC; // (I - rho C)
  vector[n] zMinv = (1 / tau^2) * z .* D_inv; // z' * M-1
  vector[n] ImrhoCz;             // (I - rho * C) * z
  vector[n] ldet_ImrhoC;
  ImrhoC[Cidx] = rho * ImC[Cidx];
  ImrhoCz = csr_matrix_times_vector(n, n, ImrhoC, ImC_v, ImC_u, z);
  for (i in 1:n) ldet_ImrhoC[i] = log1m(rho * lambda[i]);
  return 0.5 * ( -n * log( 2 * pi() ) - 2 * n * log(tau) + log_det_D_inv + sum(ldet_ImrhoC) -
dot_product(zMinv, ImrhoCz));
  }

  real car_lognormal_lpdf(vector y, vector mu,
                     real tau, real rho,
                     vector ImC, int[] ImC_v, int[] ImC_u, int[] Cidx,
                     vector D_inv, real log_det_D_inv, vector lambda,
                     int n) {
  vector[n] z = log(y) - mu;
  vector[num_elements(ImC)] ImrhoC = ImC; // (I - rho C)
  vector[n] zMinv = (1 / tau^2) * z .* D_inv; // z' * M-1
  vector[n] ImrhoCz;             // (I - rho * C) * z
  vector[n] ldet_ImrhoC;
```

```
 ImrhoC[Cidx] = rho * ImC[Cidx];
 ImrhoCz = csr_matrix_times_vector(n, n, ImrhoC, ImC_v, ImC_u, z);
 for (i in 1:n) ldet_ImrhoC[i] = log1m(rho * lambda[i]);
 return 0.5 * ( -n * log( 2 * pi() ) - sum(log(y)) - 2 * n * log(tau) + log_det_D_inv + sum(ldet_ImrhoC) -
dot_product(zMinv, ImrhoCz));
 }
}

data {
 // cpue data
 int n;
 int chinook[n];
 int coho[n];
 vector[n] offset_term;
 // CAR data
 int n_area;
 vector[n_area] Delta_inv;
 real log_det_Delta_inv;
 vector[n_area] lambda;
 int nC;
 int nAx_w;
 vector[nAx_w] Ax_w;
 int Ax_v[nAx_w];
 int Ax_u[n_area + 1];
 int Cidx[nC];
 // cpue linear model portion
 int<lower=0,upper=n_area> area[n];
 int<lower=0> nCovarCh;
 int<lower=0> nCovarCo;
 matrix[n,nCovarCh] x_Ch;
 matrix[n,nCovarCo] x_Co;
 int<lower=0> nDisp;
 int<lower=0> nDisp_co;
 int<lower=0,upper=nDisp> disp_id[n];
 int<lower=0,upper=nDisp_co> disp_co_id[n];
 int<lower=0> nWeeks;
 int<lower=0,upper=nWeeks> week_id[n];
 vector[3] prior_alpha_tau; // prior on standard deviation of varying intercepts
 //int<lower=0> ngear;
 real mu_prior_ch;
 real mu_prior_co;
 real sig_prior;
 int<lower=0> neg_binom; // indicator for statistical family
 // overflight boat count
 int n_flight;
 int counts[n_flight];
 real mu_prior_eff;
 real sig_eff_prior;
```

```
  int<lower=0> nCovarEffort;
  matrix[n_flight,nCovarEffort] x_Effort;
  int<lower=0,upper=n_area> area_boats[n_flight];
  int<lower=0,upper=nWeeks> week_boats_id[n_flight];
  vector[n_flight] overflight_correction;
}

parameters {
  // real intercept;
  vector[n_area] mu_pfma_ch;
  vector[n_area] mu_pfma_co;
  real<lower=0> tau_ch;
  real<lower=0> tau_co;
  real<lower=0, upper=1/max(lambda)> rho_ch;
  real<lower=0, upper=1/max(lambda)> rho_co;
  real<lower=0> sigma_ch_week;
  real<lower=0> sigma_co_week;
  real<lower=0> sigma_boat_week;
  vector[nCovarCh] beta_ch;
  vector[nCovarCo] beta_co;
  vector[nWeeks-1] mu_ch_week_raw;
  vector[nWeeks-1] mu_co_week_raw;
  vector[nWeeks-1] mu_boat_week_raw;
  vector<lower=0>[nDisp_co] co_phi;
  vector<lower=0>[nDisp] ch_phi;
  vector[n_area] mu_pfma_effort;
  real<lower=0> tau_effort;
  real<lower=0, upper=1/max(lambda)> rho_effort;
  vector[nCovarEffort] beta_effort;
  real<lower=0> boat_phi;
}

transformed parameters {
  vector[n] log_mu_ch;
  vector[n] log_mu_co;
  vector[n] fit_ch;
  vector[n] fit_co;
  vector[n_flight] log_mu_effort;
  vector[n_flight] mu_boats;
  vector[nWeeks] mu_ch_week;
  vector[nWeeks] mu_co_week;
  vector[nWeeks] mu_boat_week;
  mu_ch_week[1] = 0;
  mu_co_week[1] = 0;
  mu_boat_week[1] = 0;

  for(i in 2:nWeeks)
  {
```

```
    mu_ch_week[i] = mu_ch_week_raw[i-1];
    mu_co_week[i] = mu_co_week_raw[i-1];
    mu_boat_week[i] = mu_boat_week_raw[i-1];
  }

  for (i in 1:n) {
    log_mu_ch[i] = (x_Ch[i]*beta_ch);
    log_mu_co[i] = (x_Co[i]*beta_co);
    fit_ch[i] = exp(log_mu_ch[i]+mu_ch_week[week_id[i]]+mu_pfma_ch[area[i]]);
    fit_co[i] = exp(log_mu_co[i]+mu_co_week[week_id[i]]+mu_pfma_co[area[i]]);
  }
  vector[n] mu_ch = offset_term .* fit_ch;
  vector[n] mu_co = offset_term .* fit_co;
  for (i in 1:n_flight)
  {
    log_mu_effort[i] = (x_Effort[i]*beta_effort);
    mu_boats[i] =
exp(log_mu_effort[i]+mu_boat_week[week_boats_id[i]]+mu_pfma_effort[area_boats[i]])*overflight_co
rrection[i];
  }
}
```

model {

```
  real prec_ch = 1 / (tau_ch^2);
  real prec_co = 1 / (tau_co^2);
  real prec_effort = 1 / (tau_effort^2);

  vector[n_area] log_mu_pfma_ch = rep_vector(0, n_area);
  vector[n_area] log_mu_pfma_co = rep_vector(0, n_area);
  vector[n_area] log_mu_pfma_effort = rep_vector(0, n_area);

  target += car_normal_lpdf(mu_pfma_ch | log_mu_pfma_ch, tau_ch, rho_ch, Ax_w, Ax_v, Ax_u,
Cidx,Delta_inv,log_det_Delta_inv,lambda, n_area);
  target += car_normal_lpdf(mu_pfma_co | log_mu_pfma_co, tau_co, rho_co, Ax_w, Ax_v, Ax_u,
Cidx,Delta_inv,log_det_Delta_inv,lambda, n_area);
  target += car_normal_lpdf(mu_pfma_effort | log_mu_pfma_effort, tau_effort, rho_effort, Ax_w, Ax_v,
Ax_u, Cidx,Delta_inv,log_det_Delta_inv,lambda, n_area);

  target += gamma_lpdf(prec_ch | 2, 0.005);
  target += gamma_lpdf(prec_co | 2, 0.005);
  target += gamma_lpdf(prec_effort | 2, 0.005);

  target += normal_lpdf(beta_ch[1] | mu_prior_ch, sig_prior);
  for(i in 2:nCovarCh){
    target+=normal_lpdf(beta_ch[i] | 0, 1);
  }
  target += normal_lpdf(beta_co[1] | mu_prior_co, sig_prior);
  for(i in 2:nCovarCo){
```

```
  target+=normal_lpdf(beta_co[i] | 0, 1);
 }
 for(i in 1:nCovarEffort){
  target+=normal_lpdf(beta_effort[i] | mu_prior_eff, sig_eff_prior);
 }

 // model ar1 on week-level effects;
 for(i in 2:nWeeks)
 {
  mu_ch_week_raw[i-1] ~ normal(mu_ch_week[i-1],sigma_ch_week);
  mu_co_week_raw[i-1] ~ normal(mu_co_week[i-1],sigma_co_week);
  mu_boat_week_raw[i-1] ~ normal(mu_boat_week[i-1],sigma_boat_week);
 }
 sigma_ch_week ~ cauchy(0, 2);
 sigma_co_week ~ cauchy(0, 2);
 sigma_boat_week ~ cauchy(0, 2);

 if(neg_binom==1) {
  co_phi ~ inv_gamma(0.1,0.1);
  ch_phi ~ inv_gamma(0.1,0.1);
  coho ~ neg_binomial_2(mu_co,co_phi[disp_co_id]);
  chinook ~ neg_binomial_2(mu_ch,ch_phi[disp_id]);
 }
 if(neg_binom==0) {
  target += poisson_lpmf(chinook | mu_ch);
  target += poisson_lpmf(coho | mu_co);
 }
 boat_phi ~ inv_gamma(0.1,0.1);
 counts ~ neg_binomial_2(mu_boats,boat_phi);
}
```

generated quantities {

```
 vector[n] log_lik_ch;
 vector[n] log_lik_co;
 vector[n] ch_ppd;
 vector[n] co_ppd;
 vector[n_flight] boat_ppd;
 vector[n_flight] log_lik_flight;

 for(i in 1:n){
  if(neg_binom==1){
   log_lik_ch[i] = neg_binomial_2_lpmf(chinook[i] | mu_ch[i],ch_phi[disp_id[i]]);
   log_lik_co[i] = neg_binomial_2_lpmf(coho[i] | mu_co[i],co_phi[disp_co_id[i]]);
   ch_ppd[i] = neg_binomial_2_rng(mu_ch[i],ch_phi[disp_id[i]]);
   co_ppd[i] = neg_binomial_2_rng(mu_co[i],co_phi[disp_co_id[i]]);
  }
  if(neg_binom==0) {
   log_lik_ch[i] = poisson_lpmf(chinook[i] | mu_ch[i]);
```

```
      log_lik_co[i] = poisson_lpmf(coho[i] | mu_co[i]);
      ch_ppd[i] = poisson_rng(mu_ch[i]);
      co_ppd[i] = poisson_rng(mu_co[i]);
    }
  }
  for(i in 1:n_flight){
   log_lik_flight[i] = neg_binomial_2_lpmf(counts[i] | mu_boats[i],boat_phi);
   boat_ppd[i] = neg_binomial_2_rng(mu_boats[i],boat_phi);
  }
}
```