**Temporal Patterns in Chinook Salmon Migration Across Western Alaska Watersheds**

Ben Makhlouf, Daniel Schindler, Elizabeth Lee, Eric Ward, Tim Cline, Sean Brennan

**Introduction:**

Chinook salmon populations are experiencing unprecedented declines across much of their range. This trend is especially severe in Western Alaska watersheds, which contain some of the world's last pristine Chinook habitat but have seen steep declines in returning Chinook and Chum salmon in recent years. Salmon from this region support lucrative commercial fisheries and contribute billions of dollars to regional and global economies. These fisheries have also historically supported subsistence harvests for dozens of communities in the region and hold deep cultural importance for upstream communities, many of which have voluntarily reduced or ceased subsistence fishing amidst the decreasing returns. As a result, the collapse of Chinook salmon in Western Alaska has triggered a region-wide crisis of food insecurity, cultural loss, and the potential disappearance of a critical economic resource. Fisheries managers in this region therefore face the difficult task of balancing ongoing harvest opportunities with the urgent need to rebuild salmon populations and strengthen their resilience to future perturbations.

There is growing recognition that biological complexity, expressed through diverse life history strategies and genetic variation, is essential to the stability of both aquatic and terrestrial ecosystems. This diversity can generate a “portfolio effect,” wherein risk is distributed across space and time through multiple locally adapted populations. In salmon, for example, variation in migration timing, ocean residence, and spatial habitat use reduces overall population variance and enhances resilience to environmental change by buffering the population against localized or short-term disturbances. \* Add in literature supporting portfolio effect in salmon\*

Efforts to conserve the long-term resilience salmon runs must therefore account for this spatiotemporal complexity in harvest methods, including overall exploitation rate as well as the timing of harvest throughout the season. For example, harvest strategies that concentrate harvest in periods of peak abundance (e.g., highest CPUE per day) may fail to account for whether this peak consists of a mix of vulnerable, weak stocks or a single, more robust stock that can sustain higher exploitation. An optimal harvest strategy should aim to maximize harvest opportunities on healthy stocks while minimizing the risk of overexploitation for co-migrating weak stocks. However, implementing such stock-specific management is often not possible due to the limited available data on the spatiotemporal ecology of Chinook salmon, especially within Alaska’s largest river basins.

Advances in isotopic methods offer a promising tool to study fine-scale spatial patterns in remote ecosystems. In salmon, isotopic signatures are incorporated into ear stones, or otoliths; metabolically inert structures that record environmental information and can be analyzed post-mortem using laser ablation. Using these techniques, researchers estimate the natal origin of individual fish by comparing isotope ratios such as that of Strontium (⁸⁷Sr/⁸⁶Sr) recorded in otoliths to values measured or modeled across the landscape. In geologically diverse regions like Western Alaska, unique strontium isotope ratios are distributed across the riverscape at relatively fine spatial scales, enabling provenance estimates to the sub-basin or tributary scale. However, in very large systems such as the Yukon River Basin, redundant isotope signatures at multiple locations can limit the spatial resolution of otolith-based methods. Current best genetic baselines for Chinook salmon in this region using genetic stock identification (GSI) can estimate provenance at relatively coarse spatial scales, however, integrative approaches that explicitly combine genetic and isotope data can overcome these challenges and enabling the exploration of fine-scale spatiotemporal patterns even in Alaska’s largest river basins.

Here, we apply otolith-based methods to reconstruct within year spatiotemporal patterns for Chinook salmon in the Yukon and Kuskokwim River basins. Specifically, we aim to: (1) identify the spatiotemporal structure of returning populations in Alaska’s most productive salmon-bearing watersheds; (2) assess how this structure varies with overall run dynamics; and (3) evaluate the potential impacts of harvest strategies, including front-end closures, on stocks across these systems.

**Methods:**

**Otolith Sample set**

We analyzed otoliths collected from two major Chinook salmon monitoring efforts in Western Alaska: the Bethel Test Fishery and the Lower Yukon Test Fishery. Samples were collected across multiple years—2017 through 2021 for the Bethel site, and 2015, 2016, 2017, 2018, and 2021 for the Lower Yukon site. From these collections, 250 otoliths were subsampled to represent the full duration of the Chinook salmon migration, with equal representation across early, middle, and late portions of the run. Otoliths were sectioned along the transverse plane, mounted on microscope slides, and polished to expose internal growth structures. Prepared samples were then sent to the University of Utah Strontium Isotope Laboratory for analysis using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Ablations were performed along a transect from the core of each otolith to just beyond the onset of marine growth, which was identified based on the presence of dark annuli. The analysis captured both strontium isotope ratios (⁸⁷Sr/⁸⁶Sr) and elemental concentrations (⁸⁸Sr), producing a continuous geochemical time series spanning early freshwater development through marine entry.

To isolate the region of the otolith corresponding to freshwater natal origin, we applied a manual selection protocol that considered several features. First, we identified a decline in ⁸⁸Sr concentrations associated with movement away from the embryonic core. Next, we used empirically derived estimates of the distance from the core to the expected natal origin region. Finally, we examined otolith morphology along the transect to identify transitions between early life stages. The resulting data were used to infer natal origin by comparing the measured ⁸⁷Sr/⁸⁶Sr values within this region to spatially explicit strontium isotope isoscapes developed for the Yukon and Kuskokwim river basins.

**Isoscapes:**

Isoscapes were produced of the Yukon and Kuskokwim river basins using spatial stream network modeling, which considers etc. etc.

**Bayesian Model and Priors**

Provenance estimates were produced using a probabilistic Bayesian framework which includes… bring in from the old paper. For samples in the Yukon river basin, a genetic prior was added which incorporates posterior values from genetic stock identification (Makhlouf et al., 2025). Additionally, spatial priors derived from the USGS intrinsic potential model— which synthesizes presence data from telemetry, manual counts, and habitat suitability—were applied to the highest and second highest order tributaries in each basin. This approach constrains assignments away from extensively sampled areas lacking evidence of Chinook spawning. Thresholding values were then assigned to keep only those values in the top 30% of posterior values.

**Polygon binning and conversion to point data**

**Resulting timeseries (25 reads per individual)**

**Spatiotemporal modeling**

To identify areas of consistent Chinook salmon production across multiple years, as well as locations exhibiting temporal variability or absence of production, we employed a spatial modeling approach using the {sdmTMB} package in R. This framework implements spatial and spatiotemporal generalized linear mixed models (GLMMs) based on stochastic partial differential equations (SPDE), allowing for flexible modeling of spatial dependence and temporal variation in abundance indices. We first constructed a spatial mesh over our study area using sampling coordinates (latitude and longitude) to implement the SPDE approximation. A mesh cutoff of 20 km was selected to balance model resolution and computational efficiency. The mesh defines the spatial structure over which spatial and spatiotemporal random effects are estimated.

We then fit a Tweedie GLMM to the observed production data, using a log link function to model density as a function of relevant covariates (e.g., depth or habitat variables), including spatial and spatiotemporal random fields. The temporal component was modeled as independent and identically distributed (iid) across years, capturing year-to-year variability at each location.

To generate spatial predictions for each year, we applied the fitted model to a prediction grid spanning the study region, replicating it for each year of data. From these predictions, we extracted the spatial random field (omega\_s) representing persistent spatial patterns, the spatiotemporal random field (epsilon\_st) capturing temporal fluctuations, and the combined random field (est\_rf).

We summarized temporal variability in production by calculating the standard deviation (SD) and coefficient of variation (CV) of predicted values across years at each grid cell. Mapping these statistics enabled us to classify areas as consistently productive (low temporal variability), variably productive (high temporal variability), or unproductive (low predicted production across years). These spatial maps provide insight into the stability and dynamics of Chinook salmon production, informing management decisions for harvest strategies and conservation priorities.

**Front end closure simulation**

**Results:**

**Discussion:**